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Communication Interface Manager for Improving Performance of Heterogeneous UAV Networks.

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This work is dedicated to everyone who has always
believed in my success and academic potential,
wishing happy and fruitful days along of my life. In
special, to my parents, to my love, and to my twin boys.

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I lift up my eyes to the mountains— where does my help come from?
My help comes from the Lord, the Maker of heaven and earth.
(PSALM 121, A song of ascents)
When our last hour comes, we will have the great and ineffable
joy of seeing the One whom we could only glimpse in all our work.
(GAUSS, 1809)

RESUMO

Prover troca de mensagens com conexões estáveis em missões compostas por múltiplos veículos aéreos não tripulados (VANT) é uma tarefa complexa. Além disso, o tráfego de diferentes classes de acesso de mensagens como voz, dados e vídeo, necessitam de diferentes requisitos de rede. Desta forma, a confiabilidade na entrega das mensagens e a qualidade do enlace são desafios importantes para garantir a troca de diferentes mensagens de forma dinâmica, atendendo aos diversos requisitos de rede com qualidade de serviço (QoS). O uso da comunicação heterogênea tem mostrado ganhos na manutenção da conexão entre nós altamente móveis, aumentando a confiabilidade na transmissão de dados, conforme visto nas MANETS e VANETs. Neste contexto, esta tese propõe um gerenciador de interface heterogêneo (IM) para redes sem fio compostas por múltiplos VANTs. Assim, dado um conjunto predefinido de interfaces, o gerenciador proposto define dinamicamente a melhor interface para enviar as próximas mensagens com base nas condições de voo detectadas e calculadas dinamicamente a partir do meio sem fio. O gerenciador considera dados de monitoramento atualizados que representam o estado atual dos enlaces de comunicação entre os VANTs durante a sua trajetória. Atualmente, uma árvore de decisão combinada a uma heurística de soma de pontos é utilizada como base para a abordagem proposta e visa apoiar as decisões do IM decidindo em tempo real entre duas ou mais interfaces de comunicação sem fio. Primeiramente, o IM é avaliado usando duas interfaces de comunicação sem fio IEEE 802.11n IEEE 802.11p empregando diferentes bandas de frequência. Em um segundo momento, o IM aplica várias interfaces de comunicação local sem fio: IEEE 802.11n, IEEE 802.11p, IEEE 802.11ac e IEEE 802.11ax, para validar a sua característica de modulariedade. Diversas simulações são realizadas usando uma configuração de simulação realista (e complexa) baseada no simulador de rede NS-3, conectado a simuladores de mobilidade Gazebo ou SUMO, gerando cenários de mobilidade 2 D e 3 D. Um comparação é proposta, avaliando o desempenho das interfaces de comunicação aplicadas de forma homogênea (com uma única interface) e heterogênea (usando o IM proposto com um conjunto diferente de interfaces). Dois conjuntos de métricas são constituidos para avaliar o IM em termos de camada MAC e física e de aplicação. Os resultados obtidos mostram que comparado com os casos em que uma única interface é utilizada, o IM permitiu duplicar a vazão da rede e apresentar a melhor proporção de pacotes transmitidos e recebidos com potência de recepção (-60 dBm a -75 dBm) e perdas de sinal (-80 dB a -85 dB), resultando em conexões de rede mais eficientes e estáveis.

Palavras-chave: Communicações sem fio. VANT. Redes Móveis. Protocolos e Padrões IEEE 802.11.Confiabilidade. Estabilidade das conexões.Simulador de Rede. Simulador de Mobilidade.Redes veiculares.

RESUMO EXPANDIDO

Um Gerenciador de interfaces de comunicação para estabelecer redes heterogêneas compostas por múltiplos VANTs.

Palavras-chave: Communicações sem fio. VANT. Redes Móveis. Protocolos e Padrões IEEE 802.11.Confiabilidade. Estabilidade das conexões.Simulador de Rede. Simulador de Mobilidade.Redes veiculares.

Introdução

Prover meios para troca de mensagens com estabilidade na conexão, em redes ad hoc compostas por múltiplos veículos aéreos não tripulados (VANTs), é uma tarefa complexa principalmente, devido a característica de alta mobilidade e topologias variantes que os veículos assumem ao longo da missão.

Outro fator que corrobora com a complexidade é que o tráfego proveniente destas redes, também podem ser constituidos por diferentes classes de acesso de mensagens como voz, dados e vídeo. Além disso, para transmitir estas mensagens com qualidade de serviço (QoS, Quality of Service), diferentes requisitos de rede precisam ser verificados na constituição destas redes, tais como: latência, throughput, delay, perdas de sinal, dentre outros, de acordo com a aplicação da missão.

Neste contexto de comunicação altamente dinâmico, maximizar a entrega de pacotes e melhorar a qualidade das transmissões são requisitos de suma importância na consituição e sucesso de uma missão composta por FANETs (SAYYED, 2016b; SCHERER *et al.*, 2015). FANET (Fly Ad-Hoc Network) é uma denominação usada para representar uma rede ad hoc cujos os nós de comunicação são VANTs. Estas são escaláveis, dada a capacidade de adicionar e remover VANTs de forma dinâmica, são flexíveis, pois permitem uma integração com outras redes e podem assumir diferentes topologias ao longo do voo e, possuem alta capacidade de sobrevivência, uma vez que a comunicação não depende de um único nó (ZENG; ZHANG, R.; LIM, 2016; YANMAZ, Evşen *et al.*, 2018; BEKMEZCI; SAHINGOZ; TEMEL, 2013).

Sistemas multi-VANTs consistem em soluções que utilizam veículos voadores para desempenhar uma determinada tarefa ao longo de uma missão, estas podem ser compartilhadas e colaborativas ao longo do voo, por meio do estabelecimento de links de comunicação entre os VANTs (as FANETS). A exemplo disto temos as missões de busca e resgate, conhe-cidas como missões do tipo SAR (Search an Rescue), onde os veículos podem compartilhar e dividir as tarefas de localizar uma possível vítima de afogamento, transmitir o sinal de vídeo para uma estação de controle e carregar uma bóia salva-vidas (YANMAZ, Evsen *et al.*, 2018; SCHERER *et al.*, 2015; MENEGOL; HÜBNER; BECKER, L., 2018).

De modo a prover melhorias na estabilidade destas comunicações, algumas pilhas de protocolos apresentam em sua camada de acesso ao meio, alterações nos esquemas de associação dos nós, como a diminuição do intervalo de geração de quadros CTS, RTS e ACK e a diminuição do tamanho do cabeçalho dos pacotes, reduzindo assim, o tempo de resposta na entrega das mensagens. Outras alternativas visando a confiabilidade nestas comunicações incluem mecanismos complementares a um protocolo de comunicação, que atuam gerenciando as atribuições dos canais de frequência e sistemas de algoritmos robustos, que otimizam a qualidade na troca de mensagens e esquemas de reposicionamento dos nós, de modo a melhorar a sua intensidade da conexão (WATANABE; TAKAHASHI; TOBE, 2017; PARK, J. H. *et al.*, 2018; HUI, K. P.; PHILLIPS, Damien; KEKIRIGODA, Asanka, 2017).

Neste contexto, o uso de diferentes interfaces ou protocolos de comunicação (redes heterogêneas) pode ser uma alternativa viável na melhoria da produtividade da rede e confiabilidade nestas transmissões, uma vez que a tarefa de aplicar um único padrão de comunicação sem fio para suportar diferentes tráfegos de rede torna-se um ponto crítico no desenvolvimento desses sistemas.

O uso inteligente das diferentes características intrínsecas presentes nos diferentes padrões de comunicação, fornecem uma maior adaptabilidade da rede a eventos inesperados, como interferências, disconexões e redução da qualidade de sinal, minimizando os impactos causados nos diferentes requisitos de estabelecimento de uma rede. Neste contexto, o uso de um gerenciador de interfaces para prover uma comunicação heterogênea robusta, entre multiplos VANTs, melhorando a estabilidade, produtividade e confiabilidade na entrega de mensagens é o objeto de estudo desta tese.

Objetivo

O foco de trabalho é desenvolver uma alternativa robusta para estabelecer links de comunicação entre VANTs, com qualidade de serviço, visando possibilitar a execução de missões que possuam tarefas colaborativas e cooperativas, com maior confiabilidade na entrega de mensagens e produtividade de mensagens entregues, a partir de avaliações dinâmicas das condições do meio.

Este objetivo geral é dividido em três objetivos mais específicos:

O primeiro objetivo é validar o desempenho de um gerenciador de interfaces heterogêneo, constituído por uma árvore de decisão combinada com uma heurística de soma de pontos, para prover decisões a partir do emprego de diferentes interfaces de comunicação sem fio nos VANTs.

O segundo objetivo é fornecer links de comunicação mais estáveis, melhorar a conectividade de comunicação e aumentar os níveis de entrega de mensagens (produtividade da rede). O desempenho das diferentes combinações de interfaces atribuidas ao IM é avaliado em termos de duas configurações experimentais: (i) resultados de camada de aplicação e (ii) resultados de camada MAC e PHY. O primeiro descreve e valida a solução em termos de taxa de transferência, taxa de entrega de pacotes (PDR), atraso *end-to-end*, latência média e número de pacotes de diferentes ToS entregues. Neste contexto, são constituidos cenários de validação, a partir dos quais a missão precisa enviar quatro diferentes classes de acesso (AC, *Access Classes*) de mensagens: voz (AC_VO), vídeo (AC_VI), dados (AC_BE) e sinalização (AC_BK), provenientes da propagação de *beacon frames*.

O segundo conjunto de testes compreende os resultados das camadas MAC e PHY e são compostos de condições de propagação dinamicamente detectadas durante todos os experimentos, como potência de recepção, atraso, perda, RSSI, ruído, efeitos de desvanescimento e SNR (relação sinal-ruído). Os resultados destas camadas são usados para avaliar a qualidade das conexões entre os VANTs durante a missão.

O terceiro objetivo é avaliar quais métricas de avaliação de rede são mais críticas nos diversos cenários empregados, destacando as decisões tomadas pelo gerenciador de interfaces e os benefícios gerados por seu uso, a partir de um determinado ToS (*Type of Service*).

Metodologia

A metodologia utilizada para o desenvolvimento desta tese se baseia em três componentes principais: (i) modelagem, arquitetura e forma do gerenciador de interfaces, (ii) mecanismo de execução, (iii) elaboração dos cenários de experimentação 2 D e 3 D e (iv) obtenção, validação e discussão do resultados gerados pelo gerenciador a partir de suas execuções nos cenários definidos.

Considerando o item (i) o gerenciador de intefaces é modelado utilizando como base um algoritmo de árvore de decisão combinado a uma heurística de soma de pontos, que decide em tempo real entre duas ou mais interfaces de comunicação sem fio. Assim, dado um conjunto predefinido de interfaces aplicadas em um veículo, o gerenciador define dinamicamente a melhor interface para envio das próximas mensagens com base nas diferentes distâncias ente nós obtidas ao longo do voo e nas métricas de rede sensoriadas e calculadas a partir do meio sem fio.

A melhor interface é contituida pela qual reunir a maior quantidade de pontos a partir das condições de avaliação de rede, que compõem cada nível da árvore. Quanto a arquitetura o gerenciador proposto é composto por 4 camadas: aplicação, processamento, enlace (MAC) e física (PHY), cuja a execução funciona no sentido *bottom-up*. Quanto a forma o gerenciador atua de maneira distribuida em cada VANT, sem pontos de concentração das mensagens, cada VANT é responsável por suas próprias decisões.

Em termos de mecanismo de funcionamento (item ii), o gerenciador armazena em um buffer cíclico os dados de monitoramento atualizados, que representam o estado atual dos links de comunicação dos VANTs dentro de um determinado ambiente. A partir disso, a árvore de decisão realiza a comparação das performances obtidas por cada interface para cada condição de avaliação, somando pontos para interface que apresentar o melhor desempenho. A heurística considera como parâmetros (inputs), as seguintes condições de rede: número de bytes recebidos, número de bytes perdidos, o throughput, o indicador de intensidade do sinal recebido (RSSI) e a relação sinal-ruído (SNR).

Seis cenários de experimentação foram consituidos (item iii), usando uma configuração de simulação realista (e complexa) baseada no simulador de rede NS-3 interoperando com simuladores de mobilidade, como, Gazebo ou SUMO. Isso permitiu que as missões fossem constituídas em cenários de mobilidade 2 D e 3 D deixando os aspectos de comunicação para serem processados e executados pelo NS-3. Assim, dois cenários 2 D e quatro cenários 3 D foram definidos para validação do gerenciador.

Em termos de resultados e validações (item iv), primeiramente são adicionadas ao gerenciador duas interfaces de comunicação sem fio, IEEE 802.11n e IEEE 802.11p, de forma a empregar diferentes bandas de frequência, validando a heurística da árvore de decisão. Em um segundo momento, o gerenciador aplica várias interfaces de comunicação sem fio, de banda única e multibanda, a saber: IEEE 802.11n, IEEE 802.11p, IEEE 802.11ac e IEEE 802.11ax, expandindo suas possibilidades de decisão. São realizados vários cenários experimentais envolvendo diferentes números de VANTs, empregando diferentes velocidades e percorrendo diferentes distâncias ou trajetórias. O objetivo foi comparar o desempenho das interfaces de comunicação aplicadas de forma homogênea (com uma única interface) e heterogênea (usando o gerenciador proposto com conjuntos diferentes de interfaces), ressaltando e discutindo o comportamento do gerenciador.

O desempenho do gerenciador é avaliado em termos de métricas das camadas de controle de acesso médio (MAC) e física, e em termos de camada de aplicação, de modo a prover um maior volume de avalições.

Resultados e Discussão

Os resultados obtidos mostram que comparado com os casos em que uma única interface é utilizada, o gerenciador de interface proposto pode aumentar em até duas vezes a taxa de transferência da rede, apresentando a melhor proporção de pacotes transmitidos e recebidos, potência de recepção em bons e excelentes níveis (-60 dBm a -75 dBm) e baixa perda de sinal (-80 dB a -85 dB), resultando em conexões de rede mais eficientes e estáveis, com maior produtividade da rede, apresentando em determinadas combinações de interfaces, quantidades até dez vezes maiores de mensagens efetivamente entregues pela rede em comparação as interfaces aplicadas de forma homogênea.

Assim, as definições providas pelo gerenciador de interface foram capazes de apresentar menor suscetibilidade a interferência de ruídos causadas por efeitos de desvanecimento em transmissões de pacotes pequenos, melhor proporção de latência em relação a quantidade de fluxos de mensagens recebidos pela rede, maiores taxas de transferência e maior quantidade de carga útil entregue com sucesso, em comparação as interfaces aplicadas de forma homogênea.

Em geral, o gerenciador apresentou maior flexibilidade e adaptabilidade para cenários de comunicações multi-VANTs atingindo melhores performances. Dentre os desempenhos das interfaces aplicadas de forma homogênea (apenas uma interface de comunicação), as interfaces IEEE 802.11 ac e 802.11 p apresentaram melhor desempenho nesses cenários em termos de métricas de camada de aplicação e, as interfaces 802.11 ax 2.4 GHz e 802.11p, em termos de métricas de camadas MAC e PHY.

Outra conclusão importante é que, dependendo das interfaces aplicadas na comunicação heterogênea, um maior número de interfaces adicionadas não implica em melhores desempenhos de rede, assim determinadas combinações podem ser mais propícias para uma determinada aplicação, considerando os diferentes requisitos de transmissão e tipos de serviço da rede.

Considerações Finais

Missões colaborativas ou missões com tarefas compartilhadas que empregam redes multi-UAV sem fio, requerem maior estabilidade de sinal e atenção especial à entrega confiável de mensagens. Uma parte importante desse desafio está relacionada à tecnologia de interface sem fio usada. Neste contexto, nesta tese é proposto um gerenciador de interface heterogêneo capaz de definir dinamicamente a melhor interface de comunicação a ser utilizada quando mais de uma opção estiver disponível. Seu funcionamento consiste em avaliações dinâmicas de parâmetros coletados do meio. Os principais benefícios desta solução é a melhoria da conectividade e estabilidade dos enlaces estabelecidos pelas comunicações VANT-para-VANT e o aumento da confiabilidade de entrega de mensagens.

O gerenciador proposto trata-se de uma solução modular, logo é possível adicionar e remover interfaces sem alterações em sua arquitetura. O gerenciador é capaz de tomar decisções acerca de qual é a melhor interface a ser utilizada para o próximo envio de mensagens, utilizando uma árvore de decisão e uma heurística de soma de pontos. Um ambiente de simulação complexo envolvendo ferramentas de mobilidade em 2 D e 3 D é definido para validar a solução proposta. A ideia base é apresentar uma simulação mais próxima do ambiente real.

Os resultados mostram que o gerenciador apresentou menor flutuação de rede, mantendo alta vazão, níveis bons ou excelentes de recepção de sinal, dadas as características das interfaces utilizadas, apresentando menores taxa de perda de pacotes. O gerenciador foi capaz de manter a potência recebida entre –60 e –75 dbm em uma distância de até 450 m entre os nós, apresentando baixos índices de perda de sinal (80 dB a 85 dB) e SNR acima de 0,52. Assim, o uso do IM promoveu maior estabilidade do enlace contituindo uma solução adaptativa, a partir de uma seleção de interfaces de acordo com às condições dinamicas do meio, aumentando a confiabilidade e a produtividade da rede quando comparado as interfaces aplicadas de forma homogênea.

Em geral, os resultados mostraram que o uso dinamico de diferentes interfaces nas decisões do gerenciador de interfaces, compõe uma solução poderosa para manter e aumentar a qualidade do link em redes compotas por múltiplos VANTs, alcançando melhorias significativas no volume de mensagens recebidas em distâncias maiores.

Como trabalhos futuros, serão validados alguns algoritmos de aprendizado de máquina como deep learning, redes neurais e classificadores, utilizando como atributos ou parâmetros as diferentes classes de acesso de mensagens. Assim, podem ser atribuídos pesos diferentes as métricas de avaliação da rede de acordo com os diferentes requisitos de rede, favorecendo algumas em detrimento de outras. Deste modo, para uma missão envolvendo mensagens compostas por transmissões em tempo real de video, por exemplo, poderia-se atribuir dinamicamente pesos maiores para métricas de avaliação como atraso, throughput e SNR. Outras validações podem ser realizadas em experimento real, de modo a comparar com os obtidos nas simulações.

ABSTRACT

Performing means for exchanging messages with stable connections in missions composed of multiple unmanned aerial vehicles (UAV) is a complex task. In addition, the use of different access classes such as voice, data, and video are increasingly present in the execution of applications involving networks composed of multiple UAVs. In this way, the reliability in the delivery of messages and link quality are relevant challenges for ensuring the exchange of different messages dynamically, meeting the several ToS network requirements with quality of service (QoS). The use of heterogeneous communication has shown gains in maintaining the connection among highly mobile nodes while increasing reliable data transmission, as needed in MANETS, VANETs, and, more recently, in FANETs. In this context, this thesis proposes a heterogeneous interface manager (IM) that is capable of improving communication in multi-UAV networks. Given a predefined set of available individual wireless interfaces, the proposed IM dynamically defines the best interface for sending messages based on on-flight conditions sensed and calculated dynamically from the wireless medium. The proposed IM is situated above the network link layer and contains a heuristic that decides in real-time between two or more wireless communication interfaces. It considers up-to-date monitoring data that represent the current state of the UAVs' communication links within a given environment. Currently, a decision tree (DT) with a sum of points heuristic is used as a basis for the proposed approach and aims to support the decisions of IM. The heuristic accounts for parameters, such as the number of bytes received, number of bytes lost, throughput, received signal strength indication (RSSI), and signal to noise ratio (SNR). Firstly, the proposed IM is designed using IEEE 802.11n and IEEE 802.11p wireless interfaces employing different frequency bands to validate the decision tree heuristic. Secondly, the IM applies several single-band and multiband wireless local area communication interfaces: IEEE 802.11n, IEEE 802.11p, IEEE 802.11ac, and IEEE 802.11ax, to extend the IM decision possibilities. The IM is validated with simulations conducted using a realistic (and complex) simulation setup based on the NS-3 network simulator, connected to the Gazebo or SUMO mobility simulators. This allows the UAV missions to be programmed in 2 D and 3 D mobility scenarios, and leave all communication aspects to be processed within NS-3. There were conducted several experimental scenarios involving different numbers of UAVs, flying at different speeds, traveling different distances and trajectories. The aim was to analyze the performance of the communication interfaces applied homogeneously (with a single interface) and heterogeneously (using the proposed IM with a different set of interfaces). The IM performance was evaluated through two set of metrics constituted by the MAC and PHY layers, and from the application layer. Obtained results show that compared with the cases where a single interface is used, the proposed IM can increase the network throughput and presents the best proportion of transmitted and received packets, reception power (-60 dBm to -75 dBm), and loss (-80 dB to -85 dB), resulting in more efficient and stable network connections. The results showed that a combination of different interfaces in the IM decisions is capable to compose a powerful solution to maintain and increase the link quality in U2U achieving message exchange over greater distances.

Key-words: wireless networks; UAV communications; mobile network; IEEE standards; reliability; connection stability; network simulators; mobility simulators.

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ACK	(*Acknowledgment*)
BC	(*backoff counters*)
BSM	(*Basic safety messages*)
CBR	(*Constant-Bit Rate*)
CTS	(*Clear to Send*)
DT	(*Decision-tree*)
GCS	(*Ground Control Station*)
GNSS	(*Global Navigation Satellite System*)
GSB	(*Ground Station Base*)
IoT	(*Internet of Things*)
LOS	(*Line of sight*)
MDC	(*Mobile Data Collector*)
ML	(*Machine Learning*)
NLOS	(*Non-line of sight*)
PSC	(*Public safety applications*)
RRM	(*Radio Resource Management*)
RSSI	(*Received Strength Signal Indicator*)
RTS	(*Request to Send*)
SARSA-Lambda	(*State Action Reward State Action with eligibility traces*)
SVM	(*Support Vector Machine*)
U2B	(*UAV-to-Base Station*)
U2U	(*UAV-to-UAV communications*)
VPN	(*Virtual Private Network*)
WSM	(*Wave Short Message*)
WSN	(*Wireless Sensor Network*)

CONTENTS

1 INTRODUCTION

The application of unmanned aerial vehicles (UAV) is proving to be extremely useful in a variety of areas, from agriculture to military missions (JAWHAR *et al.*, 2017; SALEEM; REHMANI; ZEADALLY, 2015a). The need to exchange messages appears in many of these applications, either in the form U2U (U2U, *UAV-to-UAV communications*) or U2B (U2B, *UAV-to-Base Station*) communications. This allows remote access to difficult areas, where video transmission and additional measurement data traffic are needed, such as in applications for border and cave monitoring, natural disaster monitoring, search and rescue (SAR) missions, and others (BEKMEZCI; SAHINGOZ; TEMEL, 2013).

Flying ad hoc networks (FANET) is a denomination used to represent an ad hoc network among UAVs. It promotes network scalability, given the capacity to add and remove UAVs from the network. It also aims to ensure network survivability since communication does not rely in a single node UAV (ZENG; ZHANG, R.; LIM, 2016; YANMAZ, Evsen *et al.*, 2018).

Multi-UAVs or mUAVs systems consist in applications that involve FANETs, in which UAVs operate in a collaborative way or by sharing tasks in order to achieve predefined goals during a mission. Wireless communication can use UAVs as source nodes, relay nodes, and sink nodes to expand the limits of the mobile networks, allowing to reach much higher speed than a person carrying a mobile device (PARK, J.-g. *et al.*, 2012), and with more control over trajectory than wireless sensor networks composed by spread devices in array to monitoring volcano eruptions (WERNER-ALLEN *et al.*, 2005). As applications example it can be mentioned the use of UAV networks to extend the range of communication and proposing collaborative or interoperability with other networks, such as VANETs (Vehicular Ad-Hoc Networks), MANETs (Mobile Ad-Hoc Networks), and IoT (Internet of Things) networks (BEKMEZCI; SAHINGOZ; TEMEL, 2013; PARK, J. H. *et al.*, 2018).

However, several challenges still prevent the complete establishment of FANETs, for example, the demand for reliable wireless communications to allow sending and receiving messages with lower risk of signal loss. The main issues are maintaining reliable connections between high-mobility nodes with signal quality, low delay, and a high message delivery rate between nodes. These metrics are of utmost importance for guaranteeing the quality of service in systems involving mobile UAV networks.

In some cases, problems in the transmission and reception, such as the loss of many packets, prolonged delays, and throughput variance cause missions to decrease in quality and, in the worst case, to be a complete mission failure (PARK, J. H. *et al.*, 2018). Besides, communication between UAVs require different types of packets to be sent. These packets can be short or long, depending on the payload and the kind of

MAC protocol adopted. The packets size are defined by the number of data they need to carry, including the preamble and the header. Long packets are usually composed of data files, video, and images (e.g. users accessing the Internet over a Wi-Fi network). Short packets are typically composed by traffic generated from measurement and control signals (e.g. machine-type communication) (DURISI; KOCH; POPOVSKI, 2016).

According to assigned tasks in a mission, the UAV network needs to send different kind of packets, such as video, voice, sensors data, actuators data, and coordination commands (JAWHAR *et al.*, 2017; LEE, 2021). For instance, an UAV in a SAR (Search and Rescue) mission could be used in different ways, such as for transmitting video of a drowning person to the Ground Control Station and to other UAVs, while still sharing goals with others, such as delivering supplies to or carrying life buoys to the victims (BATISTA DA SILVA *et al.*, 2017; KIM; CHOI, 2017). These goals generate different network traffics, varying in packet size, transmission rate, and bandwidth consumption.

1.1 RESEARCH CONTEXT AND MOTIVATIONS

In this way, some approaches consider pre-determined activities before the mission, as seen in UAV interaction approaches (e.g., (MENEGOL; HÜBNER; BECKER, L., 2018)), where the authors denote a fixed point P to which the UAVs should fly in order to meet each other, to fly within communication range, so that they can share and update data to perform their tasks. Other approaches aimed at buffering and exchanging messages only during the occurrence of events-of-interest (WATANABE; TAKAHASHI; TOBE, 2017) or, alternatively, within predefined time intervals (HUI, K. P. *et al.*, 2011; HUI, K.; PHILLIPS; KEKIRIGODA, 2017). In these approaches, the message exchange is severely affected in the absence of a communication signal (or when the signal quality is poor). Thus, dynamic evaluations are lacking of the communication spectrum to which each UAV node is submitted.

Other researchers applied the repositioning of nodes in the occurrence of a detected target (YANMAZ, Evşen *et al.*, 2014; SCHERER *et al.*, 2015). For example, in (SCHERER *et al.*, 2015), when an UAV from the fleet detects a target, it sends messages to the other UAVs, requesting them to reposition themselves at fixed distance intervals from it. However, other application scenarios cannot cope with trajectory modifications, e.g., on SAR missions that have tight timing restrictions (SALEEM; REHMANI; ZEADALLY, 2015a; SAHINGOZ; OKULU, 2016).

Depending on the mUAVs application, different requirements in terms of connectivity level, latency, and throughput may appear. Thus, the task of applying a single wireless communication standard to support different network traffic becomes difficult/inefficient. Depending on the type of messages, if not properly transmitted, it can a bottleneck to the proper functioning of the entire system (BEKMEZCI; SEN; ERKALKAN, 2015; HUSSEN *et al.*, 2018).

The use of different interfaces or communication protocols in the same network (heterogeneous networks) may be an interesting solution to maintain reliable communication links in networks composed of mobile nodes, given the vast number of successful cases in other mobile networks. Examples are the MANETs and VANETs (MONTEIRO *et al.*, 2019; LIMA *et al.*, 2018).

Using different communication standards in UAV networks can be helpful in increasing the reliability of communications, while also offering additional advantages when compared to using a single standard. For instance, the selection of the best communication interface/standard should take into account the types of packets to be sent and the current state of the medium. Also, the network survivability increases as each UAV defines the best interface to maintain the connectivity in the highest levels. In this context, one suitable solution is the deployment of Heterogeneous Networks, which integrates and enables access to different communication standards, like WAVE/DSRC communications and Wi-Fi/ISM networks, to support the communication requirements of UAV applications (YOKOYAMA; KIMURA; SANTOS MOREIRA, 2014; PARK, J. H. *et al.*, 2018; RIBEIRO, L.; MULLER; BECKER, L., 2020)

Experiments conducted within this thesis and published in (RIBEIRO, Laura Michaella B.; BUSS BECKER, 2019) show that even supposedly MAC and PHY layer similar interfaces such as IEEE 802.11n and 802.11p behave quite differently depending on the medium conditions. These interfaces have been widely used by researchers, who have applied their standard stack layers to develop solutions for improving UAV network reliability and stability in different UAV missions (YANMAZ, Evşen *et al.*, 2014; SCHERER *et al.*, 2015; HUSSEN *et al.*, 2018).

The 802.11 technologies became popular in the constitution of FANETs because it provides robust MAC and PHY layers that apply multiple input and multiple output (MIMO) technologies with high throughput and larger bandwidth, features that have been extensively explored in this scenario (ZENG; ZHANG, R.; LIM, 2016; YANMAZ, Evsen *et al.*, 2018). Another important factor is that 802.11 a,b,g,n,ac, and most recent 802.11 ax is commonly found in UAVs classified as common commercial devices (low cost). The IEEE 802.11p 5 GHz was developed for high-mobility networks or dynamic time-varying environments (i.e., networks composed of vehicles (LIMA *et al.*, 2018), underwater nodes (TEIXEIRA *et al.*, 2015), and robot nodes (GIELIS; PROROK, 2021)), it presented better performance also in FANETS (RIBEIRO, Laura Michaella B.; BUSS BECKER, 2019).

However, the high mobility present in UAV networks bring other challenges that do not only involve having an active quality connection to the network, but also the intensity of the connection of this node to the network. In other words, whether or not a node is able to receive and transmit quality data in communication, even if its positioning is not fixed. An important task for maintaining wireless communication in a distributed way without relay nodes is to ensure that the nodes remain within the range of at least one neighboring node that belongs to the network. This communication must occur through a reliable connection to maintain effective communication between each node (HUI, K. P. *et al.*, 2011; HUI, K.; PHILLIPS; KEKIRIGODA, 2017).

According to the application characteristics, different communication requirements need to be observed, such as the link performance while sending different access classes AC_VO (voice), AC_VI (video), AC_BK (background), and AC_BE (best-effort), since it exists several wireless technologies that can be exploited for UAV networks, taking into account the high mobility, link instability, and high medium dynamics (RIBEIRO, Laura Michaella B.; BUSS BECKER, 2019).

In this context several works proposed solutions to cover issues involving UAVs wireless ad-hoc networks, such as maintaining strong connection between network nodes (JAWHAR *et al.*, 2017), reliable transmission and reception with QoS (NASRALLAH; AL-ANBAGI; MOUFTAH, 2014), minimal latency (YANMAZ, Evşen *et al.*, 2014), low delay (SILVA *et al.*, 2019), and high packet delivery rate (MURILLO *et al.*, 2018). These issues vary depending on the kind of data that the UAVs need to exchange during the mission (eg. voice, video, data).

1.2 THESIS CONTRIBUTIONS

The present thesis investigates a heterogeneous communication solution by presenting a communication interface manager (IM) for missions involving multiple UAVs in order to maintain and improve the reliability in the communications between multi-UAVs.

First, the proposed IM is developed above the network link layer and contains a heuristic that decides “on the flight” between two or more wireless communication interfaces. It considers up-to-date monitoring data that represent the current state of the UAVs’ communication links within a given environment. The heuristic accounts for parameters, such as the number of bytes received, number of bytes lost, throughput, received signal strength indication (RSSI), and signal to noise ratio (SNR), but allow the addition of new ones. The proposed IM is initially implemented using two wireless interfaces: IEEE 802.11n 2.4 GHz and IEEE 802.11p 5 GHz.

Second, an exhaustive set of experiments are deploy extending the set of interfaces applied in the IM in different experiments: IM-2Int (using IEEE 802.11n 2.4 GHz and IEEE 802.11p 5 GHz), IM-3Int (both before plus IEEE 802.11ac 5 GHz), IM-4Int (all interfaces cited before plus IEEE 802.11ax 2.4 GHz), and IM-5Int (including all communication interfaces of others experiments plus IEEE 802.11ax 5 GHZ). Thus, it is possible to observe the modular feature of this system, which allows UAVs to transmit signals through different frequency bands, modulations, and MAC protocols.

Third, two different experimentation setups are constituted in order to validate the solution more broadly. Then, IM is applied in six different simulation scenarios, using a 2 D and a 3 D tools integration, evaluating the IM performance in both integration cases. The 3 D experimentation setup brings more realistic (and complex) simulations based on the NS-3 network simulator, connected to the Gazebo multi-UAV simulator. This allows the UAV missions to be programmed within Gazebo, and leave all communication aspects to be processed within NS-3. The six experimental scenarios involving different numbers of UAVs, flying at different speeds, traveling different distances and trajectories were adopted for analyzing the performance of the communication interfaces applied homogeneously (single interface) and heterogeneously (using the proposed IM).

1.3 OBJECTIVES AND SCOPE LIMITS

The overall objective of this thesis is researching how to improve and maintain the link quality in collaborative and cooperative multi-UAVs missions, improving the reliability in the delivery of messages and thereby allowing the execution of shared mission goals increasing the performance and efficiency of the network. This general goal is further divided into two more specific goals:

- The first objective is validate the performance of interface manager in different combinations of interfaces by sending different ToS traffic applied in multi-UAV networks.
- The second objective is to provide more stable communication links, enhances communication connectivity, and increases message delivery levels. The performance of the different IM combinations is evaluated in terms of two experimental setups: (i) application results and (ii) MAC and PHY results. The Application results describe the experiment performances in terms of throughput, packet delivery rate (PDR), end-to-end delay, average latency, and number of packets from different ToS delivered. The network impacts caused by an application that needs to send the four different access classes defined in this paper: voice (AC_VO), video (AC_VI), data (AC_BE), and control signals, network signs, and beacon frames (AC_BK) are considered in the discussions.

  The MAC and PHY results are composed of dynamically sensed propagation conditions collected during all the experiments, such as reception power, delay, loss, RSSI, noise, IM validations propagation effects, and SNR (signal-to-noise ratio). The results of MAC and PHY set are used to describe the quality of connections between the UAVs during the mission.
- The third objective is to validate which metric will be more critical in these scenarios according to mission requirements.

1.4 LIST OF PUBLICATIONS

Four papers were published along this PhD, as follows:

- RIBEIRO, L. M. B.; BECKER, L. B. **Performance analysis of IEEE 802.11p and IEEE 802.11n based on QoS for UAV networks**. In:Proceedings of the 9th ACM Symposium Design and Analysis of Intelligent Vehicular Networks and Applications. New York,NY, USA: Association for Computing Machinery, 2019. (DIVANet '19).
- RIBEIRO, L.; MULLER, I.; BECKER, L. **Gerenciamento de interfaces para prover comunicação heterogênea em redes compostas por múltiplos UAVs**. In:Anais Estendidos do X Simpósio Brasileiro de Engenharia de Sistemas Computacionais. Porto Alegre, RS, Brasil: SBC, 2020. p. 49–56.
- RIBEIRO, L. M. B.; MüLLER, I.; BECKER, L. B. **Communication interface manager for improving performance of heterogeneous UAV networks**. Sensors, v. 21, n. 13, 2021.ISSN 1424-8220.
- RIBEIRO, L. M. B.; MüLLER, I.; BECKER, L. B. **Performance Evaluation of Different ToS Using Heterogeneous Communication Interfaces in FANETs**. Frontiers in Future Transportation, Smart Multi-Vehicular Systems, v. 2, 2022. ISSN 2673-5210. DOI: 10.3389/ffutr.2021.755998.

1.5 DOCUMENT OUTLINE

This Thesis is organized into eight chapters and started with this introduction. Follows a brief description of the remainder chapters:

- **Chapter 2:** presents a background description of the IEEE standards usually applied in the context of UAV communications and also presents some algorithms that could be used in dynamic adaptive solutions such as machine learning. Other algorithms to improve UAV communications and an overview of IEEE standards used in this solution are presented.
- **Chapter 3:** presents a classification for related works considering four macro-aspects used in UAV networks composition. Some tables are showed summarizing the related works in the classification proposed, highlighting some works network aspects, and proposing a comparison between network evaluate metrics are shown in these Chapter.
- **Chapter 4:** describes the IM algorithms procedures, the decision tree with a sum of points heuristic, and the network dynamic evaluation conditions used in the IM decisions.

- **Chapter 5:** describes the tools used to create experimentation scenarios to evaluate this solution and how they are integrated into 2 D and 3 D experimentation procedures.
- **Chapter 6:** In this one, the first experiments are verified in 2 D and 3 D scenarios using CBR (CBR, *Constant-Bit Rate*) traffic, and applying two communication interfaces IEEE 802.11 n and 802.11 p.
- **Chapter 7:** presents an exhaustive set of experiments conducted to evaluate the IM performance over different ToS and different sets of interfaces perspective.
- **Chapter 8:** presents the conclusions and future work directions.

2 BACKGROUND

Missions involving cooperative and collaborative tasks employing wireless communication links between UAVs involve several design challenges. This network model has mobile nodes that fastly change your topology and distances between them along the fly. The use of small UAVs for disaster assistance, search and rescue, and aerial monitoring have presented interesting approaches (ERDELJ; KRL; NATALIZIO, 2017). Thereby, FANETs are applied to maintain efficient communication between multi-UAVs, using U2U, U2B, or U2I (U2I, UAV-to-Infrastructure) in their deployment architecture, allowing the design of different solutions for several applications.

This chapter starts presenting the main components that constitute the FANETs, presenting their features and different compositions. Afterward, it presents concepts related to most commonly wireless interfaces (devices) applied to provide communication in UAV networks. An overview of the IEEE standards used in this proposed solution is present. These wireless devices are very used in FANETs, VANETs, and Robot-to-Robot (R2R, Robot-to-Robot) research. In most cases, they are already embedded in commercial UAVs (drones) as on-the-shelf items. Lastly, some adaptive or cognitive algorithms used to improve the connectivity and reliability in UAV networks are described, once this thesis is composed of a software solution. To conclude, some machine learning techniques are present as ongoing techniques applied in this context.

2.1 FANETS

A multi-UAV system is more than the sum of many single UAVs (YANMAZ, Evsen *et al.*, 2018). They are composed by a group of systems have unique challenges in its internal communication components, since the kind of protocol using to definition of communication devices that they can be integrated. FANET appeared with goal to permit the coordination and tasks collaboration by multiple UAVS expanding its use capabilities.

According to (BEKMEZCI; SAHINGOZ; TEMEL, 2013) the advantages of the multi-UAV systems corresponds to: implantation of low-cost operation, flexible and scalable deployment of the operation, in opposite of a use of only one high cost UAV, more survivability in case of one UAV fault the others can continue the mission, the mission can be completed faster with more UAVs dividing the tasks, and the aerial transmission policy issues are reduced.

The communications between UAVs can be constituted by U2I or U2B, and UAV-to-UAV without infrastructure. The infrastructure is typically supported by a GSB (GSB, *Ground Station Base*) or GCS (GCS, *Ground Control Station*) or even a satellite.

In case of GSB and GCS, one of the biggest problem are the communication coverage bounds, which causes constant disconnections generated by obstacles, coexistent interferences and UAVs gone beyond the bounds (path control losses) (BEKMEZCI; SAHINGOZ; TEMEL, 2013; YANMAZ, Evsen *et al.*, 2018). Thus, relay techniques, range extension algorithms and cognitive algorithms are some of solutions applied in FANETs in order to reach long communication distances.

FANETs is a sub-type of ad hoc network like the MANETs and VANETs. The main difference is about node mobility, once MANET node movement is relatively slow (a person walking) when it is compared to VANET (a vehicle traveling on an urban street). In FANET, the node's mobility is much higher than MANET or VANET if compared to displacement in a short time interval (BEKMEZCI; SAHINGOZ; TEMEL, 2013), for this reason, these networks are classified as high mobility networks. Others FANETs characteristics and design differences are presented in the next section.

2.1.1 FANET design characteristics

The FANETs share common characteristics with wireless ad hoc networks, such as: node mobility, mobility model, node density, topology change, radio propagation model, power consumption and network lifetime, computational power, and nodes localization (BEKMEZCI; SAHINGOZ; TEMEL, 2013). So, to divide these challenges in study areas, a definition of the main necessary components to compose a multi-UAV system it is applied in an intuitive conceptual design diagram based on proposed by (YANMAZ, Evsen *et al.*, 2018).

Figure 1 presents these conceptual diagram with the main components from multi-UAVs systems.

- Coordination and Collaboration: It is composed of decision-making subsystems, such as path planning, task sharing, resources sharing, the definition of when it will occur the relay transmissions schemes, predict actions, and data collision avoidance. High-level coordination means cooperative generation of plans (a plan is a sequence of simple actions) for all UAVs or a subset of UAVs for performing a certain mission task (HUSSEN *et al.*, 2018). This component receives the *feedbacks* and defines constraints from all diagram components, too.
- Sensing: This component acts to acquire data from the medium where the UAV is flying. The data are achieved to analyze and make decisions in Communication & Networking component. These data could be composed by *beacons* which come from other UAVs or others devices that share the same frequency band or different bands, in heterogeneous communications cases. These components could be composed of several communications interfaces that permit listening to several frequency bands or communication systems.
- Communication & Networking: This component employs how occurs the ex-

change of data between UAVs and between UAVs and ground control stations. In this, the interface management defines how and when which interface can be used, according to decision factors that can be the kind of data to transmit, or medium sensing metrics, for example.

- Unmanned aerial vehicle platform: Compose all the hardware requirements necessary for a UAV to fly without human pilots (autopilot) such as control systems, onboard processors, sensors, actuators, and the software that associated the low-level and high-level controls. It is defined by flight controllers boards as Pixhawk (PX4, 2014).

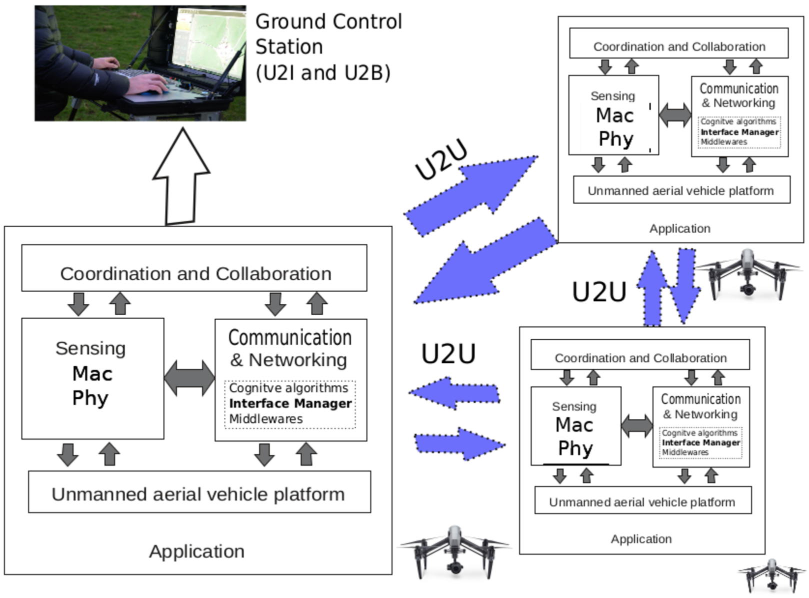


Figure 1 – Fly ad-hoc networks systems main high level components proposed by (YANMAZ, Evsen *et al.*, 2018) with changes.

Figure 1 presents some additional sub-components included by this thesis. In this one, using as baseline the diagram proposed by (YANMAZ, Evsen *et al.*, 2018), it was added the MAC and PHY blocks inside the *sensing component* to demonstrate that layers are basically responsible for the sensing through one or several baseband to establish links.

In the *communication & networking* component is also added a software solutions sub-component to describes where some solutions using only on-the-shelf components (without hardware changes) generally is included in these networks. The solutions includes cognitive algorithms, the interface manager proposed by this thesis, and middlewares as example of adaptive network solutions. The main aim of this sub-component is to extends the UAVs possibilities and wireless self-adaptability in an environment, like according to the data sensing of the medium or other dynamic thresholds. The interface manager is present as an example of heterogeneous communication, using more than one wireless communications interfaces, adapting the UAVs to use different frequency bands or different communications protocol stacks.

Others changes in the diagram includes the description with directional arrows of U2U communications (filled arrows) and U2I or U2B communications (unfilled arrows). Yanmaz *et al.* (2018) affirm that the interactions between the blocks and the required functionally from each block are dependent on the application of the system. This blocks helps to define a system focus on the design, developing directed solutions. In case of this proposal, this work will be define by the interactions between communication & networking and sensing components.

2.2 OVERVIEW OF IEEE STANDARDS

This section summarizes the IEEE standards used in the different combinations of interfaces inserted in the heterogeneous interface manager. These communication interfaces were chosen because they have wide commercial use and are present in several works involving networks composed of UAV nodes (SHI; MARCANO; JACOBSEN, 2019; SANCHEZ-IBORRA, 2016; ZENG; ZHANG, R.; LIM, 2016; BEKMEZCI; SEN; ERKALKAN, 2015).

IEEE 802.11n 2.4 GHz: This standard was developed with the main aim of obtaining more throughput, thus allowing for more parallel transmission with higher frequency channel bonding (40 MHz) than the previous versions of 802.11. Another innovation of this standard is that can operate in two frequency bands—2.4 GHz and 5 GHz—which improves the Wi-Fi communication possibilities, brings higher throughput with closest nodes (5 GHz), and allows for a longer communication range (2.4 GHz). This standard increases the number of streams to 4 (four) using MIMO (multiple input multiple output) smart antenna technology. More streams means higher spectral efficiency, with more bits per second per Hertz of bandwidth, thus reducing the fading effects while increasing link reliability (IEEE802.11N, 2009; MASIUKIEWICZ, 2014). A critical point of this standard is that 802.11 can transfer a single frame at a time to all its ports, which means more contention in the window-time.

In the search to provide applications with Quality of Service (QoS) requirements, the IEEE published the **IEEE 802.11e amendment in December 2005**. This amendment was incorporated in the IEEE 802.11 standard (IEEE802.11N, 2009). This specification extends the protocol in terms of QoS functionalities and improves its capabilities and efficiency (MELO FILHO; PIRMEZ; REZENDE, 2003). It incorporates the hybrid coordination function (HCF) that applies a Hybrid Coordinator (HC), which includes the QoS parameter set in some control frames, which affects the medium access behavior of each access classes of a node.

This way, the coordinator is able to change the transmission load according to differentiation rules and access priorities. The HCF provides two mechanisms for the support with QoS requirements, the EDCA and the Hybrid Coordination Function

Controlled Channel Access (HCCA) (MORAES *et al.*, 2008). They can use polling schemes in the contention free period or deliveries data based on different user priorities, respectively. These coordination mechanisms can help maintain the connectivity between nodes, prioritizing a message or a node of interest to send data (e.g the most susceptible to disconnection).

IEEE 802.11p 5 GHz: This standard has MAC and PHY layers based on the IEEE 802.11a standard, presenting a 10 MHz bandwidth and 1.6 μs guard period in transmissions. IEEE 802.11p employs a dedicated 5.85–5.925 GHz band of the Unlicensed National Information Infrastructure (U-NII) band. The spectrum is divided into seven sub-channels: One control channel (CCH, channel 178) and six service channels (SCHs). In the MAC layer, Enhanced Distributed Channel Access (EDCA) is used, which is a medium access mechanism that coordinates the medium priority access, according to type of messages (classified into eight levels of priority, based on voice, video, best effort, and background) (IEEE 802.11P, 2010; PARK, J. H. *et al.*, 2018).

The channel interval time alternates between CCH and SCH during 50 ms, including the guard interval. The CCH only transmits WAVE short messages (WSM, *Wave Short Message*), among devices, which is composed of non-IP data made up of management frames, like announcements and advertisements of up to 512 bytes of data. WSMs are used to send BSMs (BSM, *Basic safety messages*), as they allow the shortest delay when sending data to all devices in the propagation radius without association. This feature could be useful to exchange metadata between UAVs, especially because the CCH includes a secure scheme for safety messages transmission in a very short transmission time format (PARK, J. H. *et al.*, 2018). So, this thesis applies this interface in a channel used to send safety messages in VANETs (SCH 172), with allows to send more than CCH (512 bytes) using the same features of low latency—and very low end-to-end delay—makes this protocol useful in several different networks, including FANETs.

IEEE 802.11ac 5 GHz: This standard helps to add more scalability, reaching a higher throughput than 802.11n (on the order of Gigabits) (CISCO, 2012). Also known as Wi-Fi 5 (ALLIANCE, 2000), this standard includes more bandwidth usage, allowing up to 80 or even 160 MHz and, thus, increasing the speed by 117 or 333%, compared to 802.11n ((IEEE802.11N, 2009)), respectively. Thus, this standard has been classified as a High-Throughput standard, presenting a denser modulation using 256 Quadrature Amplitude Modulation (QAM), which means more bits per second in the spectrum when using MIMO. Another important evolution is in the number of spatial streams, making it possible to set up to eight spatial streams, which implies higher throughput. This standard is single-band (only 5 GHz band), with MU-MIMO allowing for multiple frames to be sent to multiple clients at the same time over the same frequency spectrum (CISCO, 2012). An important observation is that this standard reduces the aggregation modes found in the 802.11n standard (this standard present only A-MPDU aggregation MAC data unit protocol), in contrast to A-MPDU, A-MSDU, and both.

IEEE 802.11 ax 2.4 GHz and IEEE 802.11 ax 5 GHz: This standard is the new Wi-Fi technology available in the market. It enables high-speed gigabit wireless, together with the predictability of LTE licensed radio. IEEE 802.11ax is a protocol which is still in development, with the aim to provide greater network capacity, higher productivity, and better throughput performance with reduced latency (CISCO, 2020). IEEE 802.11ax supports new and emerging applications on the same wireless local area network (WLAN) infrastructure, while delivering a higher grade of service to older applications.

These radio standards are different applications, such as 4K video, Ultra HD, wireless office, and Internet of Things (IoT). It applies OFDMA (Orthogonal Frequency Division Multiple Access) and robust high-efficiency signaling for better operations with a significantly lower RSSI received, having a theoretical throughput of 4800 Mbps at the physical layer with effective throughput, which is more than necessary for several applications. Unlike 802.11ac, the IEEE 802.11ax is a dual-band 2.4 and 5 GHz technology.

One important feature is that 802.11ax 2.4-GHz support significantly increases the Wi-Fi range, adds standards-based sounding and beam-forming, and enables new use-cases and business models for indoor and outdoor coverage. To address the operational needs of IoT, 802.11ax and its IoT capabilities, such as low power and determinism, are expected to accelerate its adoption. Denser modulation is enabled through the use of 1024-QAM. This protocol was designed with the aim to allow for the use of Augmented Reality (AR), Virtual Reality (VR), or Mixed Reality (MR) technologies in real-time. These applications usually require throughput higher than 1 Gbps and low latency (< 10 ms), which is possible due to the advanced Multiple Input–Multiple Output (MIMO; 8×8) and scheduling capabilities of the protocol.

2.3 SOFTWARE SOLUTIONS USED IN MULTI-UAV SYSTEMS

Searching to improve and maintain connectivity in a multi-UAV system, several solutions were proposed without implies in high changes in the gain of antennas (causing stress in radio components) or using other external devices. Several solutions, also not cause any changes in the standards protocol stacks. These solutions usually are described by cognitive, adaptive, middlewares, machine learning, or biological algorithms, anyway software solutions.

In this way, focus on this thesis development the next sections will present some software solutions divided in two categories: adaptive and cognitive algorithms and machine learning.

2.4 ADAPTIVE AND COGNITIVE ALGORITHMS

Adaptive solutions consists in approaches which describes intelligent adaptability of the use of radio resources, and also are known as RRMs (RRM, *Radio Resource Management*) (JAVADZADEH, 2021). In this context, RRMs or adaptive algorithms manager the assign of radio and network resources to be use for wireless communications, according to events or thresholds generated during network executions or caused by external changes (topology changes, environment or medium conditions, sensed signals, and etc), besides these algorithms can optimize the number of successfully transmitted data from a determinate ToS per example (SALEEM; REHMANI; ZEADALLY, 2015b; YANMAZ, Evsen *et al.*, 2018).

In this context, radio resources like channel, modulations, protocols, frequencies and applications can be adapt through use of mechanisms or techniques added above the MAC and PHY layer components or accessing them from a intermediary network system.

Some works describe several adaptive and cognitive solutions (SALEEM; REHMANI; ZEADALLY, 2015b; DIAS SANTANA; CRISTO; LUCAS JAQUIE CASTELO BRANCO, 2021). Among the algorithms, in (JAWHAR *et al.*, 2017) present an example of middleware applied in a UAV network model. The middlewares simplify the implementation and operation of distributed application process offering services-oriented to run-time support, self-organization, QoS requirements, configurable services, and others (JAWHAR *et al.*, 2017). This component could be an application, a virtual client service, service routines, and so on, in this way the interface manager proposed by this thesis also could be seen as a middleware. (MOHAMED *et al.*, 2010) present a Muni-Socket-UAV middleware which provides interconnections for UAVs onboard computers to improve communication performance and reliability. In this one, multiple networks interfaces are employed in a self-configured way allowing reach better performance, and reliability with different interconnection scenarios.Figure 2 presents the position of MuniSocket-UAV in the networking protocol layer.

Different of this thesis, which uses only wireless network metrics to make actions, these Figure 2 solution proposes the use of the kind of network infrastructure of communication (U2U or U2I), and a multihop routing protocol as conditions of making decisions through particular network interfaces. Basically, the main aim is to find the network path between nodes that meets QoS requirements of bandwidth and end-to-end delay.

Some solutions involves beaconing-based communication algorithms to make calculations of network metrics and distances between nodes. Yokoyama *et al.* (2014) present a Multilateral Verification algorithm which calculates the distance between a node and two neighbors nodes using *beacon-frames* as reference. In these validation the intensity of RSSI (RSSI, *Received Strength Signal Indicator*) is also considered to give more accuracy in the classification of distance in different areas.

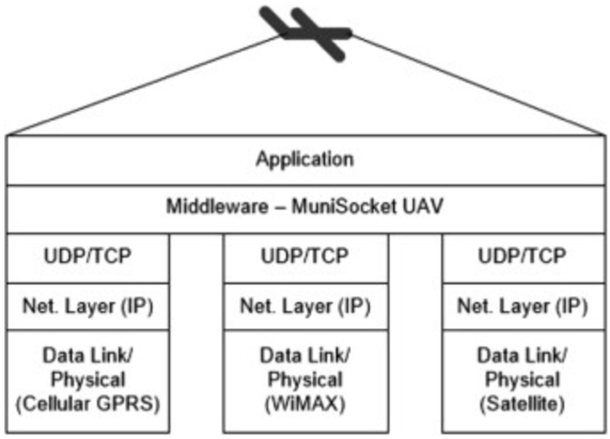


Figure 2 – An example of middleware applied in UAV networks proposed by (MOHAMED *et al.*, 2010).

Game theory and bio-inspired algorithms are also explored in these scenario. Yan *et al*. (2018) uses a hierarchical game framework to proposes access competition among groups of UAVs to assist terrestrial base stations of IoT (IoT, *Internet of Things*) devices applying the Stackelberg game theory searching the equilibrium in UAVs distribution. Some models of multi-agent systems inspired by biological social systems could be related as adaptive solutions, for example in (EL HOUDA BAHLOUL *et al.*, 2017) the *Boids of Reynolds* mechanism is used to maintain the connectivity and route while data is being transmitted adapting the communication routes according to performance. *Boids of Reynolds* mechanism is inspired on the decentralizes organization of formation of shoals of fish and flocks of birds.

Decision-making solutions are vastly explored in the UAVs networks resource manager. These solutions consists in take some parameters, heuristics, weights to make changes in radio resources. An example of decision-making solution are the DT (DT, *Decision-tree*). These algorithms can be developed using the decision-tree as classifier employing machine learning approaches (XIA *et al.*, 2021) or using search tree data structures for locating specific keys or reach target state (ZHANG, X.; DUAN, 2018).

DT solutions can be used by cognitive solutions to propose decisions between radio resources finding the best setting of frequency channel (GREENBERG; BAR; KLODZH, 2019), communication interface (RIBEIRO, Laura Michaella Batista; MÜLLER; BUSS BECKER, 2021), network routes (LU; NAN, 2019) and security level (BOHACIK, 2021). This algorithm is adopt as part of the interface manager solution proposed by this thesis.

2.5 MACHINE LEARNING

These solutions can be defined as solutions that make predictions, decisions, or classifications autonomously, without human intervention, using parameters, conditions, or triggers obtained previously by dataset or dynamically, using sensed data, signs, and others *execution time* events.

According to (TAHA; SHOUFAN, 2019) these solutions have several categories where can be aggregated in four macro-sets, according to input data: supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning.

Supervised learning are algorithms which most common application is in classification and regression. They aim to use a mapping function using a training dataset that can be thought of as a teacher supervising the learning process. So, in the case of a new input data, it can predict the output variables for that data. In this case, the dataset has labeled input data that pair with desired outputs and are used to mach the input and the output data. These groups includes, SVM (SVM, *Support Vector Machine*), Discriminant Analysis, Naive Bayes classifier, linear regression, and neural networks. The Naive Bayes classifier is further detailed, given that this thesis includes it to solve a policy of weights defined by this algorithm based on the sensed data.

Usually, the Naive Bayes classification is very explored in the multi-UAV systems applied to provide adapt parameters tuning for other intelligent algorithms making decisions, calculations, and combinations. An approach is the use of environmental sensed data (HO *et al.*, 2018), others include triggers obtained by network signs, and also, it can use data logs obtained in previous turns. This classifier is used to compound the proposed of this thesis, because this classifier performs well on data do not interact like in wireless networks metrics, e.g. high throughput not imply in low delay.

Unsupervised learning set is composed by algorithms that also depend on previous dataset but, differently of supervised leaning, do not requires label inputs. It means that it is not needed to supervise the model, so all the decisions are based only on input data (JAVADZADEH, 2021). In this case, the classifications is based on clustering discovery applied in available data, addressing to find all kinds of unknown patterns. Some examples of algorithms includes Hidden Markov, K-means, Hierarchical models, anomaly detection, and pattern recognition.

Semi-supervised learning compose solutions that are based on labeled and unlabeled data mixed for the training. The output data is composed by known inputs with unknown inputs (resulting known input applied in a function). Semi-supervised SVMs, Graph-based algorithms, Multiview Algorithms, and Self-Trainning are examples of these solutions.

Reinforcement learning are algorithms that use the previous taken decisions for training, applying a sequence of actions including error and trial rules. In this set of algorithms the categorical target variable can be available or not for solving the problem. So, in this case, the algorithm learn from mistakes. Some examples of these algorithms are Q-Learning, Deep Q-Learning, and SARSA-Lambda (SARSA-Lambda, *State Action Reward State Action with eligibility traces*).

Bithas *et al.* (2019) and Taha *et al.* (2019) bring an exhaustive overview of machine learning solutions applied to multi-UAV system improvement of communication. In general, supervised learning algorithms are employed for classification and regression of network measurements and mobility features. In terms of classification, some previously fail measurements can be used as dataset to predict how much a system is favorable to give fails or disruptions (OKTAVIANA *et al.*, 2019), other example is predict the accuracy of channel behavior based on UAV RSS behavior prediction (GOUDOS; ATHANASIADOU, 2019), a example of regression algorithms approach is the optimizing the positioning of UAVs acting as aerial relays in air-ground wireless networks (CHEN; YATNALLI; GESBERT, 2017).

Regarding unsupervised algorithms include clustering approaches, which employ classifications according to similarity of medium behavior. A example is the application in user association problem, when UAVs are used to recover the connectivity in damage areas (CHENG *et al.*, 2019), and mobility prediction and object profiling (PENG, H. *et al.*, 2018). Unsupervised learning also includes association approaches, for example using k-means algorithms for mobility control of UAVs reducing handoffs (LI, Q. *et al.*, 2018).

Considering semi-supervised solutions applied in Multi-UAV networks, it can be find examples in multi-UAV defense systems and network planning approaches. In these solutions, supervised classifiers as SVM and Random Forest algorithms are used to define and adopt a defense policy in a UAV network based on pre-defined attacks modes or based on drones deployments constraints, and for unexpected attacks or out of range nodes Q-learning or Deep Neural Networks algorithms are used to determine the optimal defense policy or safe estimate positions (MIN *et al.*, 2018; MOZAFFARI *et al.*, 2019; AL-SA'D *et al.*, 2019).

Lastly, reinforcement learning techniques expands the solution for Multi-UAV networks turning the network nodes into a kind of intelligent agents because of the requirement of awareness of the complete environment. In this way, it is possible to have baseline for time-domain processing (ZHANG, D. *et al.*, 2018), prediction of network conditions (EGI; OTERO, 2019), and interference management (ATHUKORALAGE *et al.*, 2016) solutions. All these approaches commonly uses predictions with data collected, sensed or measurement from environment.

The use of machine-learning algorithms in multi-UAVs networks has been present promising approaches to improving and maintaining connections between UAVs with quality of service, allowing the development of low-complexity solutions for an overall network optimization from the physical layer up to resource and network management (BITHAS *et al.*, 2019). According to the application of a mission, including the input and output data requirements, the definition and use of ML techniques can extend the network possibilities for novel network paradigms and perspectives to improve communications between UAVs. These solutions can provide dynamic and autonomous adaptability and flexibility, especially when implies in low execution cost and processing of local decision estimate (BITHAS *et al.*, 2019; TAHA; SHOUFAN, 2019).

2.6 SUMMARY

In this chapter, some components and features of FANETs or multi-UAVs networks were described. Different solutions and techniques are applied to establish, maintain and improve FANET communication design are presented. These components include communication interfaces, the kind of communication infrastructure, and software solutions for radio resource managers. Based on possible solutions to propose reliability communication in multi-UAV networks, different approaches could be employed consisting of adaptive or machine learning algorithms. These solutions design and support the system presented by this thesis.

Considering the multi-UAV design process, despite the existence of several network features in multi-UAVs composition, a classification of related works is present in the next chapter. In this sense, this classification aims to guide the development of a UAV network using four main features, providing a mean to represent several applications and development characteristics.

3 RELATED WORKS

Developing a communication architecture for mobile nodes is a challenging task that requires verifying behavioral features (pre-existing interference, coexisting networks, nodes trajectories and etc), the definition of medium access protocol could be applied, the type of network management (e.g. decentralized, centralized), and which applications-specific traffic (voice, video, data, control signal). Thus, the selection of the communication standard and/or the communication interface to be used should consider the specificity of the networks, and also other communication requirements like: delay, throughput, and link quality variations at a high mobility scenario (BEKMEZCI; SAHINGOZ; TEMEL, 2013).

Regarding the high mobility networks management as UAV networks, efficient deployment strategies need to be designed to maintain data transmission and reception in the flight time. To provide an overview related to the establishment and maintaining the connectivity in these architectures, a classification of solutions was proposed. In this one, four sets of related works can be categorized: amount of communication interface, architecture and system type, network management and communication range. Additional studies related to vehicular ad hoc networks are also included, since the vehicles have similar features of mobility to UAV networks. The related works present in this Chapter are summarize highlighting the evaluated metrics used, the number of interfaces applied (and what are they), the type of traffic and obtained performance. The common goal of these works is maintaining the network connectivity and link quality in high mobility scenarios.

3.1 PROPOSED CLASSIFICATION FOR MULTI-UAV COMMUNICATIONS SOLUTIONS

Figure 3 presents the proposed classification to organize the works in four macro-aspects categories: (i) according to the amount of technologies applied in the communication systems based on multi-UAV; (ii) according to the architecture and systems used to develop solutions; (iii) according to network type of management; (iv) according to wireless communication range.

Each category presents sub-groups which describes a mUAV system in more restricted ways. Regarding the amount of communication interfaces, a solution can be heterogeneous or homogeneous, which means the use of a single interface (homogeneous) in opposite the use of several interfaces to communicate (heterogeneous).

In terms of architecture and system type used to proposed a solution, a multi-UAV system can apply cognitive and SDN networks, which are software solutions including middlewares, ML (ML, *Machine Learning*) techniques and protocol changes, or it can propose hardware modifications (hardware changed), when some default or

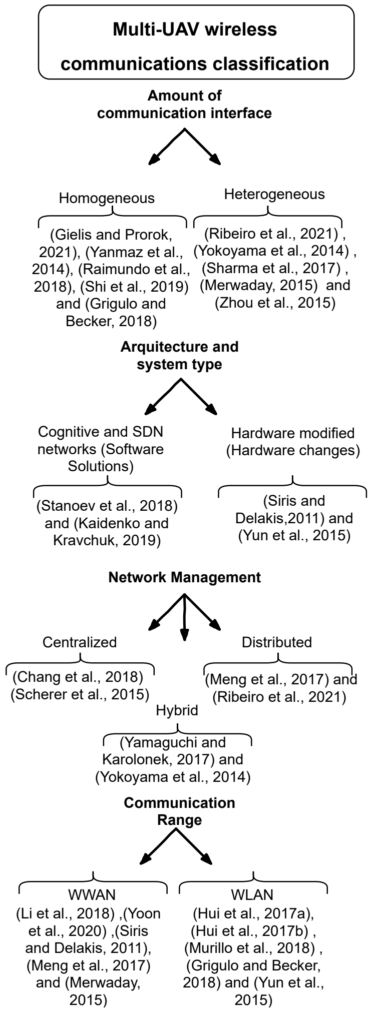


Figure 3 – Proposed classification and related works.

fabric hardware features is changed in order to provide communication.

In relation of network management a multi-UAV system can have centralized, distributed or hybrid coordination, manager and control of how the nodes can communicate in a network. Finally, the multi-UAV system can be described in terms of the size of coverage area, WLAN or WWAN (Wireless Wide Area Network). WLAN usually allow communication between nodes up to 1 km (maximum) and the WWANs up to 50 km, without intermediary devices.

These sub classifications and subgroups present the feature of aggregating classifications, such as the mUAV system developed in this paper, which can be classified as:

- Amount of communication interface (heterogeneous)
- Architecture and system type (software solution)
- Network management (distributed)
- Communication range (WLAN)

Thus, each sub-classification and group served to academic base to guide the development of this research. So, the classification uses the main development features of this approach, which are: a network composed of multiple autonomous UAVs; The UAVs have more than one interface communication; The UAVs can reach the maximum of 1 km between each other during their journeys; The network is capable to maintain a communication link during all the mission, with QoS without any hardware modifications or antenna additions.

The next sections presents the sub-classifications that will describe several solutions which supported the academic studies to compose this proposal.

3.1.1 Amount of communication interfaces

The definition of communication interfaces for a mUAV communication system should take into account the specificity of these networks which includes in several cases low delay tolerance, need for high throughput maintenance, and link quality instability caused by higher mobility of communication nodes constituted by UAVs (SKOROBOGATOV; BARRADO; SALAMI, 2020; SHI; MARCANO; JACOBSEN, 2019).

For that, some authors concentrate their efforts on the use of a single communication standard applying cognitive radio techniques to serve these networks, for example, by reusing white spaces slots during communication for management or increasing the number of hops between nodes (GIELIS; PROROK, 2021; YANMAZ, Evşen *et al.*, 2014; RAIMUNDO *et al.*, 2018).

Other approaches include the use of more than one standard (heterogeneous systems) expanding the possibilities of network communication managing the communication interfaces according to a context, such as the appearance of new interferences in the medium (RIBEIRO, Laura Michaella Batista; MÜLLER; BUSS BECKER, 2021; SHARMA *et al.*, 2017; MERWADAY; GUVENC, 2015). So, it is important summarize a few of these works divided in two subgroups Homogeneous and Heterogeneous systems.

3.1.1.1 Homogeneous Systems

Among the researchers that applied homogeneous solutions, (SAYYED *et al.*, 2015) used a double-stack communication architecture applying bidirectional communication to a UAV node, which establishes communication with the wireless sensor network (RSSF) and its sink node using the same radio. In addition to establishing the link, this architecture provides different QoS characteristics, such as best-effort and reliability responsible for maintaining UAV-RSSF and UAV-Sink links, respectively. The results suggest that it can maintain two-way communication using a single radio, based on a flexible communication infrastructure, which defines the protocol stack to be applied according to the detected communication, mobile data collector (MDC), or communications with the sink.

Bekmezci *et al.* (2015) proposed a system with more than one UAV to provide real-time communication. The main objective was to show that using low-cost hardware and devices easily found in the market it was possible to create FANETs that meet the requirements of real-time applications. The authors employed an Ar.Drone 2.0, a closed architecture commercial flight unit, along with a Raspberry Pi Model B card with two IEEE 802.11n interfaces, one to allow communication with the other UAV and the other to receive streaming video of the Ar.Drone 2.0 flight. However, the authors only performed latency tests using two UAVs, one static and one that performed a fixed trajectory along the signal range of the static UAV, without evaluating the effects of the use of the second interface in this communication, which could have caused variations due to network coexistence.

In (SHARMA; BENNIS; KUMAR, 2016), the problem of user-demand-based UAV assignment over geographical areas subject to high traffic demands was investigated. The proposed model is based on a cost function for multiple UAV deployment, using user demand patterns to assign a cost and density function to each area and UAVs. The authors used a reverse neural model based on user-demand patterns to match each UAV to a particular demand zone. The goal was to provide continuous data between macro cells and UEs, using the UAVs to enhance load balancing by forming multiple intermediate links between the macro cell and the small cell UEs.The results showed that using UAVs yielded 37.7% fewer delays in comparison with a network comprising small and macro cells without UAVs. Regarding altitude variation, it was shown that increasing the altitude provides less interference and appropriate LOS, but also introduces more delays. The probability of guaranteeing the SINR for a particular user in a macro cell was closer to one in both cases using the UAV, showing high connectivity during the connectivity time in comparison with existing ground-based wireless networks.

The experimental performance of commercially quadrocopters communicating via IEEE 802.11a was evaluated (YANMAZ, Evşen *et al.*, 2014), comparing the infrastructure of one-hop and two-hop wireless communications. The main purpose of this research was analyzing the network layer versus MAC layer relaying in terms of throughput and link quality. The results showed that with the two-hop networks infrastructure, the standard 802.11a using the routing protocol based on number of hops is insufficient for multi-UAV systems if high throughput is necessary to deliver large amounts of sensor data or if stable links are required to support users.

Lastly, an emerging solution relates to the use of satellite-based augmentation systems (SBAS), which promote the integration of UAVs in the National Airspace System (NAS). It allows UAVs to operate harmoniously, close to each other, in conjunction with manned aircraft, occupying the same airspace and using the same air traffic management (ATM) systems and procedures (YOON *et al.*, 2020).

3.1.1.2 Heterogenous Systems

Among the works applying heterogeneous interfaces, Yokoyama, Kimura and Santos Moreira (2014) presented a communication architecture in which UAV nodes communicate over a cellular network and an IEEE 802.11p network. The purpose of the study was to provide a secure positioning algorithm for UAVs swarms, using RSSI beacon frames sent by UAVs as a distance estimate. The authors considered a communication scenario where UAVs use the cellular network (3G or 4G) to send messages to this base and IEEE 802.11p interfaces for U2U communication, operating at 5.8 GHz. Network management is centralized, as only beacon messages are exchanged between UAVs. The results showed that the uncertainty rates in relation to the calculation of the distances between UAVs, generated by RSSI values received by the triangulation of neighboring nodes, is reduced to a distance up to 50 m between them. However, it gradually increases above this distance.

A still-open challenge is the access of multi-UAV networks to remote areas, using the limited range of wireless transmissions that operate in unlicensed bands. In (YAMAGUCHI; KAROLONEK, 2017), the authors used retransmission and routing algorithms to provide a wider range in wireless transmissions in multi-UAV networks. The system uses a wireless interface that operates at 2.4 GHz for communications between the cluster-leading UAV and its base, and a 5 GHz interface in U2U transmission. Management is centralized, as UAVs advance their positions in accordance with the improvement in the RSSI signal received between the swarm leader and the base. The results show that it is a scalable solution, extending the reach of communication inserting new UAVs, and improving the UAVs' network connectivity.

In (CHANG *et al.*, 2018), the authors developed a communication system that divides UAVs into cluster heads and members of the cluster. The cluster head UAVs are equipped with interfaces of LTE and WiFi technologies in access point (AP) mode, and the members of the cluster are equipped only with WiFi interfaces in this mode. Cluster heads can connect to a virtual private network (VPN) server to receive control commands through the LTE interface and receive data from the sensors through the WiFi interfaces present in the cluster members. The authors evaluated the system using bandwidth consumption, latency, and received strength signal (RSS). The results indicate that the latency is stable up to a distance of 18 m between the cluster heads and the member clusters with support for real-time video transmissions, presenting rates between 4 and 6 Mbps and RSS above –60 dBm considering pre-existing integrated communication interfaces in UAVs (without hardware extensions).

Zhou *et al.* (2015) proposed an aerial–ground cooperative vehicular networking architecture where each UAV is assigned to a ground vehicles. So, UAVs can be employed to assist the vehicular network in an environment where the communication infrastructure is not available and network connectivity is poor. Thus, UAVs fly in a given formation to the affected area, where they perform sensing and acting as intermediate communication relays to forward data packets, among vehicles when direct multihop V2V links are not available, due to their flexible mobility. In that for A2A (aerial-to-aerial) communications, heterogeneous communication was considered, such as XBee-PRO (based on IEEE 802.15.4) for command transmissions and Wi-Fi (IEEE 802.11) for sensing data.

Besides common flight control, wireless communication technologies are increasingly applied to UAVs or drones equipment, in some cases many of them leave the factory with more than one communication interface embedded or in other cases they have the feature of allow the addition of more than one. In general, these communication interface are composed by WLAN standards, which is ubiquitous nowadays.

3.1.2 Architecture and System type

Considering the architecture and systems classification some papers use a SDN solutions, and other propose some hardware modifications searching to provide adaptive solutions for example, according with some parameters (using RSSI as threshold) or network metrics (sensing noise). Depending of solution more time of processing is needed or physical changes is make in UAVs. Some approaches are described below.

3.1.2.1 Software solutions

Stanoev *et al.* (2018) propose a network architecture defined by software, which presents a decoupling of the control plane and the data plane, with sharing of physical link. The goal of the author's system is monitoring a rocket airstrip to avoid collisions, and a prioritization scheme for image data traffic is applied in order to avoid excessive latency over this kind of message traffic or system instabilities. (KAIDENKO; KRAVCHUK, 2019) use additional reception channels for analysis of interference conditions, increasing the network survivability with two or more data transmission channels using optimal algorithms for selection of the operating range.

Some approaches changes the MAC layer using mechanisms, in order to propose a solution to improve the reliability of vehicular networks using only one standard. (LEI; RHEE, 2017) developed a solution to ineffective use of data traffic prioritization applied by EDCA (enhanced distributed channel access) especially, when it is of no use when the traffic consists of only one type of safety messages. The authors presents other important issue that is the utilization of a fixed contention window in a dense or sparse network. In the first, the possibility of collision is increased since, more vehicles tend to choose an identical BC (BC, *backoff counters*) and, in the second a fixed contention window brings in long period of idle channels without needs.

The algorithm acts during the backoff process, when the vehicles sensing the channel count the number of idle time slots occurred between any two transmissions. Based on this, a vehicle reserve a BC for its next wireless channel access sending the ongoing message. The BCs values predefined is share to all the vehicles, resulting in reduce at collisions from utilization of identical BCs. The IEEE 802.11p by default mode and the proposed scheme present increase in the packet loss probability with the increase of number of vehicles added to network. The proposed scheme path losses increases in a lower level then 802.11p (up to 20%), improving the throughput with the increasing of number of vehicles, and reducing BC reservation collisions and the idle channels.

Hui, Phillips and Kekirigoda (2017) developed a composition of three papers to the development of a framework based on intelligent agent-oriented developed capable of improving the survival of the wireless network connections between mobile nodes for military missions, called OPAL. The first work describes the modules that composes framework (HUI, K. P. *et al.*, 2011), the second one is related to the use of the solution in environments without interference and finally the last one includes in OPAL framework, a jammer estimation capable of detecting the positioning and signal intensity defining new positions for a UAV which acts as an extension node of the network range, between ground mobile nodes and a mobile ground control station (HUI, K. P.; PHILLIPS, Damien; KEKIRIGODA, Asanka, 2017). The results were presented considering the and a metric denominated NCL (network connection level) composed of the link quality measured from the signal reception between two mobile ground nodes.

In the simulation, a controlled jammer node spreads signals over ground mobile nodes with the same intensity, it is positioned presenting the same distance to both ground nodes during the execution. In the simulation without UAV uses the OPAL the maximum SINR (dB) is 10 dB reducing with the increase of the distance traveled by the nodes, during the respective time samples the passage through the jammer occurs a disconnection with both nodes with duration of about 125s. In the simulation with the use of OPAL acting in an embedded form in the UAV the SINR is improved to 15dB, reducing the time of disconnection between the nodes during the passage through the jammer to 70s in one terrestrial node and only 20s to the other terrestrial node. The NCL follows the same behavior since, the quality of the link is measured considering the variation of the SNR that composes the SINR.

3.1.2.2 Hardware solutions

Hardware modifications also can be applied in order to get more quality in transmissions between nodes. For example, Yun *et al.* (2015) and Siris *et al.* (2011) propose modifications applying combinations of antenna with tripolarization and interference-aware channel assignments using directional antennas (YUN *et al.*, 2015; SIRIS; DELAKIS, 2011).

Chang *et al.* (2018) developed a UAV communication system divided in two parts: cluster heads and cluster members. A cluster head is composed by UAVs equipped with LTE and WiFi in mode AP modules, and the cluster members are equipped only with WiFi in mode station. The cluster heads can connect to a VPN (VPN, *Virtual Private Network*) server to receive control commands via LTE technology, they send commands and receive sensor data to cluster members via WiFi.The controller and cluster heads are connected to the same VPN server and communicate with each other using ROS. The authors evaluated the system using bandwidth (amount of data transmitted per second), latency (using ICMP echo) and RSS.The system was applied in real testbed scenario in semi-open test site to minimize the blockage of LTE signal and interference of crosswinds, maintaining fixed altitude for UAVs.The results show that up to a distance of 18m between a cluster head an a cluster member, the latency was stable in 50ms, and the performance of bandwidth can support live time video streaming applications, with data rate of 4-6 Mbps and RSS above 60 dBm considering off-the-shelf dongles. The authors reinforce that to increase the reach of the network it is necessary to use additional directional antennas applying LOS or greater power dongles.

The UAVs can be used as unmanned aerial base stations (UABSs) at PSC (PSC, *Public safety applications*) during natural disasters.

Yanmaz *et al.* (2014) also proposed a validation of a multi-antenna extension to IEEE 802.11a to be used on multi-UAVs networks and showed the impact of UAV's height and orientation variations on the link quality for single-hop and two-hops networks. The authors conduct outdoor experiments, measuring the communication performance in terms of throughput and link quality. IEEE 802.11a in access point mode (ground station) and IEEE 802.11s extension in mesh point mode were used to provide one-hop communication (from a single UAV to a ground station) and two-hops communication (mesh networking between two UAVs and one ground station), respectively. Experimental results show that stable throughput can be achieved using two-hop networks where all traffic goes through an access point UAV as relay. The authors conclude that the standard mesh protocol will be insufficient for multi-UAV systems if high throughput is necessary to deliver large amounts of sensor data (e.g., in SAR missions) or if stable links are required to support users. The use of one UAV in AP mode in two-hop architecture implies in lower jitter. This highlights the difficulty one can find for defining a communication system that can support different network requirements.

3.1.3 Network Management

Regarding network management it can be verified or managed by centralized way, distributed way or hybrid way (both). In centralized way, the network connectivity is managed by cluster heads, sink nodes or by ground control station (fixed or mobile) (SHI; MARCANO; JACOBSEN, 2019; SANCHEZ-IBORRA, 2016). Centralized coordination network, in general, its necessary that the manager node has line of sight with others networks nodes or at least, that presents communication with cluster head nodes, sink nodes or controller (CHANG *et al.*, 2018). In case of distributed way, the nodes themselves are responsible for establishing and managing their connections (MENG *et al.*, 2017), maintaining connectivity between them. A common case of hybrid coordination for UAV networks occurs when a swarm head communicates with a ground control base in a centralized way and replies the base control messages to others swarm members using decentralized mesh communications (YOKOYAMA; KIMURA; SANTOS MOREIRA, 2014). Some works is verified in the next sections.

3.1.3.1 Centralized manager

Some works use the UAVs as network range extension devices in a implicit way, as seen as works which employ UAVs to collect data in WSN (WSN, *Wireless Sensor Network*) (SAYYED, 2016a). In that the UAV behaves as a MDC (MDC, *Mobile Data Collector*) relaying WSN collected data to a ground base station using LOS (LOS, *Line of sight*) transmissions. Others present approaches use UAVs as *bridge* nodes connecting different networks *gateways* or even establish a network infrastructure, for example using these devices as access points, in case of NLOS (NLOS, *Non-line of sight*) transmissions (CHOU; YEN, 2017).

Chou and Yen (2017) employ the use of UAVs as access points to terminals located in areas where terrestrial infrastructure is absent or damaged. So, the authors propose two autonomous service deployment approaches for UAVs based on a generic game model. They concluded that UAVs can be used to extend the communication capability by relaying wireless signal, studying how to efficiently and effectively deploy a fleet of UAVs serving as access points in an area of interest. So, the autonomous navigation scheme acting moves the UAVs toward some location where the average SIR experienced by all terminals associated with it is maximized. In this case, the UAV decides its next move based on the spectral efficiency gain of its previous move, if it detects any terminal during the movement, it starts moving toward the terminal and attempts to increase spectral efficiency.

Two schemes was adopted: one scheme attempts reducing the distance from UAV to some associated terminal using Pareto improvements (PIA), and the other one attempts minimizing the average distance from UAV to all terminals associated with it (MAD2T).The authors measured two metrics, the average SNR for measures the coverage quality of UAVs received by served terminals, and total traveling distance for measures the cost. The results of the average spectral efficiency was better to MAD2T compared with increases of number of terminals, in this case, the greater the number of terminals within the coverage area of a UAV, greater than its spectral efficiency. In case of PIA scheme, the average spectral efficiency is not improved with more terminals, because an UAV serve a number fixed of terminals in this scheme, since its first association to them. But, PIA presents the total traveling performance better than MAD2T because the number of terminals receiving signals presents low variation, avoiding a longer time to stabilize communications. The MAD2T presents the better performance in relation to average spectral efficiency even when a Gaussian distribution is applied to generate positions for the terminals.

3.1.3.2 Decentralized manager

Grigulo and Becker (2018) present an experimental validation of the Efficient Geometry-based Location (EGL) technique using a mobile sink node carried by an UAV system. This mobile sink applies a GNSS (GNSS, *Global Navigation Satellite System*) receiver to provide localization of sensor nodes, evaluating the locations using only-GNSS and a module with GNSS plus RTK (Real-Time Kinematic). So, the UAV (mobile node) scans the network area to help sensor nodes to determine their location.

These communication occurs by sending beacon messages from UAV to static sensor nodes (WSN) using WiFi IEEE 802.11n standard with ESP-NOW real-time protocol. The results indicate that the performance of GNSS RTK presents an absolute error estimation of 1 m considering an average error of the received beacon and accuracy of 1 cm during the short overflight time. These results were possible, because the authors used WiFi stack without infrastructure mode, using the ESP-NOW protocol that allowing the nodes to send beacons in broadcast mode without requiring any connection between them, reducing the costs of overhead, power, and decreasing the time for sending beacons. This protocol will be object of future studies of this proposal.

3.1.3.3 Hybrid manager

Yokoyama. Kimura, and Santos Moreira (2014) present a communication architecture provided by a cellular network, and WiFi protocol. The aim is provides a secure positioning in a UAV swarm using RSSI beacon frames for distance estimation. The authors considered a scenario, where UAVs use a cellular communication via 3G/4G in case of communication as the base and using IEEE 802.11p cards for communication between them, operating in the frequency of 5.8GHz, which is used in vehicular communications. Network management is performed in centralized mode, although exists data exchange between UAVs. Since, whenever that it is necessary to improve the link quality of a UAV node, it sends request to the base station that sends a request to verifiers nodes (UAV neighbors nodes), requesting to move its position in order to improve signal reception by this UAV.

The results showed that the 5.8 GHz frequency adopted had a small signal propagation range measured from RSSI (dBm) which at a distance of 30 m between the nodes already had an unstable signal of -84 RSSI, similar results to obtained by (ALMEIDA *et al.*, 2018). Other results provided by the authors are related to classifying the position of a UAV in a swarm using RSSI techniques to calculate the distance between nodes. The results showed that, the rates of uncertainty in relation of distance calculation using RSSI frames received by IEEE 802.11p cards is close to 0 in range of 45m of distance between nodes, but quickly increasing above this distance.

Zhou *et al.* (2015) propose an aerial–ground cooperative vehicular networking architecture where each UAV is assigned to a ground vehicles. So, UAVs can be employed to assist the vehicular network in an environment where the communication infrastructure is not available and network connectivity is poor. Thus, UAVs fly in a given formation to the affected area, where they perform sensing and acting as intermediate communication relays to forward data packets, among vehicles when direct multihop V2V links are not available, due to their flexible mobility. In that for A2A (aerial-to-aerial) communications, heterogeneous communication was considered, such as XBee-PRO (IEEE 802.15.4) for command transmissions and WiFi (IEEE 802.11) for sensing data. In the preliminary results, the average latency obtained was 25ms by ZigBee and 230 ms by IEEE 802.11a, with the average throughput by 64 kb/s for ZigBee and of 19Mb/s by 802.11a (using UDP protocol).So,the ZigBee presents the better performance in terms of delay and IEEE 802.11a in terms of data flow. But, these results is not conclusive, because the authors emphasized the need of networks to be characterized from large-scale fading (pathloss and shadowing) to small-scale fading (multipath effects).They concludes that this is essential to study the impacts of height, velocity, and orientation of UAVs over these networks.

Yanmaz *et al.* (2014) bring experimental performances comparing IEEE 802.11a interfaces available commercially for quadrocopters applying in two operation types: in infrastructure mode and mesh modes, for one-hop and two-hop communication paths. These comparisons are important in defining the best type of wireless communication for UAV teams that will be used to gather information on large areas or to create communication bridges for affected areas by disasters at critical time missions (YANMAZ, Evşen *et al.*, 2014). According to authors, the best wireless communication is the one that maintains connectivity between the nodes during all the mission, delivering the largest number of packets between the UAVs and ground control station.The performance are present in terms of throughput and link quality for three experimental sets: (i) standard one-hop communications from a UAV to a ground station, (ii) two-hop communication from a UAV via another UAV running in access point mode to a ground station, and (iii) mesh networking using the 802.11s extension with two UAVs and one ground station all running in mesh mode. The second set of experiment presented more stable throughput since, the 802.11s depends on chosen routing protocol in this case, if the protocol uses a single-hop as metric to define the route, even there is a two-hop path that performs better throughput, the route is not changed. The authors conclude that for distances up to 500m, the communication range obtains by one-hop communications is limited by the path loss of environment and transceiver properties. Thus, two-hop or mesh communications are options of use for communications up to this distance for scenarios with low jitter requirements as UAV-to-UAV networks.

3.1.4 Communication Range

To establish communication in missions which involves UAVs as communication nodes towards a global goal is not composed by only imperative tasks of disseminating observations, data sense and catch, and control information, but also how to maintain communication between them during the flight time (YANMAZ, Evsen *et al.*, 2018). Maintaining connectivity is the basis of a communication infrastructure. In this case, the communication range is an important factor of observation in this network conceptions about that to simplify the works are grouping in only two groups WWLAN and WLAN.

3.1.4.1 WWLAN

The multi-UAV networks can be classified as WWLAN if the communication interface used is 3 G/LTE, WiMAX, and Satellite communications (SBAS) and ultra-reliable 5 G band, for example. In general, for a network to be classified as WWAN, it has to reach distances higher than >50 km of communication between a sink node and source node (ALPERN; SHIMONSKI, 2010).

Sharma, Bennis and Nagdev (2016) investigate the problem of user-demand-based UAV assignment over geographical areas subject to high traffic demands.So, the proposed model is based on a cost function for multiple UAV deployment, using user demand patterns to assign a cost and density function to each area and UAVs. They used a reverse neural model based on user demand patterns to match each UAV to a particular demand zone.

The goal is provisioning continuous data between macro and UEs, using the UAVs for enhance load balancing by forming multiple intermediate links between macro cell and the small cell UEs. To evaluate the performance of this proposed the network capacity, reliability and delay threshold were observed using 5G networks.The LOS link was used to connect UAVs and UEs, varying the altitude up to an optimum altitude that guarantees availability of LOS for better coverage.The delay threshold is fixed at 200 ms, which defined the upper limit above which the packet drop increases abruptly.

The result showed that using UAV yields 37.7% lesser delays in comparison with a network comprising of small and macro cell without UAVs, in the vary of the altitudes demonstrating that increasing the altitude provides less interference and appropriate LOS, but also introduces more delays. Throughput coverage was defined as based on rate of users whose SINR is above the threshold (0.03 bps/Hz), where the UAVs presents the greather rates increasing the 5th percentile spectral efficiency without the use of reverse neural deployment by 15.5% and using reverse neural by 38%. The probability of guarantee SINR for a particular user in a macro cell was more nearest of one in both cases of use of UAV, showing high connectivity during the connectivity time in comparison to existing ground-based wireless networks.

Merwaday and Guvenc (2015) present an approach that employ an interference management, evaluating the throughput gain while exploring features of UAVs, such as, the mobility and self- organization capabilities. The authors consider a cellular network with MBS (macrocell base station) and UE (user equipment) locations modeled as two-dimensional homogeneous PPP (Poisson point process). They perform Monte Carlo simulations to evaluate capacity and throughput coverage of the network simulating the loss of a base station, for analysis of the impact of infrastructure damage on the capacity of coverage. The authors conclude that in the scenario of loss, UABSs can be deployed rapidly to form smallcells and consequently improve the network coverage. The MCBs and UAVSs share the same common transmission bandwidth, using a different frequency band for UABSs assuming that, they have very large capacity for access links.The throughput and spectral efficiency rate shown significant improvement with increases of number of intra-cell UAVs, but the spectrum efficiency is decrease at inter-cell communications, otherwise. This shows the need of a traffic management.

Satellite-based augmentation systems (SBAS) uses performance-based navigation (PBN), and some studies are presenting that can be applied to UAVs to operate similarly to aircraft that rely on satellite positioning. SBAS was originally designed and developed for civilian aviation, but now it will be probably possible to also use SBASs in non-aviation applications. Some studies reported good performance in terms of battery consumption, extending its flight time, and improvement in its navigation performance without additional communication channels and receipt of correction messages from a ground control system (KRASUSKI; WIERZBICKI, 2021; KARAMCHEDU, 2020). The base idea is to use the existing message exchange structure from PBN to UAVs, through reference stations using its global navigation satellite system (GNSS) to define which stations are used for communication establishment.

Li, Fei and Zhang (2018) describe an exhaustive description of several papers that employs 5G communication techniques in order to extend the primary mechanisms and protocols for the design of airborne communication networks by considering the LAP (Low Altitude Platform)-based and HAP (High Altitude Platform)-based communication networks with cellular networks. More recently, the use of SBAS (Satellite-Based Augmentation System) messages to support inter-metropolitan UAV communication has gained prominence. (YOON *et al.*, 2020) proposes the use of an onboard module that includes correction conversion, integrity information calculation, and fast initialization requests to enable the application of an online SBAS for drone operation. The authors expected that their system could be a useful and practical solution to integrate drones into the airspace in the near future.

3.1.4.2 WLAN

The WLANs are very used to provides and maintain the communication between mobile nodes with theoretical limits of up to 1 km. In these group of interfaces devices there is IEEE 802.15 (known as WPAN group), IEEE 802.11x, IEEE 802.11a/b/g/n, IEEE 802.11p, and RF (900MHz) (ZHOU *et al.*, 2015; YAN; PENG, M.; CAO, 2018).

Several research papers already developed performance evaluations and comparisons between wireless technologies, for example, a performance modeling and analysis of access class performance of 802.11p EDCA is presented in (ZHENG; WU, 2016) . In this one, the aim of the authors is modeling the IEEE 802.11p enhanced distributed channel access (EDCA) mechanism developing performance models to analyze in Vehicular Ad-Hoc Networks (VANET) scenarios using a 1-D discrete-time and 2-D Markov chains. The simulation results presented that derived or extended Markov chain are accurate and effective in the analysis of the access performance of the 802.11p EDCA mechanism. So,it could be useful to realize infinite modeling of the contention period of an AC queue under both saturated and non-saturated conditions, evaluating the relation transmission versus collision probabilities. At this work, the authors did not include the mobility effects.

The IEEE 802.11b,g/n standard stack is very popular to serve as baseline protocols layers to develop solutions to improve the UAVs network reliability and survivability (YANMAZ, Evşen *et al.*, 2014; SCHERER *et al.*, 2015). This is clear as this standard provides robust MAC and PHY layers, that apply MIMO (Multiple Input and Multiple Output) technologies. Other characteristics, like using two unlicensed bands (2.4 GHz and 5 GHz), are also considered. The high throughput and larger bandwidth are characteristics that have been extensively explored in this scenario (ZENG; ZHANG, R.; LIM, 2016; YANMAZ, Evsen *et al.*, 2018). One important factor is that the standard is still most commonly found in other commercial devices (usually IEEE 802.11n), which reduces the risks of integration with other devices (e.g. IoT, sensors, etc).

In this context several works propose solutions to cover issues involving UAVs wireless ad-hoc networks, such as maintaining strong connection between network nodes (JAWHAR *et al.*, 2017), reliable transmission and reception with QoS (NASRALLAH; AL-ANBAGI; MOUFTAH, 2014), minimal latency (YANMAZ, Evsen *et al.*, 2018), low delay (JAWHAR *et al.*, 2017), and high signal power reception (MURILLO *et al.*, 2018). These issues vary depending on the kind of data that the UAVs need to exchange during the mission (voice, video, data, coordinates).

In conclusion, the composition and choice of wireless communications IEEE standards is a critical point in the network consumption and needs extra attention, especially for FANETs, due to their mobility and flexibility characteristics (BEKMEZCI; SAHINGOZ; TEMEL, 2013; YANMAZ, Evsen *et al.*, 2018; SALEEM; REHMANI; ZEADALLY, 2015b).

3.2 ADDITIONAL REMARKS

Maintaining stable wireless connections between high-mobility mobile devices, such as UAV networks, is a research field facing several challenges due to the mobility, flexibility, and variant topologies that constitute these networks known as FANETs (BEKMEZCI; SAHINGOZ; TEMEL, 2013).

Overall, the above-mentioned studies did not evaluate the entire network conditions along the flights. In the studies that adopted heterogeneous communications, many assumed pre-existing mission conditions, defining offline which interface will be used for a given purpose, reducing the network's adaptability to unexpected events. So, most of them is not consist in dynamic solutions not implying in events adaptive solutions. In case of homogeneous solutions, these could be more affected in presence of network coexistent, once they will shared the same frequency band.

In terms of software solutions, the IEEE have been work in protocols stacks including reduction in generation interval of CTS (CTS, *Clear to Send*), RTS (RTS, *Request to Send*), and ACK (ACK, *Acknowledgment*) frames, decreasing the size of the packet header implying in very short response time. An example of this is the stack of the IEEE 802.11p protocol, which serves for communication between vehicles, and provides the alternative of allowing the transmission of messages within a network range based on the geo-positioning, so that the nodes do not need previous authentication in the network (JIANG; DELGROSSI, 2008; IEEE 802.11P, 2010). Another example, is the IEEE 802.11 ah (IEEE-802.11AH, 2017) task group, which the main idea is improving the connections for IoT networks and M2M (Machine to Machine) applications where it will support long-range and energy-efficient communication in dense network environments for short-packets data traffic.

Other alternatives to maintain the reliability of these wireless networks include complementary mechanisms to a communication protocol (classified by this thesis as software solutions), which function by managing the assignments of the frequency channels (GREENBERG; BAR; KLODZH, 2019) and promoting traffic in multi-protocols and paths (LEE, 2021) generating traffic redundancies, and efficient algorithm systems that optimize the quality of the message exchange repositioning nodes (LIU *et al.*, 2018) in order to improve their connection intensity (WATANABE; TAKAHASHI; TOBE, 2017;

PARK, J. H. *et al.*, 2018).

These solutions have directly correlation with the kind of network management for example, in the solution for charge in real-time multi-UAV nodes during the flight, using manned aircraft as charge wireless devices present in (LI, L. *et al.*, 2015). In this one, a hybrid network manager is used, where the base station control the aircrafts in a centralized way and the multi-UAVs present decentralized autonomous control. Hardware changes solutions basically employ changes in the antenna physical structure (TEIXEIRA *et al.*, 2015) and addition of extra platforms as Raspberry PI (YANMAZ, Evşen *et al.*, 2014).

Some emergent technology solutions, such as the use of SBAS communication (YOON *et al.*, 2020), software-defined networks for U2U communications (KAIDENKO; KRAVCHUK, 2019), and the use of IoT protocols (RAIMUNDO *et al.*, 2018) have produced promising results in these communication scenarios. The first one, in terms of extends the range of communication to metropolitan distances and the second one, in terms of high scalability and very-high time of response.

Other alternatives in order to extend the communication range of mUAVs systems is the use of relay nodes that have been shown to be promising in the rescue of communication with disconnected nodes (nodes that overcame the communication range) (JAWHAR *et al.*, 2017; BEKMEZCI; SAHINGOZ; TEMEL, 2013). These nodes act as ICD (Intermediary Communication Devices) by amplifying or re-transmitting the signal to nodes beyond the reach of the network node (HUI, K.; PHILLIPS; KEKIRIGODA, 2017; HUI, K. P.; PHILLIPS, Damien; KEKIRIGODA, Asanka, 2017).

About the viewpoint of algorithms procedures, biological algorithms (HAZRA *et al.*, 2021) and dynamic relay nodes selections (YANMAZ, Evşen, 2021) have provided signal gains and continuous connectivity in search and rescue missions. In this context of emergent solutions, the use of heterogeneous networks solutions can also be useful for addressing the problem of maintaining connectivity between these types of nodes, seeking quality and reliability in the delivery of messages (LIMA *et al.*, 2018; RIBEIRO, L.; MULLER; BECKER, L., 2020).

UAV networks employed to allow collaborative and cooperative missions are very useful in several areas and it is easy to find new applications, but implement, test, find constraints, operate and constitutes this kind of ad hoc networks are not trivial as a number of technical challenges involved faced in designing these applications (JAWHAR *et al.*, 2017). Finally, to know how a work is classified in academic nixes is very important to get related ones in order to propose comparisons and improvements highlighting the differences among approaches.

3.3 EVALUATION AND DISCUSSION

Some related works present in this chapter were summarize in Table 1 using the classification proposed. In this one, the works are relationed using criteria proposed by seeing the four macro-sets of classification: the amount of communication interface, architecture and system type, network management, and communication range.

Table 1 – Related Works summarize per Classification Proposed

Related Work \ Classification	Homogeneous [1]	Heterogeneous [1]	Software Solution [2]	Hardware Solution [2]	Centralized [3]	Distributed [3]	Hybrid [3]	WWAN [4]	WLAN [4]
(GIELIS; PROROK, 2021)	✓		✓			✓			✓
(YANMAZ, Evşen *et al.*, 2014)	✓			✓			✓		✓
(RAIMUNDO *et al.*, 2018)	✓		✓		✓				✓
(MERWADAY; GUVENC, 2015)		✓	✓				✓	✓	✓
(YOKOYAMA; KIMURA; SANTOS MOREIRA, 2014)		✓	✓				✓	✓	✓
(SHARMA *et al.*, 2017)		✓	✓				✓	✓	✓
(GRIGULO; BECKER, L. B., 2018)	✓		✓			✓			✓
(ZHOU *et al.*, 2015)		✓	✓				✓	✓	✓
(STANOEV *et al.*, 2018)	✓		✓		✓				✓
(KAIDENKO; KRAVCHUK, 2019)	✓		✓		✓				✓
(YUN *et al.*, 2015)	✓			✓		✓			✓
(SCHERER *et al.*, 2015)	✓		✓	✓			✓		✓
(YAMAGUCHI; KAROLONEK, 2017)		✓	✓		✓				✓
(KRASUSKI; WIERZBICKI, 2021)	✓		✓	✓	✓			✓	
(KARAMCHEDU, 2020)	✓		✓	✓	✓			✓	
(LI, B.; FEI; ZHANG, Y., 2018)	✓		✓				✓	✓	
(YOON *et al.*, 2020)	✓		✓	✓	✓			✓	
(HUI, K.; PHILLIPS; KEKIRIGODA, 2017)	✓		✓			✓			✓
(MURILLO *et al.*, 2018)	✓			✓		✓			✓
Interface Manager		✓	✓			✓			✓

In this one, the expressive number of software solutions against hardware solutions provides that it is possible to give better adaptability and flexibility of UAV communication development, without hardware customization needs. The use of hybrid network managers is increasing and most of them provide interoperability between different networks. In this case, both criteria WLAN and WWLAN can be applied according to the communication range of interface applied. Homogeneous networks are still the most used approach, once more interfaces are attached to a platform much energy is consumed. Generally, the authors propose adaptive solutions to define how the resources of an interface will be used. This thesis, it is not verified the energy consumption of the

[1] Amount of communication interface set of classification.
[2] Architecture and system type set of classification.
[3] Network management set of classification.
[4] Communication range set of classification.

solution proposed, considering that is not energy constraints. The interface manager energy consumption will be evaluated in future work.

In general, the works employ network centralized management when it is needed to have the domain over UAVs paths or in cases of the undefined mission area, an example in missions to provide communication in natural disasters areas. The hardware solution works correspond to make changes in antennas or add specific devices to UAVs, like satellite/GPS communication cards.

Some related works aspects are present in Tables 2 and 3. These aspects include frequency band, communication interfaces adopted a brief description of the solution, the type of traffic required by the application network (type of service), and highlights the performance obtained in terms of network metrics. These aspects describe at the macro-level, the kind of approaches for multi-UAV networks used by these works.

In general, the solution with more than one frequency band, presenting the heterogeneous use of WWLAN and WLAN interfaces. The main application of this solution is to extend the range of communication to communicate U2U with other networks as VANETs, R2R, or IoT networks. Usually, these solutions employ WLAN interfaces using 5 GHz frequencies to avoid interferences founded in the 2.4 GHz spectrum. The 802.11 protocol still is the largest in use, since is very commonly founded on on-the-shelf platforms and in general, presents throughput and delay sufficient for several kinds of application for multi-UAV networks.

The increasing of works related to the use of satellite links to provide communication and localization in UAV networks highlights the importance of solutions which presents open-architectures or consist of modular solutions, like proposed by this thesis solution, allowing to insert more algorithms, classifiers, services, remove/add more MAC protocols and communication devices.

The number of works performing from different ToS traffic is more restricted, so works like this thesis, which performs its solution from data, voice, and video traffic is more scarce constituting a differential of this work. Short-packets which are packets with a payload between 4-100 bytes are very present in multi-UAV communications, these packets are composed of coordinates for UAVs positioning and localization solutions.

Table 2 – Related works aspects - Part. 1

Related Work	Aspects				
	Frequency Band	Comm.Interfaces	Solution	Type of Service	Performance
(GIELIS; PROROK, 2021)	5.9 GHz	802.11p	improvements to 802.11p protocol for inter-robot navigation information control avoiding collisions	beacon frames	4 times more PDR with average of 25 ms of latency
(YANMAZ, Evşen *et al.*, 2014)	5.2 GHz	802.11a	compare performance of infrastructure and mesh modes, using one or two hops for UAV networks	TCP traffic for packet sizes of 1460 bytes	throughput of 16 Mbps for one hop against 8 Mbps in two hops
(RAIMUNDO *et al.*, 2018)	2.4 GHz	LoRa	Getting GNSS positions at maximum rate possible	GNSS	centimeter-level accuracy of positions with low transmission rate and payload length cost
(MERWADAY; GUVENC, 2015)	2.4 and 5 GHz	LTE, 802.11n	capacity of Public Safety Communications	user-demand	improve the throughput coverage and the 5th percentile spectral efficiency of the network
(YOKOYAMA; KIMURA; SANTOS MOREIRA, 2014)	5 GHz	LTE, 802.11p	security positioning of UAVs in a swarm applying beaconing-based communication	coordinates and positioning	RSSI improvements
(SHARMA *et al.*, 2017)	5 GHz	LTE and 802.11p	UAV as intermediary relays for ground vehicles in disasters rescue	several packets sizes	improve rx power with low RTT and reduces the packet loss in 20%
(GRIGULO; BECKER, L. B., 2018)	2.4 GHz	802.11n	provide localization for WSN	coordinates	accuracy <10 m of localization
(ZHOU *et al.*, 2015)	2.4 GHz	802.11a, 802.15.4	UAV networks as relay nodes to collect and transmitted data to ground vehicular networks	UDP protocol data rate	latency of 25 ms for Zigbee and 230 ms for Wi-Fi, average throughput of 64 KB/s by Zigbee and 19 Mb/s by Wi-Fi highlighting the importance of fading performs

Table 3 – Related works aspects - Part. 2

Related Work	Aspects				
	Frequency Band	Comm.Interfaces	Solution	Type of Service	Performance
(STANOEV *et al.*, 2018)	not specified	not specified	adaptive image system to avoid collision in a rocket airstrip	video streaming	image quality ans latency
(KAIDENKO; KRAVCHUK, 2019)	not specified	not specified	UAV system based on SDR and SoC technologies	different data rate	survivability of the radio signal
(YUN *et al.*, 2015)	5 GHz	802.11p	a magnetic tripolarization antenna is proposed for Dedicated Short Range Communication applications	level of signal	improve signal reception
(SCHERER *et al.*, 2015)	5.2 GHz	802.11a, 802.11s	propose a modular architecture of an autonomous UAV system for search and rescue missions	video streaming	delays below 5 ms and GPS delays of 1 to 2 seconds have been noted
(KRASUSKI; WIERZBICKI, 2021)	1575.42 MHz	GPS L1 C/A	a new concept of determining the resultant position of a UAV based on individual SBAS determinations	coordinates	coordinates' standard deviation better than 0.2 m
(KARAMCHEDU, 2020)	4 GHz and 5 GHz	cellular	U2U communications applied to extends Device-to-Device communication	Signal Reception	a feasible solution to extends communication
(YOON *et al.*, 2020)	1575.42 MHz	Satellite	Improving navigation	coordinates	initialization time reduced to 1 s and position accuracy improved in 40%
(HUI, K.; PHILLIPS; KEKIRIGODA, 2017)	not specified	not specified	use UAVs to maintain the link between exploration ground robots in contested environment	maintain link	maintain the SINR in levels desired reducing the disconnection time
(MURILLO *et al.*, 2018)	2.4 GHz and 5 GHz	802.11n and 802.11p	performance evaluation of of the 802.11n and 802.11p standards in vehicular networks	received signal power	good signal reception up to 50 m
Interface Manager	2.4 GHz and 5 GHz	802.11n, 802.11p, 802.11ac, 802.11ax	provides a heterogeneous communication using a modular solution, allowing add/remove interfaces or decision-making algorithms	voice,data,video streaming and *beacon* frames	improve rx power with low loss rate, reaching SNR > 0.5 and delay acceptable, and others.

The main aim of the Tab.(4) is to present the most commonly wireless networks metrics applied to evaluate and perform the multi-UAV approaches. According to this Table, the metrics more used are throughput, latency, and delay, when the solution has the aim of increase the reliability of message/packet delivery, and RSS, RSSI, Loss, and Distance effects when maintaining the connectivity is the main aim of work. It highlights the importance of define evaluated metrics according to tasks and goals of a mission.

It also demonstrated that the data rate received concerning a time interval is very important depending on the type of service of a UAV network, mainly because a

UAV can be inside a wireless coverage area during a very short time interval. So, the RSS, RSSI, Loss, SINR, and SNR are metrics that relate to the power of transmission and connectivity of a network, considering the impacts of noise over the transmissions, since having a high rate of the data flow will not imply in the increase of the efficiency in the transmissions if they are annulled by noise in the transmitted signal. The Interface Manager proposed by this thesis aims to improve the reliability and connectivity between UAVs, thus all these network metrics are verified to evaluate this solution.

Table 4 – Network evaluated metricc

Related Work \ Network Metric Evaluation	Latency/Delay	Throughput	Packet Loss/PDR	SNR/SINR	RSS/RSSI	Loss/Fading/Atten.	Distance	Different ToS
(GIELIS; PROROK, 2021)	✓		✓	✓				
(YANMAZ, Evşen *et al.*, 2014)		✓			✓	✓	✓	
(RAIMUNDO *et al.*, 2018)		✓					✓	
(MERWADAY; GUVENC, 2015)	✓				✓			✓
(YOKOYAMA; KIMURA; SANTOS MOREIRA, 2014)				✓	✓		✓	
(SHARMA *et al.*, 2017)	✓	✓			✓		✓	✓
(GRIGULO; BECKER, L. B., 2018)					✓		✓	
(ZHOU *et al.*, 2015)	✓	✓						
(STANOEV *et al.*, 2018)	✓		✓					
(KAIDENKO; KRAVCHUK, 2019)				✓	✓			
(YUN *et al.*, 2015)	✓				✓	✓		
(SCHERER *et al.*, 2015)	✓	✓					✓	
(YAMAGUCHI; KAROLONEK, 2017)	✓			✓	✓	✓	✓	
(KRASUSKI; WIERZBICKI, 2021)	✓	✓			✓	✓	✓	
(KARAMCHEDU, 2020)	✓	✓			✓	✓	✓	
(LI, B.; FEI; ZHANG, Y., 2018)	✓	✓	✓	✓	✓	✓	✓	✓
(YOON *et al.*, 2020)	✓	✓			✓	✓	✓	
(HUI, K.; PHILLIPS; KEKIRIGODA, 2017)		✓		✓	✓		✓	
(MURILLO *et al.*, 2018)				✓	✓		✓	
Interface Manager	✓	✓	✓	✓	✓	✓	✓	✓

3.4 SUMMARY

This chapter presented several solutions to improve, establish and maintain connectivity between UAVs. To provide an organization of these works, a classification was proposed using four-macro aspects. Some Tables were constituted to highlights the main differences observed by the criteria used by this classification, and summarize some main works aspects. A table summarizing the network evaluation metrics used by these works is defined.

The table used by works classification highlights that most of the works use homogeneous communication employ software solutions, and provides short-range communication. According to the application of network the type of management is chosen, generally, a hybrid manager is used to extends the range of communication and allow interoperability with other networks.

The tables used to brings the macro-aspects from related works describe that the type of service composed by coordinates traffic is very needed in UAVs networks. Generally, the UAVs use 5 GHz frequency applying 802.11 protocol for short-range and LTE for long-range communication. The SBAS technology is seeming in the UAV network context, it is capable to extends the range areas to WMAN (Wireless Metropolitan Area Networks) levels. The last table composed of network metrics highlights the use of differed metrics to evaluate multi-UAV networks systems, according to the aim of the solution.

Despite different authors providing approaches to provide reliable in UAV networks, using homogeneous or heterogeneous communications devices and different kind of solutions, in the general context, this is an area that still it is evolving which implies in a field with much opportunities to develop studies, due to the vast number of open issues. In this way, define the scenarios and setups of a network application is of most importance to define the network constraints, so the next chapter describes in detail the scenarios of applications of this thesis proposal.

4 HETEROGENEOUS COMMUNICATION INTERFACE MANAGER

Given the medium characteristics and the composition of FANETs, including limited flight time (in several cases, short deadline of missions), natural interferences (e.g. rain and wind), and out-of-range communications issues cause several challenges for the composition of these networks. The mobile distance and variable speed of nodes further contribute to the problem of reliable communication by UAVs nodes (SALEEM; REHMANI; ZEADALLY, 2015a; YANMAZ, Evsen *et al.*, 2018).

In this way, communications between multi-UAVs demonstrate some features that could be helpful to employ different wireless communication standards. According to tasks that can be done in a mission, the UAV networks need to send different kinds of packets, such as video, voice, sensors data, actuators data, and coordination signals (BEKMEZCI; SAHINGOZ; TEMEL, 2013; M. S. MENEGOL J. HUBNER, 2018). The use of heterogeneous communication could improve the communication requirements for each type of service.

In this context, solutions that employ dynamic network measurements or dynamic evaluation conditions allow the continuous search of the best network performances during mission (in flight time).

Based on this, this Chapter shows the interface manager to provide heterogeneous communication in networks composed of multiple UAVs. The main object of this manager is to maintain the connection with quality of service between the mobile nodes improving the reliability of connections for different types of service between them throughout the mission.

Firstly, the architecture of the interface manager is presented in Section 4.1 describing all the layers in details. Secondly, in Section 4.2, it is presented the heuristic and system model containing the network evaluation conditions that are employed by a decision-tree heuristic. In Section 4.3 the algorithms used in the development of this solution are described in steps. Lastly, the Section 4.4 presents some conclusions, highlighting the benefits and improvements that IM could apply in mUAVs networks.

4.1 ARCHITECTURE OF THE INTERFACE MANAGER

This section presents the architecture of the proposed interface manager (IM), which aims to provide heterogeneous communication in networks composed of multiple UAVs. Figure 4 illustrates the layers of the proposed architecture.

According to (YANMAZ, Evsen *et al.*, 2018), each UAV that belongs to a multi-UAV system needs to communicate while meeting some requirements: observing the environment, evaluating their own observations and those received from other UAVs, reasoning from the observations, and acting in an effective way. Thereby, each layer illustrated in Figure 4 meets one of these requirements, as further detailed.

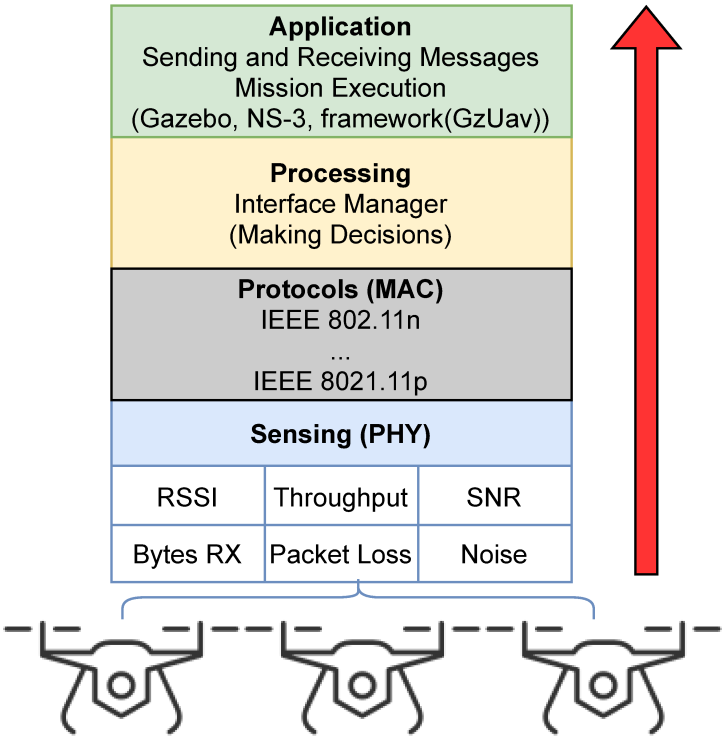


Figure 4 – Interface manager (IM) architecture.

- Application: In this layer, the mission of each UAV is defined. This includes the definition of trajectories, their mobility features, their goals, the type of messages that will be transmitted by each UAV, the recipients, and their payload. In addition, other details are defined in this layer such as the frequency of sending, definition of the protocol used for routing, and packet size. This layer can synchronize with other applications, in our case, with the NS-3 network simulator and the Gazebo virtual environment.
- Processing: This layer is responsible for executing systems, mechanisms, reasoning or decision-making entities, and coordinating systems. More specifically, it is responsible for the number of vehicles (nodes) in the network, the amount of interfaces, analyzing the parameters sensed by the medium, and calculating other parameters or conditions. Such parameters are used as the input of the decision-making process. This layer evaluates the parameters received from the sensing layer composed by its own and other sensing nodes to define the interface that will improve the link. To ensure a fair decision, it is necessary to use parameters common to all employed wireless interfaces.
- Sensing (PHY): This layer is responsible for sensing medium information and metrics (signal strength, background noise, latency, throughput, packet loss, and quantities of sent and received bytes). In the proposed architecture,

periodic beacon frames are transmitted to allow calculation of the desired metrics.

In summary, the sensing layer serves to “listen” to the medium to sense the network parameters of interest. The protocol layer is used to enable each interface to calculate and sense such parameters according to their intrinsic characteristics of frequency, range, bandwidth, and transfer rates. Although one interface is chosen for communication, the other(s) remain in a listening state to maintain dynamic sensing. The processing layer uses the collect data to execute a heuristic, which aims to select the best interface to be used at a given moment. Finally, the application layer defines the UAV mission, which includes the messages to be sent by each UAVs. It also details the UAV mobility features, such speed, acceleration, deceleration, and waypoints. The protocol layer and the sensing layer can be considered as modules that support the addition of other wireless interface cards to the system.

To guarantee the survivability of an ad hoc network, each node needs to be connected with at least one neighbor through a strong link with acceptable data flow. The aim of this method is to establish the reliable exchange of messages with the maximum possible QoS and to perform the maximum number of successful packet deliveries.

4.2 HEURISTIC AND SYSTEM MODEL

The main goal of the proposed IM is to improve communication connectivity by providing more stable communication links. As a consequence, it increases the reliability of the delivery of messages between the UAVs. Therefore, its use of a set of conditions that are essentially composed of the following parameters: quantity of bytes received, quantity of bytes lost, network throughput, the received signal strength indication (RSSI), and the signal to noise ratio (SNR). These parameters are used to analyze the strength of a connection established between neighboring nodes that use the same network interface.

A strong connection is defined by the composition of various network conditions dynamically evaluated during the mission according to calculated network metrics and to the sensed metrics, calculated online, during each UAV journey. These conditions define a decision heuristic used by the interface manager to make decisions about which interface will provide a strong a connection.

The best interface will be the out of the IM consisting the one with more best performances along with the evaluation conditions. The best communication interface is defined by the interface which present the better performance in the most of conditions.

Equal weights for each metric were adopted, aiming to maintain connectivity and stability in the communication links, given that these metrics have the same importance in this kind of high-mobility wireless networks. So, it is not enough to simply have a larger volume of bytes received, but also how often these bytes are received and with which quality they are received. Otherwise, if, in the presence of high loss and low RSSI, such received bytes could be constituted by trash or truncated messages.

So, when heterogeneous communication is used, a set INT is constituted, formed by all communication interfaces that integrate the system.

The decision conditions must be evaluated for each communication interface INT_X based on the last sample interval. The heuristic currently adopted is based on a rewards mechanism, where each interface accumulates points based on its performance through the defined decision conditions. Thus, a given interface INT_X increases one every time its decision condition c_i is better classified, as shown in ((1)),

$$INT_X^{c_i} = \begin{cases} 1, & \text{if } c_i^X \text{ has the best performance,} \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

c_i^X stores the value of a network metrics i from Table 5, sensed or calculated using an interface x in the last messages sent/received by each UAV. Thus, the intensity of a connection is defined by the sum of the points obtained from a comparison of the decision conditions obtained by each interface.

The proposed IM is distributed in a set $X = \{x_k\}_{k=1}^{|X|}$ of UAVs that are part of an ad hoc network established for a mission. Each UAV represents a mobile node belonging to the network, which must be able to communicate with each other in order to enable the sending of the execution status of the tasks, sharing goals in mission time.

Here, a decision tree is used to evaluate which communication interface will provide the strongest connection for sending the next group of messages within the current sample interval. The DT evaluation conditions describes how much an interface could imply to strong communication, which means more number best performance conditions.The quality of communication is evaluated based on the communication of a node with its neighbors within the communication range.

Notably the DT is run in a distributed way, i.e., it runs separately within each UAV node. The entire process of deciding which interface will be used occurs based on the data of the wireless medium collected by a determined UAV and on the network metrics sensed in the communications with its neighbors.

Table 5 presents the metrics used in the DT. Each of these metrics is applied as a condition c_i, as stated in Equation (2).

The IM captures information either through directly sensing the medium or by calculating each decision condition. Therefore, it uses the last frames received by the UAVs, verified at each sample interval $N = n_0, n_1, n_2, \ldots, n_n$ defined for a new metric sample. Thus, the value of a condition c_i used in the decision heuristic is the average of the values obtained in the last sensed or calculated samples $\sum_{n-1}^{n} c_n^i$ for each interface

Table 5 – Metrics used as requirements for decision making.

Condition (c_i)	**Network Metric**
c_1	Throughput
c_2	Total Bytes Sent
c_3	Total Bytes Received
c_4	RSSI
c_5	SNR

belonging to the *INT* set.

$$INT_x^{c_i} = \frac{\sum_{n-1}^{n} c_n^i}{(n+1)}, \forall n \in N \tag{2}$$

Each condition in Table 5 represents a level from the decision tree presented in Figure 5. It reaches the target state (final decision) after checking all the decision conditions, comparing the interfaces that compose the *INT* set. For cases where the DT does not make any decision for an interface, or at the beginning of the mission, at least one sample interval is considered of the operating samples for each interface $(n+1)$. This prevents having no values (null) in a given sample of Equation ((2)). So, for example, if three interfaces are used, the first three samples correspond to the exchange of messages between the UAVs, alternating using one of the interfaces, without implying the IM decisions.

As such, the DT is established, constituting a heuristic based on the accumulation of points for each interface INT_x, with the decision of each level by the interface that presented the best performance in the condition that composes the level. The target state consists of the interface with the best performance in a larger number of conditions featuring a stronger connection.

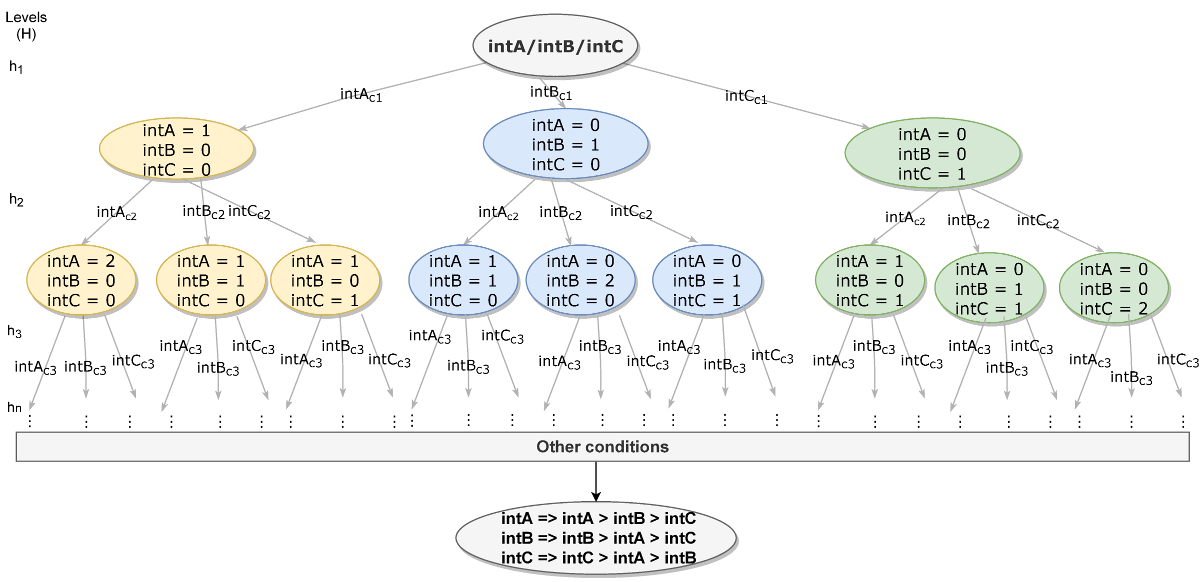


Figure 5 – Decision tree used by the interface manager.

The target state of the DT is reached from a non-complete binary subtree, since only one interface is chosen for the next message flow.

Therefore, the definition of an interface is an optimal local choice based on the decision conditions evaluated along the levels of the tree,

$$INT_x = \sum_{h}^{H} r_h^x, where - r_h = 1, \forall h \varepsilon H$$
$$x_k = INT_x \Rightarrow INT_x > INT. \quad (3)$$

The DT score is composed of the points added by each interface $\sum_h^H r_h^x$, where r_h^x is the accumulative variable that stores the sum of points of an interface along the levels h of the set of levels that comprise a tree H, in which the interface with the highest sum of points $INT_x > INT$ is chosen by a UAV x_k for the next sending of messages $x_k = INT_x$. The other interfaces (not chosen) stay in a state of listening to receive the messages sent by other UAVs that are using other interfaces.

The definition of the best interface is verified in each IM execution, maintaining the last IM decision in case of the same result. So, in each validation all the points obtained and stored by an interface is empty and a new decision tree validation is verified.

The algorithm worst case complexity is $O\ log(n)$, where n is the number of tree levels. The number of decision conditions compose the height of tree. It happens that, for a fixed number of conditions like in our case, the system presents a linear complexity n. As such, the algorithm can be implemented with low computational costs. The single requirement is allowing parallel readings of the sensed conditions by the set of interfaces applied, enabling the heterogeneous sensing of the environment.

The aggregation of sensing samples from the medium, from the different interfaces applied by interface manager, must be stored in buffering schemes so that the sample intervals are the same.

4.3 ALGORITHM DESCRIPTION

Figure 6 summarizes the IM execution, divided into blocks. The main steps consist of sensing, interface manager routines (calculate and extract network evaluate conditions, buffer, and decision-making procedures), and output validation.

In the sensing steps, all of the interfaces attached to the system sense the medium, thus capturing *beacon* frames. These frames include the Rx power and noise conditions obtained by the interface. When an interface has established a communication link, it is possible to obtain the number of bytes received and dropped, compounding dynamic evaluation conditions used by IM. In this case, the others maintain the *listen* state, in order to provide continuous medium validation. These medium-sensed metrics are aggregated and stored in a buffer. Throughput and SNR are calculated metrics composed of the number of bytes and packets received, as well as packet sending and reception times. These medium-sensed metrics are used to calculate the SNR.

The extracted packets per interface block consist of routines to obtain the amount of received, transmitted, dropped, lost, and successful packets per flow of messages (which occurs when a link is established). Each set of packets that composes a message has a *tid* (i.e., an identification field that describes the kind of access class of a packet). All of these blocks, which comprise the calculated medium-sensed conditions and the extraction of packets routines, are stored in a cyclic buffer, in order to avoid fluctuation effects, as this measurement is of a dynamic medium.

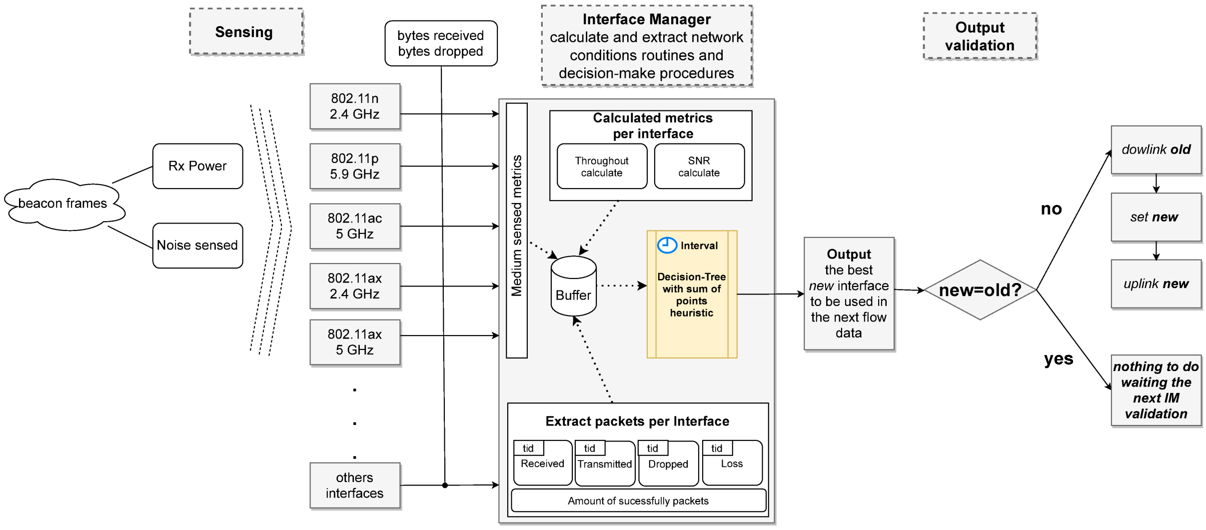


Figure 6 – Block diagram showing overall idea of the interface manager system.

In each interval defined for a new IM validation, the decision-making algorithms are verified using the network-evaluated conditions stored in the buffer. The output of the interface manager is the best new interface to be used for the next message sending step. In this way, all the sum of points scored by each interface, and the medium sensed metrics stored in the buffer are empty to allow a new IM validation. So, once the decision tree presents five-level each interface could accumulate a maximum of five points.

The output of the interface manager is the best new interface to be used in the next message sending step. In this case, validation of this *new* interface is carried out, in order to compare it with the last one defined. If the new interface is different from the last one, the routines of *downlink* for the interface in use, then *set* and *uplink* for the new interface are started. Otherwise, the same conditions are maintained and nothing is done.

The block diagram that composes the interface manager system is formulated by algorithms consisting of two main parts: sensed and calculated metrics, and a heuristic of sum of points. Algorithms 1 and 2 describe these parts, respectively, and are applied in a decentralized manner. Thus, each UAV makes its own decision, based on the blocks sensed and calculated by itself, independently of others.

Algorithm 1 presents the sensed and calculated metrics used for dynamic evaluation of the medium dynamic conditions. The sensed metrics are described by **rxPower** (line 2), **noiseSensed** (line 3), **bytesReceived** (line 4), and **bytesDropped** (line 5). All of these metrics are obtained using *beacon frames* and signals from an established link. The *beacon frames* are obtained from the listen state of interfaces which are not in use, and the sign messages captured by the interface used to establish the link in use. Thus, the procedure *BufferSensingAndCalculateMetrics* has, as inputs: *MACframesDetected*, which is composed of all frames received by a UAV using the MAC and PHY layer by *interfaces*, which uses a *frequency* band, where each frame has labels to identify the node that sends this message *receivFrom*, which node requires a link *sendFor*, and also which nodes stay within range (i.e., nodes remaining in the neighborhood; *sourceNodes*). In this way, *rxPower* (line 2) and *noiseSensed* (line 3) are captured metrics from *beacon frames* sensed by *sourceNodes*; while *bytesReceived* (line 4) and *bytesDropped* (line 5) are metrics obtained by a link established by a sink *sendFor* node and a source *receivFrom* node.

To analyze the network performance at application level from transmission of different types of services, the MAC frames are aggregated, using the A-MPDU (Aggregated MAC Protocol Data Unit), into trailers which generate sets of packets in the network OSI layer, attaching their respective headers for each protocol, including fields such as destination and source IP address, and the ToS field for identification of the type of service (IEEE-802.11, 2007). The ToS packet header field is used for identification of packet access classes, as all the communication interfaces were set with QoS-enabled MAC models.

Thus, the packets are extracted between lines 6–11 of Algorithm 1, where all the *extractPackets* functions include the *tid* field as input. The *tid* is the ToS tag, which should mark packets forwarded down to the MAC layers, in order to set a TID (transmission and reception id) for that packet; otherwise, it will be considered as belonging to AC_BE.

The calculated metric is described in lines 12–14 of Algorithm 1; that is, the **SNR** (line 13), calculated using the relation between the *rxPower* and *noiseSensed* from a MAC frame received calculated by *calculateSNR* function.

The **throughput** (line 14) is calculated using the *calculateThroughput* function, which considers the amount of bytes received *totalBytesRx*; the reception time of the last packet *timeLastRxPacket* received by a flow of messages, with respect to the amount of packets received successfully (*packetsSuccess*, confirmed by the receiver node); and the transmission time of the first packet of this flow *timeFirstTxPacket*.

In this case, for each flow of messages *v* that belongs to the set of all flow mes-

Algorithm 1 Sensing and Calculate metrics.

```
Require: MACframesDetected,interface, receivFrom, sourceNodes;
Ensure: BUFFERSENSINGANDCALCULATEMETRICS;
{Medium-sensed metrics}
rxPower ← signalDbmAvg(MACframesDetected, frequency, interface, sourceNodes,
    signalsensed);
noiseSensed ← noiseDbmAvg(MACframesDetected, frequency, interface,
    sourceNodes, noiseSensed);
bytesReceived ← extractBytes(MACframesDetected, receivFrom, interface);
bytesDropped ← extractBytes(MACframesSended, sendFor, interface);
{Extract Packets}
packetsReceived ← extractPackets(MACframesDetected, tid, receivFrom, interface);
packetsTransmitted ← extractPackets(MACframesDetected, tid, sendFor, interface);
packetsDropped ← extractPackets(MACframesSended, tid, sendFor, interface);
packetsLost ← extractPackets(MACframesDetected, MACframesSended, tid, sendFor,
    receivFrom, interface);
packetsSuccess ← PacketConfirm(packet, tid, sendFor, receivFrom, interface);
{Calculated metrics}
SNR ← calculateSNR(rxPower, noiseSensed, interface);
Throughput ← calculateThroughput(totalBytesRx, timeLastRxPacket,
    timeFirstTxPacket, interface);
for ∀v ∈ V do
    AmountofPackets_v ← (packetsReceived,packetsTransmitted,packetsDropped,
        packetsLost,packetsSuccess);
    if tid_v is = 0x70 then
        ToS_v ← AC_BE;
    else
        if tid_v is = 0x28 then
            ToS_v ← AC_BK;
        else
            if tid_v is = 0xb8 then
                ToS_v ← AC_VI;
            else
                if tid_v is = 0xc0 then
                    ToS_v ← AC_VO;
                end if
            end if
        end if
    end if
end for
for ∀i_i ∈ I do
    {I is set of interfaces}
    AmountofRxPower ← sum(rxPower,i);
    AmountofNoise ← sum(noise,i);
    AmountofbytesReceived ← sum(bytesReceived,i);
    AmountofbytesDropped ← sum(bytesDropped,i);
    AmountofSNR ← sum(SNR,i);
    AmountofThroughput ← sum(throughput,i);
    {storing in the buffer}
    CalculateAvgBuffer(AmountofRxPower, i);
    CalculateAvgBuffer(AmountofNoise, i);
    CalculateAvgBuffer(AmountofbytesReceived, i);
    CalculateAvgBuffer(AmountofbytesDropped, i);
    CalculateAvgBuffer(AmountofSNR, i);
    CalculateAvgBuffer(AmountofThroughput, i);
end for
```

sages transmitted by network V, the amount of packets generated **AmountofPackets** is verified (line 16). Each packet has a *tid* tag, in order to classify the packets received (lines 17–29). Here, *tid*=0*x*70 denotes AC_BE data, *tid*=0*x*28 denotes AC_BK network signals, *tid*=0*x*b8 denotes AC_VI video, and *tid*=0*x*c0 denotes AC_VO voice , according to the IEEE AC classification.

Lines 30–45 in Algorithm 1 describe routines to calculate aggregated network samples (lines 32–37) and the storage process in a buffer of ten positions, in order to avoid the fluctuation effects caused by medium dynamic variations (lines 38–45).

The *CalculateAvgBuffer* function calls the cyclic buffer of samples received, and calculates the average obtained by each metric sample for each interface. The average obtained by the evaluation metrics are attached for each data set that belongs to an interface, which are used by the interface manager algorithm in its decisions.

Algorithm 2 describes the interface manager operation. The algorithm has data sets as input *interfaceA, interfaceB, interfaceC* (or, how many interfaces are used by IM). The heuristic of sum of points consists of accumulating points (*sumPointA, sumPointB and sumPointC*) (lines 1–3), conducting comparisons of the metrics achieved by each interfaces. In this case, if the *AvgRxPower* of *interfaceA* is greater than those of *interfaceB* and *interfaceC*, *sumPointsA* accumulates one point (lines 4 and 5); otherwise, if *interfaceB* presents better *AvgRxPower*, *sumPointsB* is increased by one, while if the better performance is that of *interfaceC*, the *sumPointsC* variable that is increased by one (lines 6–10). The same process is conducted for all evaluated metrics (lines 11–18). After that, we verify which interface has more points accumulated (lines 19–28). The greatest amount defines the best interface to be used in the next send of flow messages by a node; that is, the one which has better performance in a higher number of metrics. If there is a tie between the aggregated points, the last interface which presented the greatest amount of points is maintained as the best one (line 27).

Lines 29–33 of Algorithm 2 describe the interface switching. Line 29 verifies whether the new (*new*) best interface is the same as the last best interface (*old*). If they are different, the current interface is dropped (*downlink*,) using its IP address defined (*node*), and the best interface is set to be used in the *node* transmissions (lines 30–31). The *uplink* routine sets the *new* interface to send the next data flow (line 32).

IM validations occurs in time intervals of 1 s during all simulations, where new interface data sets are obtained from the buffers stored by Algorithm 1, starting a new validation (line 35). In general, the computational cost of executing the algorithms is linear, as they are composed basically of comparisons between a determined unsorted number of elements, thus presenting $O(a\ (n * (n-1)))$ comparisons, where a is the number of evaluation metrics and n is the number of interfaces applied. Thus, it can be concluded that it is possible to run Algorithms 1 and 2 in an embedded manner in various UAV OBUs (on-board units).

Algorithm 2 Interface Manager algorithm (example using three interfaces).

```
Require: interfaceA, interfaceB, interfaceC, node, old;
Ensure: newInterface = INTERFACEMANAGER(interfaceA, interfaceB, interfaceC, node, old);
sumPointA=0;
sumPointB=0;
sumPointC=0;
if interfaceA{AvgRxPower}>interfaceB{AvgRxPower} and
interfaceA{AvgRxPower}>interfaceC{AvgRxPower} then
    sumPointA+=1;
else if interfaceB{AvgRxPower}>interfaceA{AvgRxPower} and
interfaceB{AvgRxPower}>interfaceC{AvgRxPower} then
    sumPointB+=1;
else
    sumPointC+=1;
end if
{the same routine for all evaluation metric (AvgNoise, AvgbytesReceived, AvgbytesDropped,
AvgSNR, AvgThroughput)*}
if interfaceA{metric*}>interfaceB{metric*} and interfaceA{metric*}>interfaceC{metric*} then
    sumPointA+=1;
else if interfaceB{metric*}>interfaceA{metric*} and interfaceB{metric*}>interfaceC{metric*}
then
    sumPointB+=1;
else
    sumPointC+=1;
end if
{Validation of interface which accumulated the highest sum of points}
if sumPointA>sumPointB and sumPointA>sumPointC then
    new ← interfaceA;
else if sumPointB>sumPointA and sumPointB>sumPointC then
    new ← interfaceB;
else if sumPointC>sumPointA and sumPointC>sumPointB then
    new ← interfaceC;
else
    new ← old;
end if
if old is ≠ new then
    downlink node old interface;
    set new interface in the node to send next flow of messages ;
    uplink new interface node;
end if
old ← new;
Schedule(seconds(1), &InterfaceManager, interfaceA, interfaceB, interfaceC, node, old);
```

4.4 FINAL REMARKS

Collaborative missions or missions with shared tasks that employ wireless multi-UAV networks require higher link stability and special attention to the reliable delivery of messages. An important part of this challenge relates to the wireless interface technology that is used. In this context, this chapter proposed a heterogeneous interface manager (IM) that is capable of dynamically defining the best communication interface to be used when more than one option is available. It works by dynamically evaluating parameters collected from the medium. The benefits of the proposed method are that U2U connectivity is improved and message delivery reliability is enhanced.

The current version of the proposed IM works with a heuristic formulated as a decision three with a sum of points. These algorithm presents low cost computational which probably allow its execution in embedded way in low cost platforms.

Imagining the IM implementation in a real scenario of course exists a cost of energy from use of several interfaces. Where one is transmitting and the others are in listen state for medium monitoring. However, it is possible to adopt several techniques to reduce the power consumption as enabling UAV nodes to transmit according to networks events and maintaining stations in the doze state during a predetermined sleep time interval (TUYSUZ, 2018), or using an adaptive solution that defines based on machine learning decisions about the time interval or real necessity to make new validations saving the energy (SHETH *et al.*, 2021). This validation will be object of future studies.

Next, in Chapter 5, all the tools and experimentation scenarios are present including the previous experiments using 2 D scenarios and 3 D scenarios, varying the number of UAVs and their trajectories.

5 EXPERIMENTATION PROCEDURES AND TESTBED SCENARIOS

This chapter will go through the implementation, including the integration the simulation tools used to serve as FANET's testbed scenarios. Two set of simulation tools were orchestrated in order to evaluate the IM algorithms, comparing its performance in six mobility testbed scenarios: two scenarios in 2 D dimension and four scenarios in 3 D dimension developed integrating mobility simulators. In this regard, firstly the tools employed in these experimental setups are explained whereby both experimentation procedures are discussed. Then the detail of the mobility experimentation scenarios is demonstrated. Finally, the system settings and simulation parameters are described.

5.1 EXPERIMENTAL SETUP

To validate the proposed IM, two complex simulation environment suitable for analyzing multi-UAV communication features was assembled. The first one (2 D testbed) is composed of NS-3, SUMO, and Evalvid, and the second one to get more realistic scenarios in 3 D dimensions is defined composed of NS-3, GzUAV, Gazebo, and Evalvid. Some interesting features of these five different simulation tools are listed below:

- NS-3: This classic open-source network simulator is used to compose virtual communication nodes assigning interfaces (PHY), standards (MAC), routing protocols, general settings (channel, frequency, and propagation models), loss and fading models, IP address, and other networks settings needed to deploy wireless simulation environments (RIBEIRO, Laura Michaella B.; BUSS BECKER, 2019; RIBEIRO, L.; MULLER; BECKER, L., 2020). Version 3.30.1 was used. This tool was used to validate the performance of the heterogeneous interface manager algorithms getting the evaluation network metrics and defining the services for application layer.

  The NS-3 support researches in several IEEE 802.11 (a,b,g,n,ac,ax,p,e,etc) standards, including QoS and Non-QoS MAC layer protocols, allowing to apply several operation frequencies 1 GHz, 2.4 GHz, 5 GHz, and etc, on both IP and non-IP based networks.

- Evalvid: is a NS-3 framework tool which provides services of sending video frames between nodes, in order to evaluate the AC_VI (video access class) type of service message traffic (KLAUE; RATHKE; WOLISZ, 2003). This tool allows accessing the perception of transmission quality from audio and video service. In this thesis, some modifications have been done in this framework to allow the sending of multiple video streams from multiple UAV nodes.

- SUMO: The SUMO (Simulation of Urban MObility) is a mobility simulator for VANETs that was adapted herein to simulate UAVs by maintaining only the existing features in UAVs. This is used to define different vehicle speeds, paths, positions, and the mobility characteristics of each unmanned vehicle. It also defines the size of the trajectory area. For such tests, only speed (acceleration, deceleration) and a movement uncertain coefficient features were inserted into a 2 D, and in this case the z-axis effects its not verify. The SUMO was used in its version 1.0.1.

- GzUAV: The Gazebo-based framework for ArduCopter multi-UAV simulations (GzUAV) allows running and control multiple-UAVs in the same scenario including interactions in Gazebo (URSO *et al.*, 2018; D'URSO; SANTORO, C.; SANTORO, F. F., 2019). The set of programs includes a tool called GzUAVChannel, which creates instances of virtual UAVs in Gazebo, keeping the simulation clock strictly synchronized with NS-3 and ArduCopter (allows simulated UAVs to be ready to fly), compounding more realistic wireless network simulations. ROS topics are applied by the framework that integrates the Mavlink protocol commands and simulation clocks in order to compose virtual communication channels for more than one instance of ArduCopter. Thus, each channel is defined by a UAV with different SSIDs, ports, and addresses, generating multiple instances to be connected in Gazebo. This framework also allows writing programs using the DroneKit platform.
- Gazebo (robot simulation): This tool is used to generate 3 D simulations, allowing the creation of realistic scenarios where robots, or populations of robots, perform their missions (robots are UAV in the present study). This allows the testing of algorithm performance and the validation of models. Gazebo allows the definition of real coordinates for UAVs trajectories (waypoints) and realistic experimentation scenarios. Other useful features include: speed definition, UAV flight mode, UAV model, and distance–altitude calculation. The experiments presented in this paper use the features of the Iris UAV RTF Quadcopter.

For 2 D experiments, the SUMO tool and NS-3 were integrated to create vehicles with mobility pre-defined features with wireless radio models possibilities, generating wireless communication mobility nodes. In 3 D experiments is apply NS-3 and Gazebo with GzUAV integration allowed us to create vehicles with high-mobility features and vast wireless communication possibilities including effects of altitude.

With the synchronization of tools became possible to run experimentation scenarios using multiple UAVs as communication nodes, sending different ToS, including video streaming services integrating the Evalvid tool in all scenarios of mobility.

5.1.1 2 D and 3 D experimentation procedures

Figure 7 presents a Sequence Diagram that illustrates the interaction among the NS-3 and SUMO tools, as further detailed.

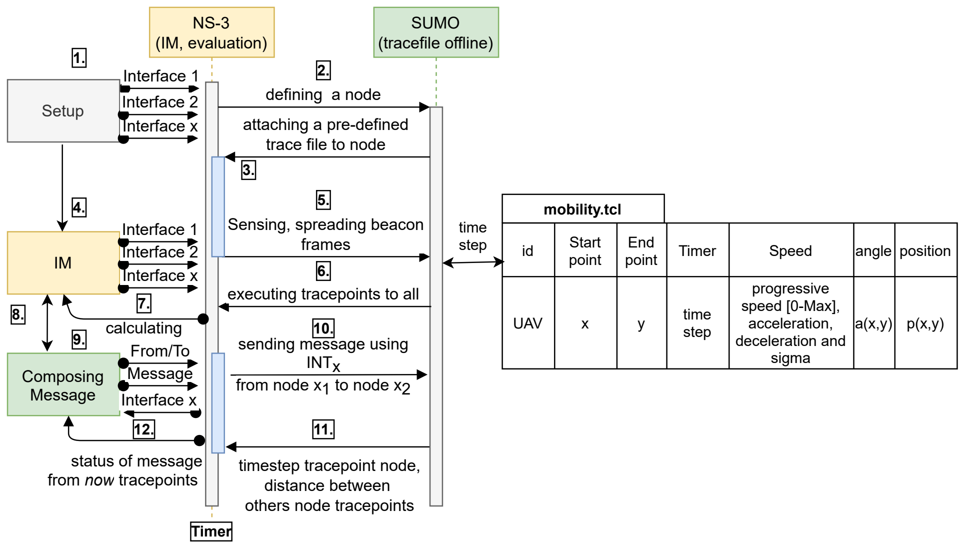


Figure 7 – Interaction among the 2D simulation components.

The interaction steps for both experimentation procedures form three groups of interaction: input, processing, and output group. The tools sequential diagram has to input steps 1, 4, 9, and 3, as processing steps 2, 5, 6, 10, 11, and finally as output steps 7, 8, and 12, as shown in Figure 7.

The blocks are *setup*, *IM*, and *composing message*. They constitute NS-3 blocks and a *mobility.tcl* file produced by SUMO. The blocks' description are as follows:

1. *Setup*: This block comprises all the definitions of the nodes and the general network configurations, such as number of nodes, available routing protocols, MAC and PHY configurations, the types of messages (traffic), the transport protocol used, IP addresses, network topology, packet transmission rates, and evaluation metrics. This setup block applies one or more interfaces in nodes and provides all parameters or conditions used in the interface manager (IM) decisions block;

2. *IM*: This block compose all the interface manager execution, including the sensing and spreading (devices monitoring), the decision tree heuristic and naive bayes conditions classification, validation and calculates of the evaluation metrics.

3. *Composing messages*: The composing message block defines the access classes of messages, data rate, packets sizes, payload, and sender–receiver nodes;

4. *mobility.tcl file*: it is a data file generate by SUMO, which is a result file from integration of three files: a node file (description of node junctions, in terms of x and y axis coordinates), lane file (describing the path or UAV journey) and a route file, which describes the interconnections between nodes and lanes and how it must be run including the vehicle speed settings (initial and maximum speed, acceleration, deceleration and a imperfection sigma of mobility). The SUMO compiles all these files together generating an unique file *.tcl* that have all the mobility parameters to each UAV defining an start/end point, speed, angle, and position of each UAV for each time step of simulation.

The execution of this sequential diagram occurs as follows: 1. The NS-3 inserts in a node the interfaces defined in the set of interfaces *INT*, using the Setup block features; 2. The NS-3 starts a node with all the multi-layer settings and protocols defined in the Setup block features; 3. The *mobility .tcl file* generated by SUMO is uploaded to NS-3 instancing a mobility object routines, and then the predefined trace file is applied to a node.

4. The Interface Manager stats its execution initializing the storing of network conditions from each *INT* starting the DT heuristic, storing in buffers the initial sense and listening; 5. The NS-3 stats the mobility of nodes using the **Timer** as a schedule to sensing, spreading *beacon* frames; 6. The **Timer** used by NS-3 defines the *timestep* intervals of guests to *mobility.tcl* for executing tracepoints in all nodes making them can move from their paths; 7. The IM receives the NS-3 calculation and sensed metrics by each node to make decisions; 8. The interface defined by IM will be used to next send of messages being as input to *Composing messages* block.

9. The *Composing message* block uses this *interface x* to send a message with source and destination node identification; 10. The NS-3 starts the sending of message using the INT_x from node x_1 to node x_2 and the *timestep* identify their *now* positions guesting the mobility object; 11. The references of currently (*now*) tracepoint to all nodes are updated, and the distance between them is calculated to allow the performance evaluation in terms of distance and time of the delivery of messages (amount of packets); 12. The status of message delivery is verified using the distances of nodes from all tracepoints that composing the network executions from using the NS-3 *timesteps* as reference.

These steps describes all the integration of the tools during a network simulation execution, this one is composed of a offline simulation, once all the nodes' tracepoints are known and stored an *mobility.tcl* file.

In this one, all the nodes mobility points have behavior previously know, which are executed in the same simulation concurrently, according to timestep defined by the network execution in the NS-3. In opposite way the 2 D simulation, in 3 D experimentation procedures, a synchronism is defined to compose different multiple nodes mobility perspective, running in parallel in the same network scenario. Figure 8 illustrates the interaction among such tools, as further detailed.

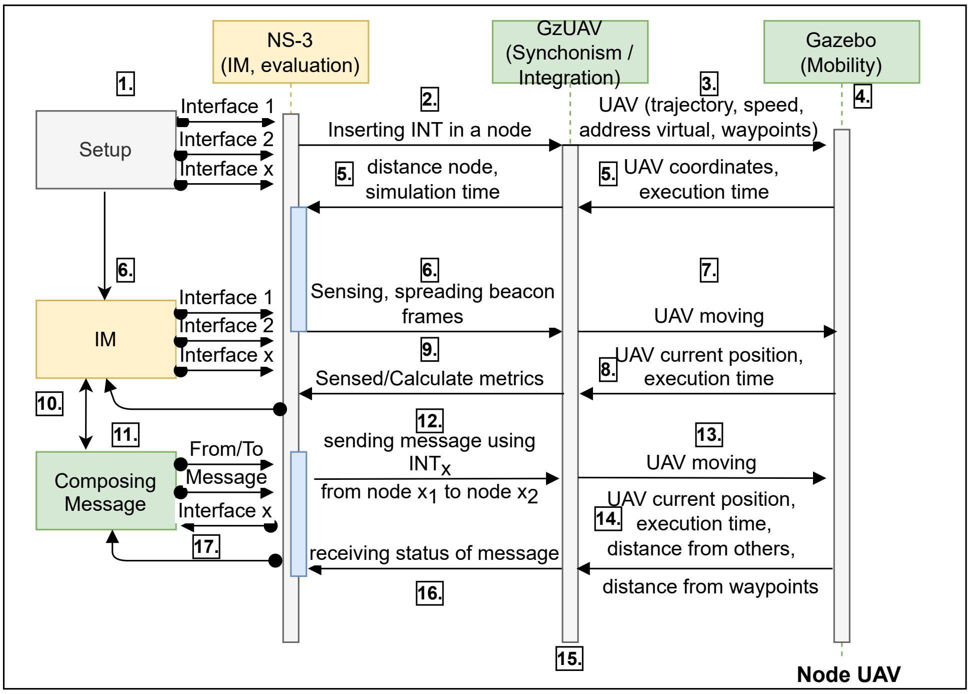


Figure 8 – Interaction among the 3D simulation components.

The sequence diagram in Figure 8 has as input steps 1, 2, 3, 6, 10, and 11, as processing steps 4, 7, 8, 9, 12, 13 and finally as output steps 5, 14, 16, and 17, some of the steps occurs at the same time, these steps are represented with the same label.

In this one, two new blocks appears *GzUAV* and *Gazebo*, which represents the two tools used to define a more realistic scenario using a 3 D mobility tools. These two blocks are describes along of the 17 interaction steps defined in communication flow, as follows:

1. Setup block is the same of 2 D procedure; 2. The NS-3 inserts in a node the interfaces defined in the set of interfaces *INT*, using the Setup block features; 3. GzUAV integrates this node in an UAV, which has the trajectory, speed, virtual address, and waypoints; 4. Gazebo inserts the UAV node in a simulation environment, executing its mobility model; 5. Gazebo sends the UAV coordinates and current time to GzUAV, which synchronizes with the NS-3 simulation time and calculates the node position; 6. The IM starts the sensing and spreading of beacon data frames using MAC and PHY interfaces; 7. GzUAV applies this behavior while the UAV is moving; 8. Gazebo sends the current UAV position and execution time; 9. GzUAV receives these data and attaches them to the node to correlate the sensed and calculate conditions with the current position of a node and the simulation time; 10. The IM receives the data and defines an interface for the next round of message transmission (messages produced by the composing message block); 11. The composing message block starts the send

of messages; 12. The IM sends this message using the interface chosen from the *INT* set of interfaces; 13. GzUAV integrates with the UAV during the flight (in movement); 14. Gazebo sends the current position, the current execution time, and its distance from other UAVs and from the waypoints; 15. GzUAV synchronizes with the NS-3 simulation time according to distance received and the current position of the node; 16. A status of message delivery is received based on the last steps, using any of the interfaces; 17. Finally, the evaluation metrics are analyzed by the IM and the next messages are sent using the allocated interface.

Each node UAV is composed of these interaction steps executing in a parallel way, using different communication sockets integrated into the same NS-3 network and Gazebo mobility scenario.

5.2 EXPERIMENTATION TESTBED

The topology adopted for experiments is ad-hoc with decentralized network management. Thus, each UAV is autonomous with pre-defined trajectory. Table 5 presents relevant configuration parameters used by all scenarios. The Friis free space propagation model is used in the simulation as a signal attenuation model, without obstacles in the line-of-sight (LOS). However, to include signal fading effects, the Nakagami statistical shading model was applied, once the nodes were in non-line-of-sight (NLOS).

The occurrences of NLOS in these scenarios were caused by the long distances between UAV in parts of the trajectory, where the fading coefficient was applied, so the Nakagami model is employed using a Rayleigh distribution, considering the variations in signal strength due to multipath fading, as seen in (RIBEIRO, Laura Michaella Batista; MÜLLER; BUSS BECKER, 2021).

All the interfaces present transmission power of 16.02 dBm (40 mW) avoiding the signal overlap, different speeds are used by UAVs to simulate different kind of vehicles. The different average speed of vehicles is define in order to simulate different kind of vehicles, these speeds is applied in both experimentation procedures.

The SUMO tools present different duration of Gazebo because in the SUMO the trajectories are composed of points onto a Cartesian plane, in opposite way to Gazebo, where the points are real coordinates that representing real distances, which a UAV needs to path.

The IM validation occurs at 1 s intervals using the average of the condition decisions from buffers containing at least 10 samples, collected every 100 ms. This avoided instantaneous value fluctuations. The first and last samples were discarded to minimize the effects of the initial and final execution of the networks in the validation of the results.

For synchronizing all tools involved on these 3D simulations, it used a framework developed by (URSO *et al.*, 2018). Thereby, it was possible to run experimental scenarios using multiple UAVs as communication nodes, sending different ToS in scenarios defined within Gazebo. For the case of SUMO tools, all the nodes movements are defined in a trace file, which includes the moving points and intervals of execution, which is read continuously during simulation. All the experimentation scenarios are evaluated in two different experimental setups: (1) Application results and (2) MAC and PHY results. The application results are validated in intervals of 1 s for better highlighting the application effects after the end of the experiments. The MAC and PHY results are generated using metrics collected during the experiment executions, in intervals of up to 1 ns, according to relevant network events (*beacon frames, signalization packets, transmissions, reception, and others*).

A CBR (Constant Bit Rate) traffic or different access classes of ToS were defined to evaluate the solution, using different samples intervals between 10 ms to 100 ms for CBR traffic and between 1 ns to 250 ms for different ToS (voice, video and data), varying the sample interval according to where the metric is get from, MAC and PHY layer or application layer.

The IEEE 802.11 n and IEEE 802.11 ax interfaces over the Industrial Scientific and Medical (ISM) band at 2.4 GHz with a coverage area of 300 m and 600 m, respectively, and IEEE 802.11ac, IEEE 802.11ax, and IEEE 80211p of the Unlicensed National Information Infrastructure (U-NII) with a coverage area from 350 m to 1 km (nominal range, according to the standard) were adopted in the experiments. All these interfaces are classified as WLANs.

Some interfaces used in the experiments allows to set more higher bandwidths (80 MHz, 160 MHz), but to gets more fair results all the interfaces were configured with the maximum bandwidth of 20 MHz–22 MHz, only the interface 802.11 p is set with 10 MHz because is the maximum supported by this protocol.

The packet size applied in the experiments is the size maximum of an Ethernet frame (1500 bytes), without fragments to get more precision in the evaluation of different access classes amount of packets. The Maximum data Rate is defined as 50 Mb/s because is the minimum rate required by IEEE standards used.

For experiments with traffic variance (ToS), the MAC protocol adopted is QoS supported to gets performance evaluations which include native traffic prioritization of protocols, and for CBR traffic the Non-QoS supported standard protocol of IEEE standards is adopted.

The constant speed propagation delay model is used to verify the delay caused by the variations of distance between the nodes and the effects of difference distances reached from the starting point. All scenarios previously described are used to perform the IM evaluations using different interfaces combinations, as presented in Chapters 6 and 7.

The OLSR (Optimized Link State Routing) protocol was used in order to reduces

Table 6 – Settings adopted in the experiments.

Parameter	Setting
Network Topology	Ad Hoc Networks
Attenuation Model	Friis Free Space
Tx power	16.02 dBm (40 mW)
Average Speed	10, 20, and 30 m/s
Fading Model	Nakagami
SUMO duration time	91 s
Gazebo Duration Time	18 min (3), 1 h 30 min (5), 2 h (8)
Interface Manager Interval Decision	1 s
Sample Interval (CBR)	10 ms,100 ms
Sample Interval (ToS)	1 ns (MAC & PHY), 250 ms (APP)
Packet size	1500 bytes
Interfaces 2.4 GHz	IEEE 80211n, IEEE 80211ax
Interfaces 5 GHz	IEEE 80211p, IEEE 80211ac, IEEE 802.11ax
Bandwidth	10 MHz, 20 MHz, 22 MHz
MAC protocol (CBR)	Non-QoS supported
MAC protocol (ToS)	QoS supported
Propagation Delay	Constant Speed Delay
Routing protocol	OLSR
Transport Layer	UDP protocol
Maximum data rate	50 Mb/s

the message overhead, using link state information only in case of network changes (add/remove a node) minimizing the number of control messages in the network.

All the experiments were performed using both homogeneous and heterogeneous interfaces, that is, using a single interface (IEEE 802.11) and using the proposed IM (which switches between them). The performance of each set of experiments is compared and discussed in the next Chapters.

5.2.1 2 D experimentation scenario

The 2 D experimentation scenario were generated from two experimentation scenarios, one containing 3 mobile UAV nodes and the other containing 10 nodes. Each scenario is formed by straight lines that define the distances to be covered by each UAV, consisting of *waypoints*, which are points formed by coordinates that connected to each other define the trajectory of each vehicle, starting from a starting point (waypoint 1). In this case, the starting point (0x, 0y) constitutes the point of origin and destination common to all trajectories, varying around up to 1.8 m (scenario 2) for initial and final positioning of the UAVs, allowing them to start their missions at the same time. Each vehicle also has different maximum speeds to be used along the trajectory with an acceleration of 0.8 m/s^2, deceleration (4.5 m/s^2) and an imperfection of 0.5% in the execution of the vehicle trajectory. The different waypoints and maximum speeds of each vehicle are presented in the legends of Figures 9 and 10.

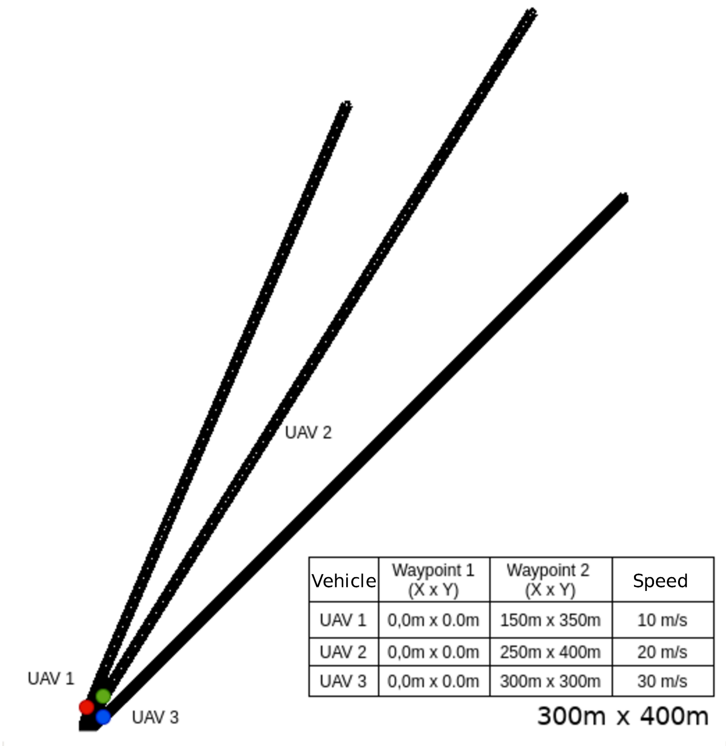


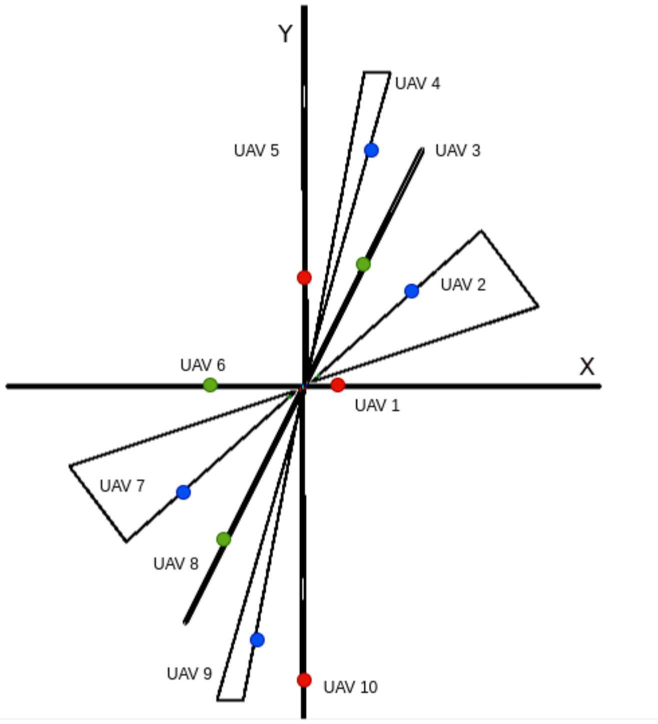
Figure 9 – First 2 D experimentation scenario formed by three mobility nodes.

The SUMO (Simulator of Urban Mobility) version 1.0.1 is used to define the waypoints and the mobility characteristics of each node (acceleration, speed), which were defined using the settings of a small UAV. The first scenario is represented in Figure 7.

This scenario is defined in an area of 300 m per 400 m in which 3 trajectories are defined for 3 nodes UAVs moving at different maximum speeds: UAV node 1 ($10 m/s$), UAV node 2 ($20 m/s$) and UAV node 3 ($30 m/s$).

Figure 10 presents the second experimentation scenario, composed of a total area of 600 m x 800 m being covered by 10 UAV nodes, which are divided as follows: 5 in 300 m per 400 m (2nd quadrant) and another 5 in another 300 m per 400 m in the opposite direction (3rd quadrant) regarding a common starting/finishing point of origin. The objective of this scenario is to represent a larger number of UAVs covering an also larger area, allowing nodes to reach greater distances about each other. The Chapter 4 presents the use of IEEE 802.11n 2.4 GHz and IEEE 802.11p 5 GHz used separately and in the interface manager, so this scenario aims to reach the limit of coverage area of those interfaces to evaluate the performance in situations where the nodes reach the coverage limit without using *gateways*, *repeaters* or RSUs (*roadside units*).

In this scenario, UAVs with three waypoints apply a maximum speed of 30 m/s, those that have up to two waypoints with the second containing one of the coordinates equal to 0, apply a maximum speed of 20 m/s, and the rest of them have a maximum speed of 10 m/s. The purpose of this variation in the number of waypoints and speeds used by each vehicle is to simulate different distances to be covered by different types of UAVs, standardizing the greater distances to be covered for faster UAVs, as seen in Figure 10.



Vehicle	Waypoint 1 (X x Y)	Waypoint 2 (X x Y)	Waypoint 3 (X x Y)	Speed
UAV 1	0.0m x 0.0m	300m x 0m	0	10 m/s
UAV 2	0.4m x 0.4m	180m x 160m	240m x 80 m	30 m/s
UAV 3	0.8m x 0.8m	120m x 240m	0	20 m/s
UAV 4	1.2m x 1.2m	60m x 320m	90m x 320m	30 m/s
UAV 5	1.8m x 1.8m	0m x 400m	0	10 m/s
UAV 6	0.0m x 0.0m	-300m x 0m	0	20 m/s
UAV 7	-0.4m x -0.4m	-180m x -160m	-240m x -80m	30 m/s
UAV 8	-0.8m x -0.8m	-120m x -240m	0	20 m/s
UAV 9	-1.2m x -1.2m	-60m x -320m	-90m x -320m	30 m/s
UAV 10	-1.8m x -1.8m	0m x -400m	0	10 m/s

Figure 10 – Second 2 D experimentation scenario composed of ten mobility nodes.

5.2.2 3 D experimentation scenarios

For the 3 D experimentation scene, we adopted the soccer field at the main Campus of the Federal University of Santa Catarina (UFSC), in Florianopolis, Brazil (UFSC's soccer field GPS coordinate is –27.603916 –48.518370). Three experimentation scenarios were used in the proposed evaluation, containing 3, 5, and 8 UAV nodes. The Figures 11, 13 and 15 describes each scenario depicted straight lines that represented the path to be covered by each UAV.

As seen in 2 D scenarios, the starting point (0x, 0y), or base point, is the point of origin (take-off) and the destination (landing) common to all UAVs (in reality, there was a few meters' difference between the two for safety reasons, cause in 3 D simulations the UAVs can collide). For this scenarios, the adopted safety-distance was 1.5 m for scenario-1, 2.0 m for scenario-2, and 8.0 m for scenario-3, allowing them to start their missions at the same time, avoiding collisions during departure and arrival.

Each UAV had one or two intermediate waypoints, which represented places where the UAV supposedly performs the mission before returning to the base. The vehicles also had different maximum speeds to be used along the trajectory, in similar way to 2 D scenarios. The total distance traveled, this respectively UTM[1] coordinates and the maximum speeds for each vehicle are shown in the legends included in Figures 11, 13 and 15, which represents pictures from Google Maps[2] described by coordinates in the start and end waypoints (x,y) columns.

The trajectories (path to be covered) of each UAV are defined so that there are variations in distances between them during the execution of their paths, this is more detailed by dotted lines in Figures 12, 14 and 17. In that, the start/end point is represent by a yellow square common to all UAVs. In that, the waypoints are described with arrows at the end of the dotted lines. A reference column located in the right corner can be used for an approximate check of the distances reached (with error rate of +-5m) between the UAVs and travelled during this paths.

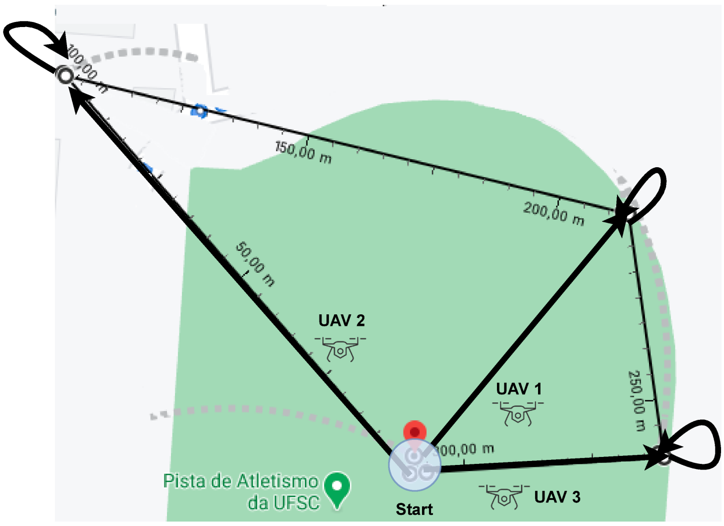
Scenario-1 is illustrated in Figure 11. This scenario had an area of circa 2200 m^2, where each UAV had its own trajectory and speed: UAV-1, 20 m/s; UAV-2, 30 m/s; and UAV-3, 10 m/s. In this scenario, the UAVs were initially positioned with distances between them up to 1.5 m, as shown in the start waypoint column values inside parentheses in the legend of Figure 11. The total distance course for UAV-1 was 66.25 m, 100.06 m for UAV-2, and 49.10 m for UAV-3. The UAVs flew to the intermediate waypoint and returned to the start waypoint. So, the distance was the same both ways.

Figures 12, 14 and 17 presents the DT (in this Chapter, it means distance travelled) by each UAV, which is showed over its dotted lines. DT is composed of the sum of the total distance traveled by the UAVs including their return to base. The distance traveled between the waypoints is also shown over on the corresponding dotted line. The average speed (Vm) of each UAV also is shown in these Figures over dotted lines. Different average speeds are defined in order to simulate different types of UAVs, for example, in the three-node scenario the UAV that has the greatest distance travelled has the highest average speed (30 m/s).

In three-node scenario (Figure 12), the UAV 1 has DT=125 m with Vm=20 m/s, the UAV 2 has DT=234 m with Vm=30 m/s and UAV 3 has DT==94 m with 10 m/s. Using the distance column and the UAV 1 path as distance reference, the UAV 1 has up to 60 m of distance from UAV 2 path and it has up to 110 m of distance from UAV 3

[1] UTM (Universal Transverse Mercator): It is coordinate system divides the world into sixty north-south zones, each 6 degrees of longitude wide.

[2] Google Map: https://www.google.com.br/maps/place/27%C2%B036'14.1%22S+48%C2%B031'06.1%22W/@-27.603916,-48.5205587,17z/data=!3m1!4b1!4m5!3m4!1s0x0:0x0!8m2!3d-27.603916!4d-48.51837



Vehicle	Start Waypoint (x,y)	End Waypoint (x,y)	Total distance (m)	Speed (m/s)
UAV 1	-27.603916, -48.518370 (0,0)	-27.60349,-48.51796	66,25	20
UAV 2	-27.603916, -48.518370 (1, -1.5)	-27.60325,-48.51906	100,06	30
UAV 3	-27.603916, -48.518370 (1,+1.5)	-27.60391, -48.51789	49,10	10

Figure 11 – Experiment scenario-1 (3 UAV).

path, this is the maximum of distance between paths reached in this scenario.

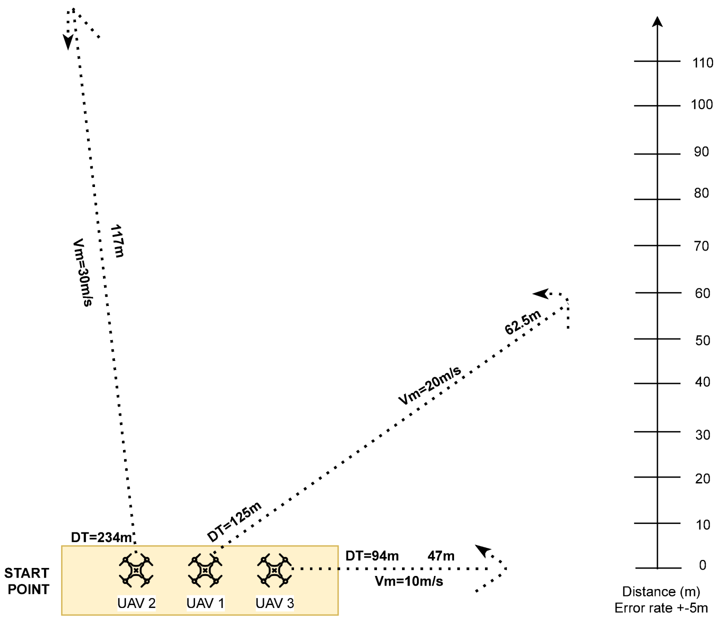
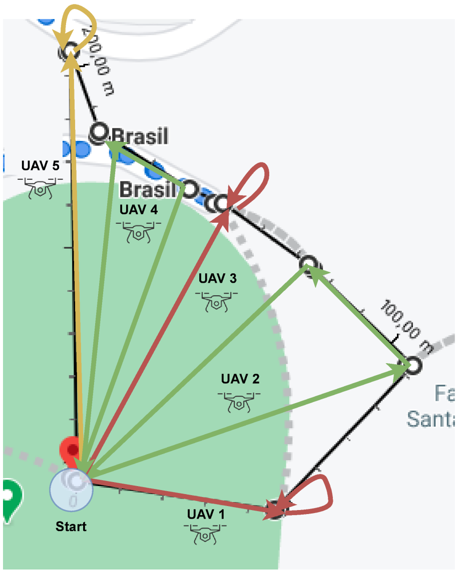


Figure 12 – Distance travelled for tree-node experimentation scenario.

Figure 13 presents scenario-2, which used 5 nodes. This scenario covered an area of circa 2500 m^2.The purpose of this scenario was to increase the message traffic volume and to add a larger number of waypoints and UAVs. This was performed in an area within the range limit of the adopted interfaces, without the need for gateways, relays, roadside units (RSU), or other range-extender devices.

As seen in scenario-1, the vehicles reached the intermediate waypoint and returned to the starting point. Vehicles designated with more than one waypoint flew at a speed of 30 m/s, vehicles that presented a trajectory of up to 70 m flew at 10 m/s, and the other vehicles flew at 20 m/s.

In five-node scenario (Figure 14), the UAV 1 has DT=100 m with Vm=10 m/s, the UAV 2 has DT=326 m with Vm=30 m/s and three waypoints, UAV 3 has DT=146 m with Vm=10 m/s, UAV 4 has DT=366 m with Vm=30 m/s with three waypoints and UAV 5 has DT=194 m with Vm=20 m/s.



Vehicle	Start Waypoint (x,y)	Waypoint 1 (x,y)	Waypoint 2 (x,y)	Total distance (m)	Speed (m/s)
UAV 1	-27.603916, -48.518370 (0,2)	-27.603978,-48.517877	0	49.94	10
UAV 2	-27.603916, -48.518370 (0.5, 1.5)	-27.60368,-48.51758	-27.60348,-48.51780	187.24	30
UAV 3	-27.603916, -48.518370 (1,1)	-27.603312, -48.518091	0	71.14	10
UAV 4	-27.603916, -48.518370(1.5,0.5)	-27.603341,-48.518038	-27.60320,-48.51831	176.45	30
UAV 5	-27.603916,-48.518370(2,0)	-27.603027,-48.518381	0	98.85	20

Figure 13 – Experiment scenario-2 (5 UAV).

In this scenario for that the UAVs have more time inside range one of them, it was defined that the UAV with intermediary waypoints (more than two) in its path have 30 m/s of average speed and UAVs that has only two waypoints with paths of up to 70 m have 10 m/s finally, the UAV which has paths with distance travelled more than 70 m have 20 m/s. Once again, using the UAV 1 as reference of highest distance reached between UAVs, it presents up to 150 m of distance from UAV 5 path. The others UAV paths, including the intermediary paths, present up to 35 m of distance between then.

Scenario-3 is illustrated in Figure 15. The flight area was increased to circa 5000 m^2 and more UAVs (8 nodes) were used in this scenario. The aim of this scenario was to include a larger number of UAVs and cover a larger area to allow nodes to reach farther distances in relation to each other in spatial topology using a single waypoint. The goal was to evaluate the performance when the limit of the interfaces

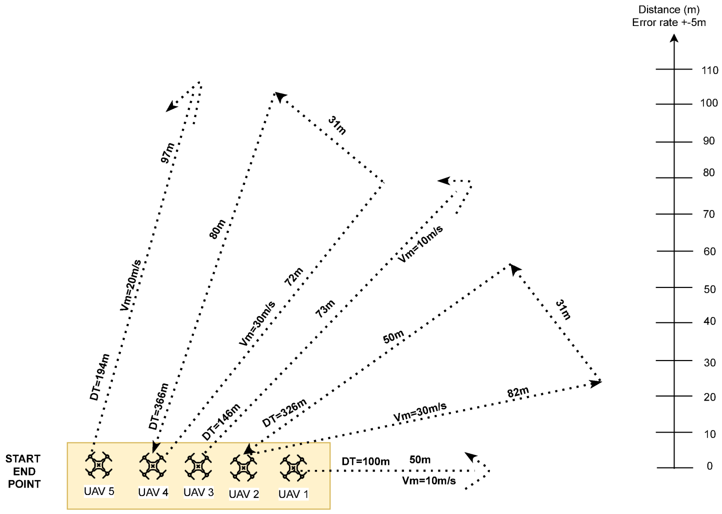


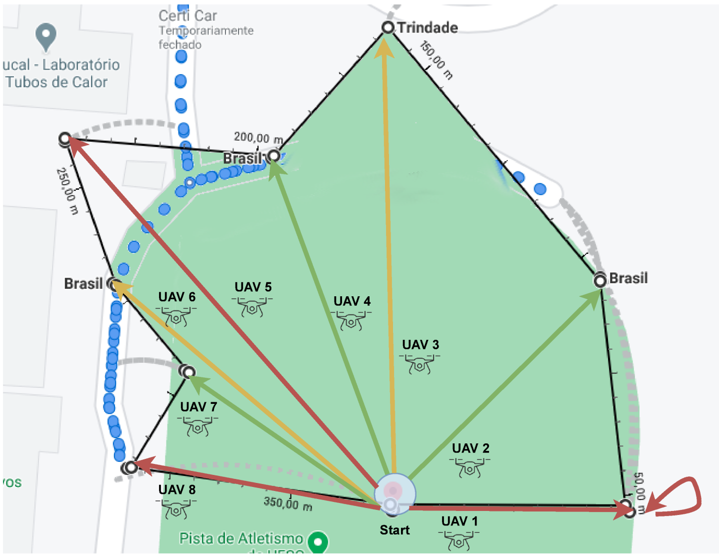
Figure 14 – Distance travelled for five-node experimentation scenario.

range is slightly exceeded, i.e. evaluating the interface manager and the interfaces used separately in situations where the nodes exceed by a few meters the theoretical wireless signal coverage limit.

In all scenarios, the purpose of this variation in the number of waypoints and speeds was to simulate different distances to be covered by different types of UAV, standardizing the longer distances to be covered for faster UAV, as shown in Figures 11–17.A complete trajectory of the mission was defined by the start waypoint, intermediate waypoints, and return to the start waypoint.

For eight-node scenario, Figure 17, the UAV 1 has DT=100 m with Vm=10 m/s, the UAV 2 has DT=126 m with Vm=20 m/s, UAV 3 has DT=94 m with Vm=10 m/s, UAV 4 has DT=200 m with Vm=20 m/s, UAV 5 has DT=234 m with Vm=30 m/s, UAV 6 has DT=142 m with Vm=20 m/s, UAV 7 has DT=106 m with Vm=10 m/s and UAV 8 has DT=148 m with Vm=20 m/s.

In this scenario the UAVs have more sparse paths reaching up to 175 m of distance between paths (UAV 1 and UAV 5), considering safety spaces of 2 m between UAVs plus the size of UAV 1 path (50 m) plus the UAV 5 greater distance reached in its second locate at 117 m from start point. The aim of this scenario was to include a larger number of UAVs in spatial topology using a single waypoint, in order to simulated more greater distances reached between UAVs without exceed the theoretical limits of communication interfaces used without relay and repeaters.



Vehicle	Start Waypoint (x,y)	End Waypoint (x,y)	Total distance (m)	Speed (m/s)
UAV 1	-27.603916, -48.518370 (0,0)	-27.60392,-48.51788	46.01	10
UAV 2	-27.603916, -48.518370 (1, 2)	-27.60349,-48.51794	63.50	20
UAV 3	-27.603916, -48.518370 (1,4)	-27.60391, -48.51789	97.80	30
UAV 4	-27.603916, -48.518370(1,6)	27.60303,-48.51838	74.36	20
UAV 5	-27.603916,-48.518370(1,8)	-27.60324,-48.51905	99.75	30
UAV 6	-27.603916,-48.518370(-1,-2)	-27.60366, -48.51887	74.31	20
UAV 7	-27.603916,-48.518370(-1,-4)	-27.60384,-48.51892	50.98	10
UAV 8	-27.603916,-48.518370(-1,-6)	-27.60350,-48.51895	53.97	20

Figure 15 – Experiment scenario-3 (8 UAV).

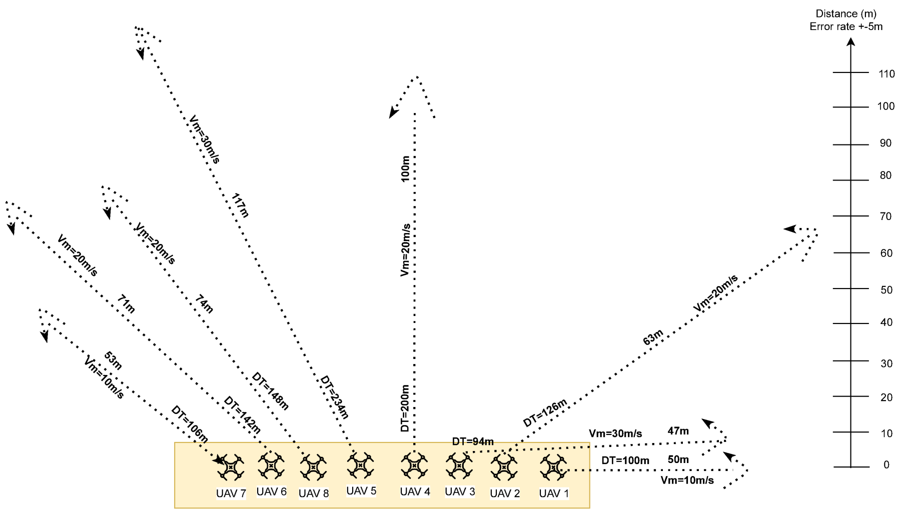
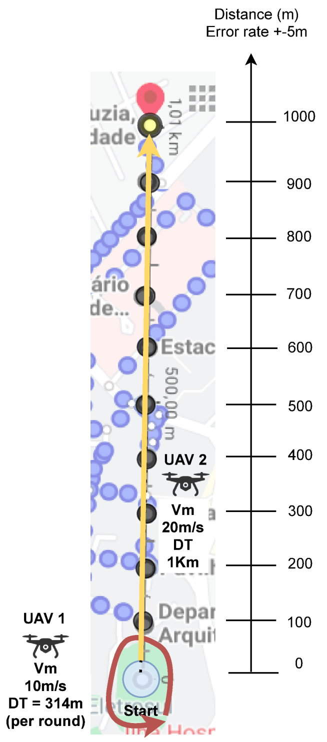


Figure 16 – Eight-node experimentation scenario.

It was standard the longer distances (more than 50 m) to be covered for faster UAV, as shown in Figure 17. A complete trajectory of the mission was defined by the start waypoint, intermediate waypoints, and return to the start waypoint.

Figure 17 presents the last scenario proposed to validate the range of communication provided by IM. In this one, the UAV 1 has a speed of 10 m/s, and UAV 2 has speed of 20 *m*/*s*. The UAV 1 stays making several rounds around the start point (UFSC soccer field) making rounds with 50 m of diameter and 314 m of the perimeter.

While this, the UAV 2 starts a journey with distance travelled of 1*km* compounded by ten waypoints located in each 100 m of distance from the start point in a straight line, reducing its speed for 1.5 *m*/*s* when next of a waypoint (distance < 5 m), making short pauses with duration of 2 s. The last waypoint is located to 1 *km* of distance from the start point.



Vehicle	Start Waypoint (x,y)	End Waypoint (x,y)	Total distance (m)	Speed (m/s)
UAV 1	-27.603916, -48.518370 (0,0)	-27.60345,-48.51828	50 m of radius (314 m per round)	10
UAV 2	-27.603916, -48.518370 (-1.5,1)	-27.59493,-48.51827	1 Km	20

Figure 17 – two-node scenario to define IM distance constraints.

The aim of this scenario is to verify and define the IM distance constraints, using the IEEE interfaces applied. So, the mainly question of this scenario is to find in which distance maximum between nodes, the interface manager is capable to improve or maintain the network communication with QoS.

The next Chapter present the Interface Manager performance in 2 D and 3 D experimentation scenarios considering a CBR data traffic and two communication interfaces IEEE 802.11 n and IEEE 802.11 p.

6 OBTAINED RESULTS

In this Chapter, the experiments were conducted applying the interfaces used by the manager homogeneously in separate experiments (IEEE 802.11n 2.4 GHz and IEEE 802.11p 5 GHz) and heterogeneously using the Interface Manager. For this one, 2 D and 3 D experimentation scenarios was verified. In this case, the 2 D scenarios was validated as previous results used to guide the development of 3 D experiments.

6.1 2 D EXPERIMENTATION RESULTS

These experiments are developed integrating SUMO and NS-3 simulators, as seen in Section 5.2.1. The duration of each experiment is 100 s, comprising a complete execution of the mission (90 s), plus the discard of the first collected samples, in order to minimize the effects of the initial execution of the networks in the validation of the results.

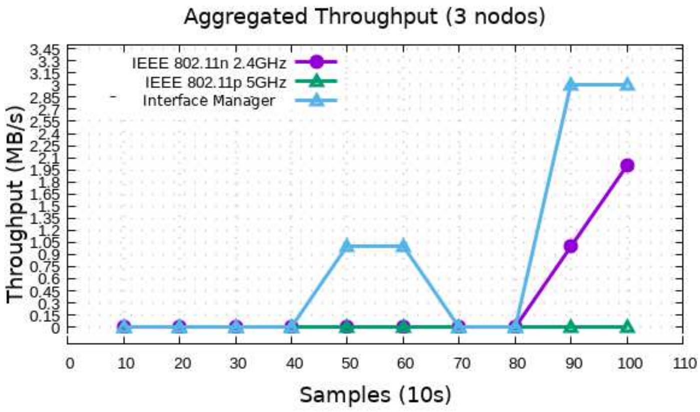
The samples are collected at intervals of 100 ms and given the volume of data collected about 1000 samples for each set of experiments, they were aggregated into groups of 10 s of which the curve points correspond to the average obtained in these groups.

Figure 18 shows the average throughput of the network obtained by 3 mobile UAV nodes corresponding to scenario 1 of experiments. In that, it is possible to see that in the initial samples from 10 s to 40 s the performance of the three experiments is the same, with a variation between the 40 s and 70 s samples, where the experiment related to the interface manager presents a superior flow performance at 1 MB/s (megabits per second) representing a greater number of data received by UAV nodes in this range.

The average throughput of the network is very close to zero in the three experiments in the initial samples, due to the adopted reference being in *megabits per second (MB/s)*, corresponding to the traffic constituted by signaling messages and *f*rames beacon (AC_BE (*best effort*) and AC_BK (*background*)). The MB/s reference was adopted because the network throughput reached values around 1 to 3 MB/s from the sending of video and voice messages in the experiments applying the Interface Manager and the IEEE 802.11 n 2.4 GHz interface of homogeneous form.

In that each interval of 10 s the type of service access class of the messages sent is changed, among the 4 types of service AC_BE, AC_BK, AC_VO (*voice*) and AC _VI (*video*), being the first samples of 0-10 s constituted by AC_BE, 10-20 s AC_BK data, 20-30 s AC_VO, and 30-40 s AC_VI data, where the interval from 40 s to 80 s refers to a new sequence of the different classes of service.

At the beginning of the third sending sequence (in 80 s) there is an increase in the data throughput of about 2 MB/s in the curve referring to IEEE 802.11n 2.4 GHz and in the curve referring to the Interface Manager, this boost refers to a new transmission



Samples	IEEE 802.11n	IEEE 802.11p	Interface Manager
10	0.80477608	0.97997002	0.834624
20	0.39713472	0.98847348	0.883008
30	0.36776854	0.91749304	0.025728
40	0.00026368	0.76528928	0.810432
50	0.60628064	0.66308192	1.2217
60	0.67989888	0.69209952	1.00397
70	0.79076384	0.84986976	0.72576
80	0.9362336	0.96014472	0.810432
90	1.84876868	0.98794354	3.41107
100	2.18404096	0.09397192	3.04294

Figure 18 – 2 D Scenario 1 - Average Throughput of network by aggregated samples of 10 s.

of AC_VI data traffic and shorter distances between nodes on their return to the starting waypoint, increasing signal strength on reception.

The curve referring to the IEEE 802.11p interface did not present greater variations in the flow throughout the experiment, keeping values very close to the flow, even at the beginning of a new sending sequence. This is mainly due to the bandwidth of this technology.

Figure 19 shows the throughput obtained by the network in scenario 2. It is noticed a higher flow was obtained in the three experiments due to the higher number of UAVs (10 nodes) and, consequently, a higher number of data transferred. Likewise, successive dispatches are applied every 10 s of different types of service access classes, where between the 40 s and 80 s samples there was a variation in the increase in throughput in this interval (second sending sequence). In the curve referring to the IEEE 802.11n 2.4 GHz interface, it was possible to reach peaks of 7 MB/s during the sending of packets belonging to the AC_VI class and of 5 MB/s when sending packets of the AC_VO class of service.

The curve for the IEEE 802.11p 5 GHz interface showed a decrease in network throughput during the beginning of the second sending sequence of the classes referring to AC_BE in 40 s and AC_BK in 50 s, starting an increase of about 1 MB/s when sending AC_VI packages in 60 s. The low data volume refers to the 10 MHz bandwidth of this interface, where the third sending sequence of the classes in 80 s it presents throughput rates of 3.25 MB/s.

The third curve concerns the performance of the interface manager, where it is

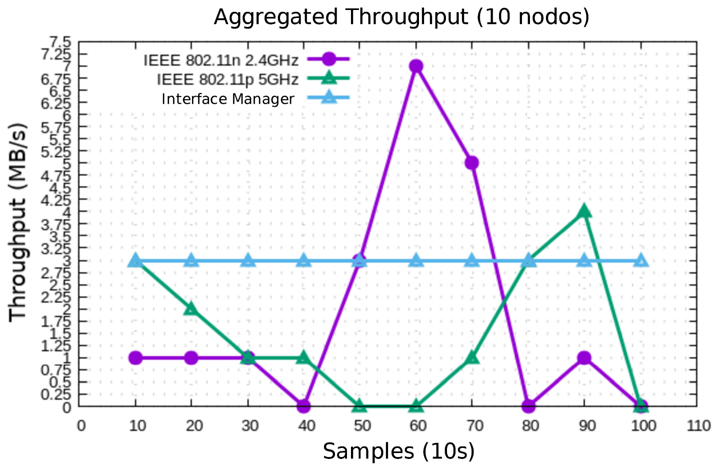


Figure 19 – 2 D Scenario 2 - Average Throughput of network by aggregated samples of 10 s.

possible to notice a behavior with less performance fluctuation in throughput, between 3 MB/s and 3.25 MB/s. It is observed that the different classes of service do not imply greater variations in throughput, allowing greater stability in communication with higher data throughput.

It is also noteworthy that the obtained throughput values refer to the average obtained by the performance of the network, which in the case of the interface manager experiment remained around 3 MB/s describing an fixed behavior due to the high number of samples collected for a larger number of UAVs and the switching applied by the manager.

Floating curves present the interfaces when applied homogeneously. They characterize a typical behavior of wireless networks composed of highly mobile nodes, which, depending on the interface used and the link conditions between the nodes, imply highly unstable connections. This adds to the complexity of the problem, i.e., of maintaining reliable connections in this type of network.

Figure 20 shows the number of packets received and lost by each UAV node for scenario 1. 128.651 packets were sent by each node considering all types of access classes. It is possible to see in Figure 20 that the interface manager used the best proportion of received/lost packets than the other interfaces employed homogeneously. UAV 1 node received about 60.000 packets, UAV 2 node 30.000 packets, and UAV 3 node 40.000 packets, with no lost packets. Thus, the interface manager presented a better packet delivery rate than the homogeneously employed interfaces, with a higher volume of sent and delivered packets.

Similar behavior can be seen in Figure 21, where, except for UAV nodes 2 and 3, the manager presented the largest number of received packets and, in all nodes, the smallest number of lost packets. In this scenario, the total volume of packets sent to each node was 38,595. In this scenario, among the homogeneous interfaces, the best

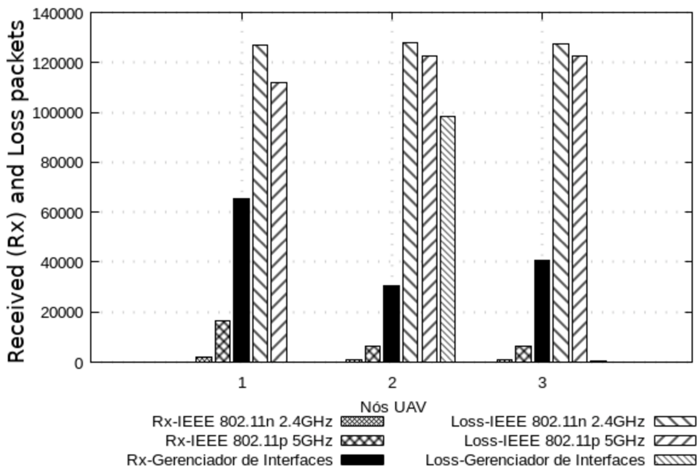


Figure 20 – 2 D Scenario 1 - Number of packets received and loss packets per UAV node.

performance was the IEEE 802.11n interface.

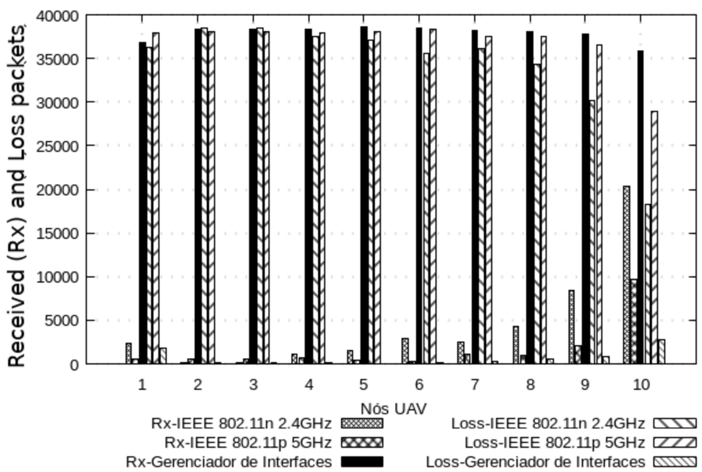


Figure 21 – 2 D Scenario 2 - Number of packets received and loss packets per UAV node.

Table 7 presents the average of the parameters sensed by the nodes from 5 random samples of both scenarios collected during the execution of the experiments. It is possible to verify that the interface manager presented SNR values higher than 0.66 in the 5 samples collected, received signal strength (RSSI) around -68 dBm and received noise power lower than -93 dBM. These conditions promote transmissions with QoS sufficient for sending and receiving data using 802.11 interfaces. The homogeneously employed interfaces also presented RSSI at levels considered very good or excellent for this type of communication (-56 dBm to -68 dBm), highlighting the lower noise received by the IEEE 802.11p interface, given the characteristic of lower susceptibility of the 5 GHz frequencies.

Table 7 – RSSI, Noise e SNR

Interface	RSSI	Noise	SNR
IEEE 802.11n 2.4 GHz	-64.3673	-93.9073	0.685434
IEEE 802.11n 2.4 GHz	-68.5251	-93.9178	0.729628
IEEE 802.11n 2.4 GHz	-68.5845	-93.9179	0.7302620
IEEE 802.11n 2.4 GHz	-69.2706	-93.9207	0.737543
IEEE 802.11n 2.4 GHz	-68.6618	-93.9343	0.730956
IEEE 802.11p 5 GHz	-56.6779	-96.7504	0.585816
IEEE 802.11p 5 GHz	-61.891	-96.8081	0.639316
IEEE 802.11p 5 GHz	-67.318	-96.7876	0.695523
IEEE 802.11p 5 GHz	-66.4942	-96.7945	0.686963
IEEE 802.11p 5 GHz	-66.3235	-96.7887	0.68524
Interface Manager	-62.7718	-93.9487	0.66815
Interface Manager	-69.4198	-93.9507	0.738895
Interface Manager	-70.1968	-93.9244	0.747376
Interface Manager	-71.9332	-93.849	0.766478
Interface Manager	-72.0667	-93.8873	0.767586

During the experiment, variations in the received signal powers were noticed, generated during the switching between the interfaces, since a disconnection is performed to effect the interface exchange (in cases where the manager decided to switch). However, the nodes did not have full disconnection, since the latency generated for reconnection did not impact message delivery, reestablishing the connection in a negligible amount of time. As the cost of the operations of a binary tree is *log n*, the overhead generated in the execution of the interface manager algorithm is also negligible.

This demonstrates that different interfaces can be applied according to the dynamic conditions of the environment, seeking to establish more reliable connections by adjusting which interface will provide better performance at a given time, based on the different metrics evaluated.

6.2 3 D EXPERIMENTATION RESULTS

All the experiments also were performed using both homogeneous and heterogeneous interfaces, that is, using a single interface (IEEE 802.11n or 802.11p) and using the proposed IM (which switches between them). The performance of each set of experiments is compared and discussed in this section. These experiments are developed integrating NS-3, GzUAV and Gazebo simulators, as seen in Section 5.2.2.

The experiment duration varied for each scenario: circa 18 min for scenario-1 (three nodes), 90 min for scenario-2 (five nodes), and 120 min for scenario-3 (eight nodes). In this case, the long simulation time was used to realistically simulate scenarios that execute in the Gazebo simulator. NS-3 converts real time into simulation time, as it uses the metrics of evaluation in its execution logs in the order of ns. As such, the simulated flights of the experiments had a duration of 140 s (three nodes), 150 s (five nodes), and 160 s (eight nodes). To evaluate performance, the experiment duration considered in the NS-3 simulator was used.

The IM validation occurs at 1 s intervals using the average of the condition decisions from buffers containing at least 10 samples, collected every 100 ms. All the IM decisions are present in Appendix A for the three scenarios.

This avoided instantaneous value fluctuations. The first and last samples were discarded to minimize the effects of the initial and final execution of the networks in the validation of the results.

Notably, the metrics received from the MAC and PHY layer occur in 1 ns intervals (NS-3 logs), being composed of sensed propagation parameters such as reception and transmission power, path loss, and quantity of transmitted and received bytes.

The obtained results are presented in two groups: (1) application evaluation, and (2) MAC and PHY evaluation. The application group targeted analyzed the reliability of delivery of messages. Therefore, we observed typical network performance metrics such as throughput, packet delivery rate (PDR), end-to-end delay, and latency. To calculate such metrics, the following variables were monitored during the experiments: bytes and packets transmitted (TX), bytes and packets received (RX), lost packets, packet delivery delay, transmission and reception time, and the successful messages flow.

The results from the application group were compiled offline after the simulation was completed. The MAC and PHY evaluation considered standard wireless network metrics: number of bytes received (Mb), Rx power (dBm), loss (attenuation coefficient in dB), delay (ms), received signal strength indication (RSSI), and noise (dBm). Notably, the results of the MAC and PHY group supported the analysis of the improvement and maintenance in the connectivity between the UAVs during the mission. The results from MAC and PHY results were collected online during the mission execution.

6.2.1 Application Evaluation

Network throughput is the first of the application metrics to be discussed. This metric was chosen to evaluate the data flow of the nodes and, consequently, the effective exchange of messages during the flight, considering their different adopted speeds (equal to or greater than 10 m/s). The average network throughput was calculated based on the average throughput obtained by the number of messages received by the nodes in each network experiment, as stated in Equation ((4)).

$$AverageNetworkThroughput = \frac{\sum_{k=1}^{N} \frac{NumberofRxBytes(k)}{LastTimeRxPacket(k)+FirstTimeTxPacket(k)}}{N} \tag{4}$$

This is composed of bytes received in each message exchanged (number of Rx bytes (k), i.e., data flow), considering the last packet reception time and the first packet transmitted of each data flow (k), divided by the number of network traffic (N).

Figure 22 shows the average network throughput from each experimental scenario. The IM performed best in all three scenarios. Another aspect of this experiment was that the throughput ratio decreased while the number of nodes increased. This was expected because the CBR data rate was divided by the number of nodes. Thus, the IM presented 2.5 Mbps in comparison with 0.5 Mbps for 802.11p and 1 Mbps for 802.11n for the three-nodes experiment. In the fives-nodes experiment, the IM presented 1.55 Mbps in comparison with 0.25 Mbps and 0.4 Mbps for 802.11p and 802.11n, respectively. Finally, for the eight-nodes experiment, the IM presented 0.62 Mbps against 0.15 Mbps (802.11p) and 0.25 Mbps (802.11n).

Another observation was that the 802.11n interface, in all three scenarios, always produced twice the 802.11p throughput. This highlights the intrinsic difference in the channel bandwidth of these interfaces, 20 MHz for 802.11n and 10 MHz for 802.11p. The 802.11n interface can have a bandwidth up to 40 MHz using two frequency channels. However, to perform a fair comparison, this was reduced to 20 MHZ with the use of only one frequency channel.

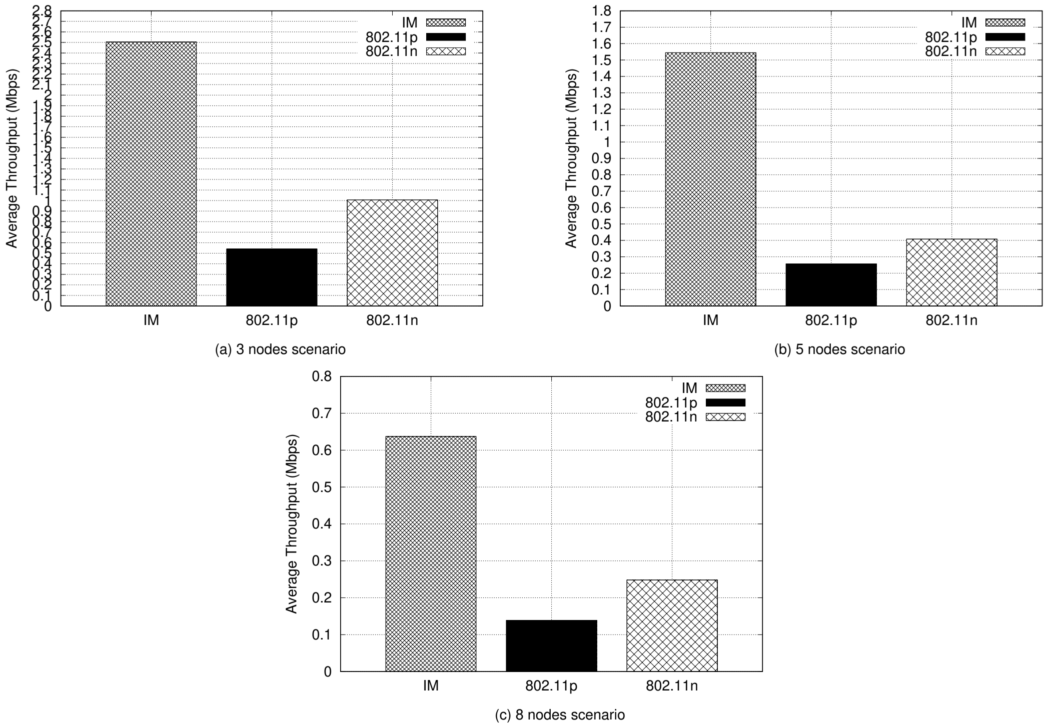


Figure 22 – Average network throughput.

Analyzing the three- and eight-node scenarios, with the average throughput obtained by the network using the IM system, in the three-node experiment, it would be possible to send about 260.41 samples of GPS coordinates per second, considering the use of a GPS device with 9600 bps resolution and about five frames per second of a 640 $\times$ 420 (480p) resolution video. For the eight-nodes experiment, it would be possible to send 83.33 samples of GPS coordinates per second and about 1.6 frames per second of the same video. We concluded that this number of GPS samples is favorable for the proposed SAR experimentation scenarios. In the case of the three-node experiment, the resolution and frames obtained from a possible video transmission by an MP4 resolution camera were satisfactory. However, for the eight-node scenario (more sparse scenario), some method of signal relay should be adopted for this video transmission resolution. Improving this will be the focus of future investigation.

Figure 23 presents the number of packets (n) trafficked in the network considering all the network traffic generated by the complete mission execution. The total number of packets transmitted and received over the network during the three experiments represents the total volume of data trafficked by the network and, implicitly, the number of packets lost (total of packets transmitted minus the number of packets received).

This metric describes the productivity of the network, that is, the more packets delivered, the more productive the adopted network settings. It allows a higher message recovery rate and, consequently, a higher volume of effective messages. The best proportion was achieved by the IM in all scenarios as shown in Figure 23. This is also shown in the last column (Flow (n)) in Table 8.

In all scenarios, the IM presented the best Tx and Rx packets relation with the highest number of packets trafficked, in the order of 3 $\times 10^6$, 4.25 $\times$ 10^6, and 3.75$\times$ 10^6 with 1 $\times$ 10^6, 5 $\times$ 10^5, and 4.5 $\times$ 10^5, for three, five, and eight nodes, respectively. This highlights that the IM produced almost twice the average throughput of both interfaces applied homogeneously.

Another conclusion that can be obtained from Figure 23 is that although the 802.11p interface had the lowest flow rate in all scenarios presented in Figure 22, its packet productivity was similar to that of the 802.11n interface, even considering its lowest nominal bandwidth. This may have occurred because the packet production interval for this technology is shorter than that for 802.11n. The header size of the WAVE protocol requires a 32 μs transmission time to the physical preamble, as opposed to the 96 μs of 802.11n, as stated in (RIBEIRO, Laura Michaella B.; BUSS BECKER, 2019).

Figure 24 shows the resulting packet delivery ratio (PDR) (see Equation ((5))) from the network packet generated by the U2U communication. This metric relates to the network packet delivery capacity. This capacity refers to the packets ratio delivered originating from the source node in its application layer, CBR, and the number of packages received by the CBR sink at the final destination (FAZELDEHKORDI; AMIRI; AKANBI, 2016). It can be observed that the IM produced the best delivery rate in all scenarios, followed by the 802.11p interface. In this case, the IM presented the best PDR rate, 0.977, which was observed in the five-nodes scenario.

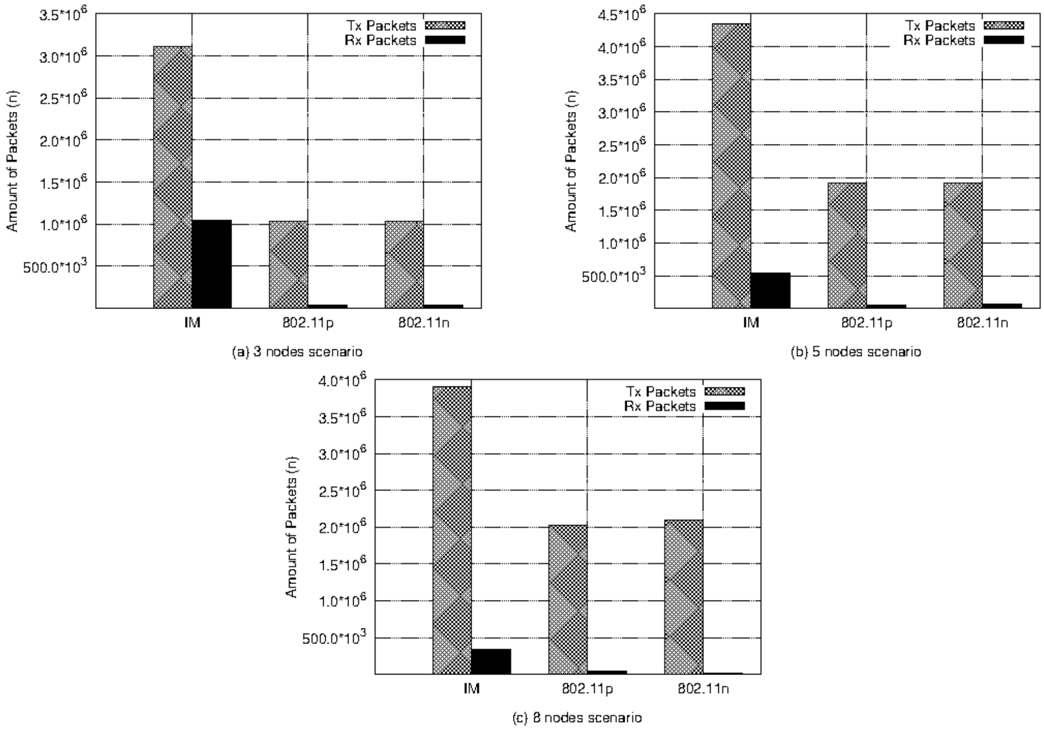


Figure 23 – Number of packets (*n*) received.

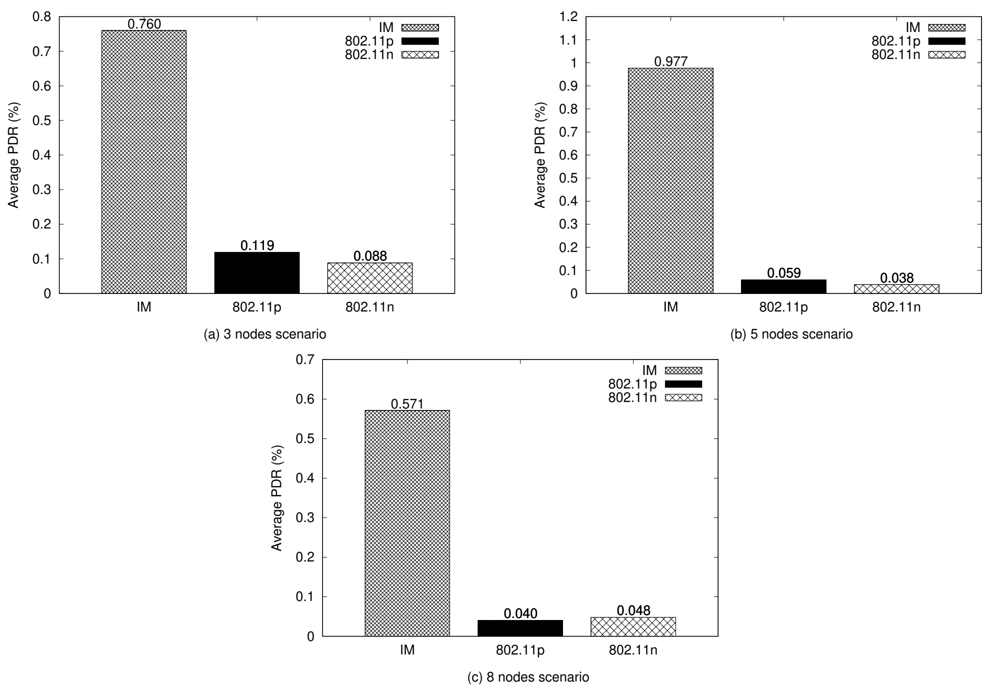


Figure 24 – Packet delivery rate (%).

In this scenario, the existence of intermediate waypoints allowed a significant increase in the number of packets trafficked (as shown in Figure 23) and, consequently, an increase in the PDR. As the intermediate waypoints were applied to the UAVs, increasing their courses (UAV-2 and UAV-4 had intermediate waypoints), this allowed these nodes to stay longer within the neighbors' coverage area: UAV-1 and UAV-3 covered UAV-2, while UAV-3 and UAV-5 covered UAV-4. For the three- and eight-node scenarios, the IM presented PDRs of 0.760 and 0.571, respectively, which implies that more messages were exchanged during the flight compared with using the interfaces homogeneously.

In practical terms, we concluded that the IM provided 76% (three-nodes scenario), 97% (five-node scenario), and 57% (eight-node scenario) of the effective capacity to exchange messages during the flight. This demonstrates that the switching resulting from the IM decisions between the available interfaces increases the effectiveness of the network in maintaining connectivity.

$$PDR(\%) = numberofRxPackets / numberofRxPackets + numberofLossPackets \quad (5)$$

A useful observation is that the IM performance in the five-node scenario, which included intermediate waypoints, highlights the idea that the use of relay UAVs or intermediate relay nodes can be beneficial for distances between vehicles greater than 70 m.

Table 8 presents the average end-to-end delay, latency, and flow of messages in all three scenarios. Each message flow was composed of 1472 byte packages, which simulated a typical application message transmitted between UAVs. The end-to-end delay (ms) and the latency (ms) describe the average obtained from all received packets. As can be observed, the IM performed worse in end-to-end delay (highest value) in all scenarios. In terms of latency, the IM was last only in the three-node scenario, but was ranked second in the other scenarios (ahead of 802.11n). The 802.11p applied homogeneously produced the best performance in end-to-end delay and latency for all scenarios; one should recall, however, that this was achieved with a low messages flow. The 802.11p standard has the feature of using short headers with no need for nodes association to communicate in the setting applied, which explains the least delay and latency. Regardless, the IM still performed the best considering the higher number of successfully delivered messages.

Table 8 – Average delay, latency, and flow of messages.

Experiment	Average End-to-End Delay (ms)	Latency (ms)	Flow (n)
3-node IM	2.34E-02	29.112	45
3-node 802.11p	1.44E-07	0.008	8
3-node 802.11n	4.50E-04	28.835	8
5-node IM	5.98E-01	2.000	78
5-node 802.11p	4.62E-07	0.026	16
5-node 802.11n	6.50E-04	38.979	16
8-node IM	2.37E-01	2.137	123
8-node 802.11p	4.15E-06	0.146	28
8-node 802.11n	1.02E-03	38.210	28

Considering the transmission of 480p video frames referenced in the discussion in Figure 22, the performance produced by IM in terms of average end-to-end delay and latency is satisfactory, as it received a “Very Good” quality reproduction (WISHNU; SUGIANTORO, 2019). However, for the three-node experiment, the observed latency was 29.112 ms, which would cause a reduction in quality to “Good”, by reducing the video resolution. The higher number of nodes in the network implies more neighboring nodes generating lower averages in end-to-end delay and latency and a larger number of message flow, since the messages are being sent in broadcast mode.

6.2.2 MAC and PHY Evaluation

This section highlights the effects of the proposed IM on standard wireless network metrics. The first metric to be discussed is the number of application-related data (payload) received by each node, as depicted in Figure 25.

The number of data generated in the three-node scenario was 5096 Mb, 4011 Mb for the five-node scenario, and 4233 Mb for the eight-node scenario. Figure 25 shows the number of bytes received by the network in 5 s intervals. The IM decisions (interfaces switching) are also presented.

These decisions are composed of the aggregated average of decisions of 5 s, presented using labels with the IM curve. The labels represent the aggregate decision composed of blocks of sample intervals, which the IM considered in most decisions. This means that the interface shown in the samples is the one chosen by the IM on most of the nodes in a given time interval. More details about the IM decisions using the Gazebo duration of experiment is presented in Appendix A, where the decisions are described in intervals of 10 s.

With respect to the payload transmission in bytes received (Mb), the IM performed the best only in the three-node scenario (Figure 25a). The IM initially chooses the IEEE 802.11n interface, changing to the IEEE 802.11p interface in the intervals of 20, 40, 48, and 65 s to maintain the growing curve of the transmitted bytes. Thus, for the scenario with three nodes, 802.11n provided a higher transmission rate until to the end of the experiment (141 s). When using homogeneous interfaces, data transmission was interrupted before reaching the end of the experiment, reducing the number of data received.

For the five- and eight-node experiments, the IM predominantly selected 802.11p, only using 802.11n in the initial 15 s. Three factors can explain the reasons for this occurrence: nodes reached longer distances from each other during the route, up to 75 m in the three-node and up to 100 m in the five- and eight-nodes experiments; the sparser layout of routes; and, lastly, the Rx power factor in the decision tree reasoning. As shown in Figure 26, most of the time 802.11p presented an Rx power between –50 and –65 dbm, which indicates a “Good” or “Strong” signal. The volume of bytes transmitted was smaller than in the experiment with three nodes, as 802.11p has a smaller bandwidth compared with 802.11n. Less traffic was generated (CBR data rate). However, this interface achieved lower flow rates, so we were able to notice a stability in the transmission, which represented a continuous growth with less fluctuations, maintaining the connection without interruptions.

Another observation was that in the five- and eight-node scenarios, the UAVs trajectories covered wider areas, allowing UAVs to be more distant from each other at certain points. Theoretically, the IEEE 802.11p on its on-board unit (OBU) version can reach a coverage of up to 1 km, which would justify its preference given its longer communication range.

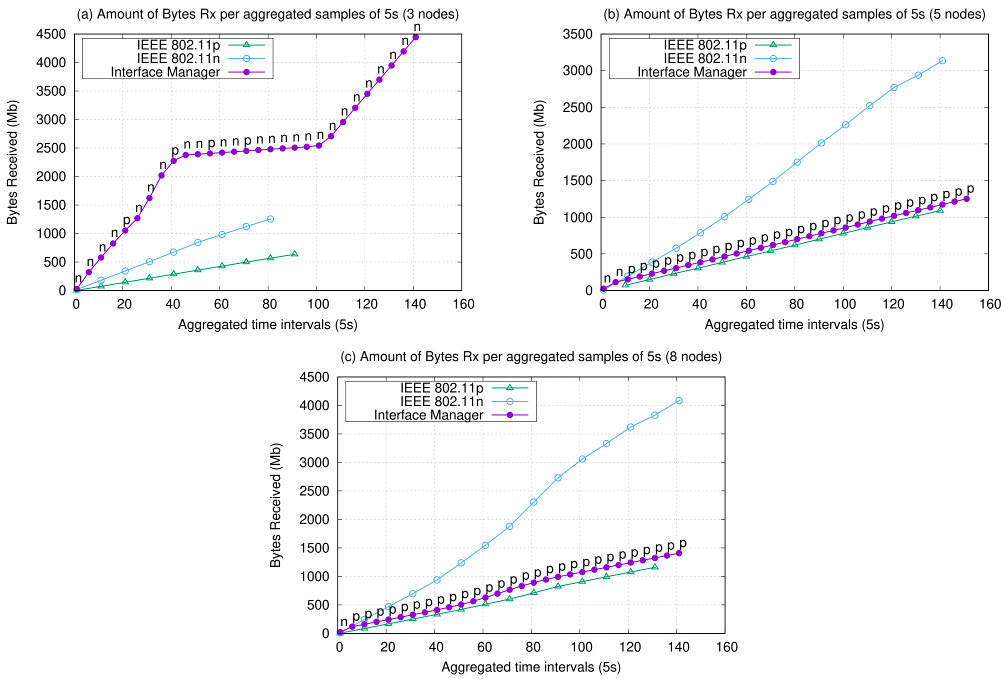


Figure 25 – Number of bytes received (Mb) measurement in PHY layer per aggregated time intervals (s).

Although, the IM did not present the best performance in terms of received bytes in the PHY layer in the five- and eight-node experiments, we observed that achieved values for the IM are satisfactory because the IM presented the best performance in terms of effective message delivery at the application level, as shown in Table 8 and Figures 23 and 24. An effective message delivery means that more messages were successfully delivery at the destination, probably because of the linear and continuous behavior of the PHY layer, with suitable Rx power and loss, which allowed a better message recovery performance at the destination.

Figure 26 presents the performance of the average aggregated of Rx power obtained by nodes over the sample time intervals. For experiment, a sharp curve can be observed, equivalent to the samples derived from the average signal power received from the nodes during their trajectories.

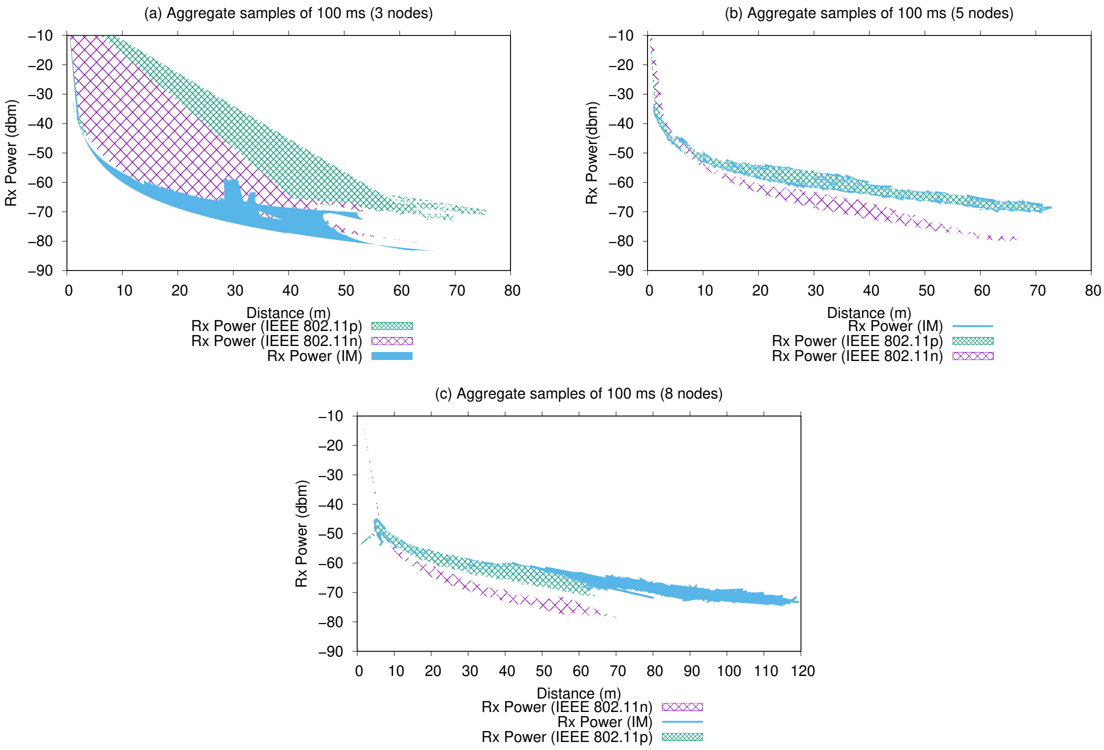


Figure 26 – Rx power per distance (m) using aggregate samples intervals of 100 ms.

For the three-node experiments (Figure 26), where the interface manager decided more often to use the 802.11n interface, we verified that up to a 10 m distance between the nodes, the reception power increased up to –60 dbm. This was also observed when interfaces were applied homogeneously. These intervals included the time of establishment and spread of the signal by the nodes in the spectrum (the nodes become audible). Thus, from a 20 to 50 m distance between the nodes, we verified that the IM presented a performance similar to IEEE 802.11n, maintaining the signal reception to between –60 and –75 dbm, which is considered a good reception quality for the 802.11 standard. However, the 802.11p interface showed better performance ,maintaining the signal reception around –65 dbm, which is considered an excellent reception quality, maintaining the link at these levels up to a 70 m distance between the nodes. The IM possibly chose 802.11n more often due to the higher volume of transmitted bytes (Figure 25), lower attenuation received (Figure 27), and lower delay generated (further discussed).

For the five- and eight-node scenarios, the IM performance was similar to that of 802.11p. As shown in Figure 25 b,c, the IM decision was predominantly for 802.11p. An important observation here is that the large number of samples obtained caused a denser curve compared with the 802.11p experiment. This means that the IM switching caused a better signal reception on the network in general, allowing maintenance of message exchanges with good reception power with larger distances between nodes: 70 m (five nodes) and 120 m (eight nodes).

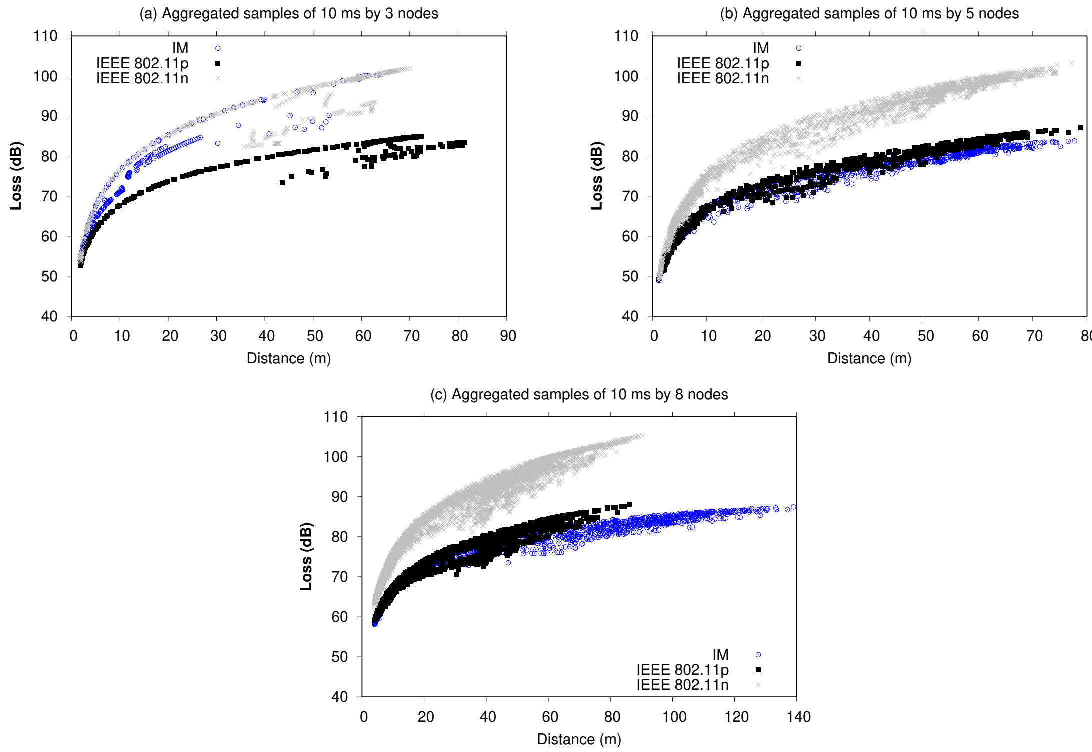


Figure 27 – Loss (dB) versus distance (m) using aggregated samples of 10 ms.

The performance of the Rx power presented by the network operating with IM is considered very good, since it maintained the levels of signal reception at levels classified as high reception for networks constituted by the 802.11 protocol; this allowed network traffic over greater distances between nodes and maintained the connection for a longer period of time, as shown in Figures 25 and 27. In SAR missions, the connection time intervals and greater signal reception by the nodes during the flight are desirable features in the constitution of mobile networks composed of such high-mobility nodes.

Figure 27 shows the loss in dB from the network during the UAV trajectories. These experiments correspond to the average value obtained in each aggregated sample, considering the attenuation caused by Nakagami fading and the power received by neighboring nodes.

The loss (dB) for interface manager experiments in the five- and eight-nodes scenarios presented the lowest signal loss indexes, maintaining a rising curve up to about 82–85 dB. This means that 30% of the path signal attenuation was caused by multi-path transmissions and fading effects between Tx and Rx nodes. In Figure 27, for the three-node experiment, the loss obtained by the IM experiments is similar to that of 802.11n, once the IM decided to use this interface more. However, during 0–30 m, the IM alternated, presenting minor losses compared with 802.11n maintaining the losses between 85–100 dB. Additionally, the variable values of loss from 30 m demonstrated that the IM attempted to decrease this rate, impacting the overall network performance.

The thicker curves generated by the five-node and eight-node scenarios represent a larger volume of data trafficked by the nodes, which can be constituted by messages and by beacon frames along their trajectories. An important point is that the UAVs remained able to communicate for a longer time, reaching greater distances.

This is more evident using as reference the typical loss of 802.11n systems of 80 dB in the 2.4 GHz band and 86 dB in the 5 GHz band considering a 100 m distance between the source transceiver and the destination transceiver obtained by free space loss attenuation, which implies a –60 dBm reference Rx power (GEIER, JIM, 2010). So, the IM and 802.11p performance for the five-node and eight-node scenarios presented a 85 dB loss maximum with an Rx power of –50 to –70 dBm (Figure 26). Theoretically, the Rx power would be –69 dBm, resulting in 16.02 dBm (power applied in the 802.11 transceivers used (Table 6)) minus the 85 dB maximum of loss in Figure 27.

Figure 28 presents the RSSI and noise aggregated samples received by the network during the experiments. Here, the IM presents the lowest variation in RSSI in the three experimental scenarios, which implies more stable connections between the nodes. The RSSI remained in the range of –38 to –34 dBm in the three-node experiment scenario, from –34 to –30 dBm in the the five-node scenario, and from –50 to –48 dBm in the eight-nodes scenario, allowing greater connectivity of the nodes during the flight.

The intensity of the received noise showed low variation throughout the experiments, remaining in the range of –92, –94, and –96 dBm considering the background noise and the noise caused by the co-channel interference between the nodes, since they used the same channel for communication for both interfaces in all experiments (homogeneous and heterogeneous).

The intensity of the connection in levels can be verified from the result obtained by the RSSI network subtracting its average values of –38 dBm (three nodes), –34 dBm (five nodes), and –50 dBm (eight nodes) by the average noise obtained –92, –94, and –96 dBm, respectively. In this case, we obtained –54, –60, and –46 dBm network RSSIs, respectively. So, on scale of 0 to –100 (with 0 meaning the best signal possible and –100 indicating the worst), the IM presented an RSSI value of around 50, which is generally considered to be good enough for most users and online activities. The SNR was calculated from the average values of the RSSI and noise obtained by the network: 0.41 (three nodes), 0.36 (five nodes), and 0.52 (eight nodes) network average signal gain.

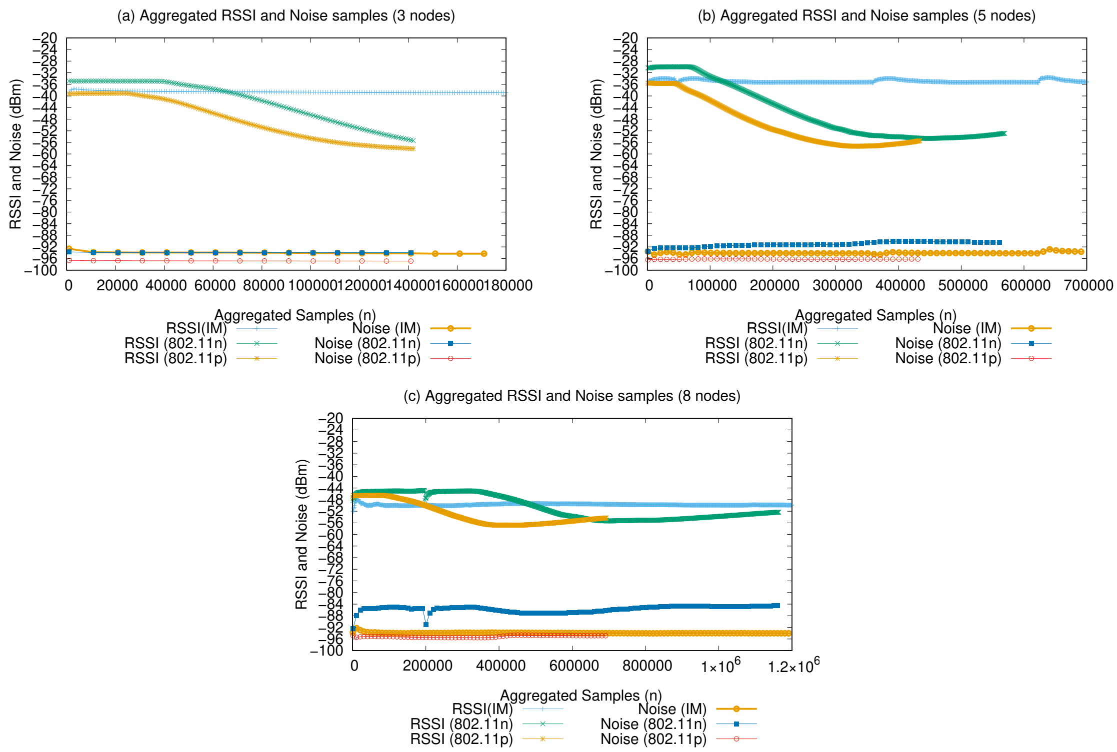


Figure 28 – Aggregated RSSI and noise samples.

Figure 29 shows the message delays considering interval samples of 10 ms. The delay measurements occurred until reaching the maximum distance between nodes. The label containing the IM decisions is shown up to 150,000 samples for the five- and eight-node scenarios. It caused the IM to not change the use of the last chosen interface.

Thus, in the three-node scenarios, the IM presented better performance for delay measurements, with an average 10 ms delay up to 200,000 samples (around a 20 m distance between nodes). After 200,000 samples, we observed a peak delay of 220 ms, which decreased soon after. For delay validation, only the trajectory to the UAV reaching its maximum distance in relation to the starting point was considered.

For the five-node scenario, we observed an IM performance similar to that of 802.11p, increasing the delay after 60,000 samples at 10 ms (approximately 16 m distance between nodes) and starting an ascendant curve after 100,000 samples (approximately 30 m distance between nodes). The 802.11n interface presented better performance, increasing the delay only after 150,000 samples (approximately 35 m distance between nodes).

Notably, this scenario contained a larger area to be covered by the UAVs, which due to the existence of secondary waypoints and to the greater number of nodes, more messages are generated, increasing the aggregated delay. Then, some nodes may have already started returning to the starting point while others were still on the way.

For the eight-node scenario, all the experiments presented 12–30 ms delays up to 150,000 samples (approximately 50 m distance between nodes). In this scenario, the UAV trajectories were sparser but in straight lines (only had start and end waypoints) reaching up 100 m distances between nodes. Therefore, after 200,000 samples, an ascendant curve started up to a 80 ms delay, as the nodes reached their maximum distance.

Observed messages delay related to the use of the IM can be considered acceptable for transmitting 480p video sessions and for sending the GPS coordinates mentioned in Section 6.2.1, and data and telemetry, where such delays generally do not result in a noticeable decay in experience by a user, for example. However, the delays recorded from 200,000 samples in the experiment with three nodes and five nodes would not be acceptable for voice-over WLAN applications, as connections are typically dropped if the delay exceeds 150 ms (GEIER, JIM, 2010). So, depending on the application data to be transmitted over the network, the delays obtained in our experiments are considered tolerable.

In general, the IM selected the best interface most of the time due to a proper dynamic analysis of the medium conditions, in accordance with the variations in the distance between the UAVs. For the five- and eight-node scenarios, with increased communication stress due to the larger communication range and number of data transmitted, although the IM did not produce the best performance in the evaluated metrics overall, it guaranteed more data being transmitted with more-stable, better-quality connections.

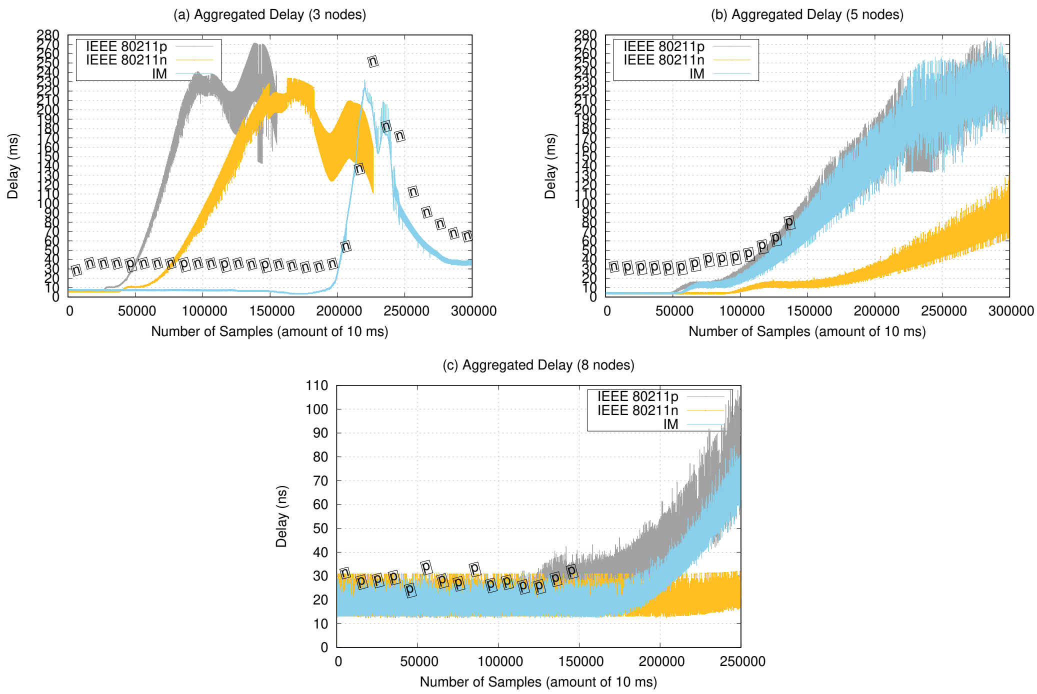


Figure 29 – Delay (ms) aggregated by number of samples (amount of 10 ms).

This is due to its performance in terms of Rx power (Figure 26) and loss (Figure 27). The IM also presented a greater throughput and PDR, and higher volume of packets transmitted, allowing better message flow.

6.3 FINAL REMARKS

From obtained results, the proposed IM presented a lower performance fluctuation in the network flow, even with the increase in the number of nodes, presenting good reception of signal by nodes during all missions, with fewer communication interruptions. The IM was able to maintain the link between –60 and –75 dbm, with a distance of up to 100 m between the nodes, with the lowest signal loss indexes (80 dB to 85 dB), and with SNR up to 0.52. Thus, the use of the IM promotes higher link stability, enabling the dynamic selection of interfaces in order to adjust the network to the conditions of the medium and to promote U2U communication with increased reliability. The IM enabled almost twice the sum of the average throughput from both interfaces applied homogeneously.

Next, in Chapter 7, the IM performance is verified in terms of video, voice, background, and best-effort traffic evaluating the IM behavior considering the different traffic that a FANET mission could need.

7 INTERFACE MANAGER PERFORMANCE WITH DIFFERENT TOS

Regarding the different access classes of service, AC_VO (voice), AC_VI (video), AC_BK (background), and AC_BE (best-effort), different combinations of interfaces applied in heterogeneous mode could get better performances for each AC. In this context, to investigate this question, this Chapter extends the benchmark of the heterogeneous interface manager (IM), introduced in Chapter 4, validating the performance of different combinations of interfaces by sending different ToS packets applied in multi-UAV networks. Such experiments consist of combinations that include the following IEEE standards: 802.11n 2.4 GHz, 802.11p 5 GHz, 802.11ac 5 GHz, IEEE 802.11ax 2.4 GHz, and 802.11ax 5 GHz. In this way, each UAV in ad-hoc mode can transmit signals through different frequency bands, PHY modulations, and MAC protocols.

In general terms, this Chapter allows observing that a previous definition of the mission application and the communication metrics requirements is of the most importance in the definition of which set of interfaces should be applied in the system. This holds because the performance obtained from the transmission of different access classes packets even considering the use of more than one communication interface could be worst in some evaluation metrics.

The remainder parts of this chapter are organized as follows. A description of performance evaluation settings is shown in Section 7.1. The composition of evaluation metrics, and the performance obtained for application layer results for different access classes are presented in Section 7.1.1. In the Section 7.1.2 is describe the MAC and PHY layer results for different interfaces compositions, including validations of a video streaming data transmissions. Finally, Section 7.3 highlights the final remarks from the experiments' analysis.

7.1 PERFORMANCE EVALUATION SETUP

Just like in Chapter 6, this one presents two experimental setups: (i) application results and (ii) MAC and PHY results, including the network effects caused by an application that needs to send the four different access classes defined in this work: voice (AC_VO), video (AC_VI), data (AC_BE), and all the network signs which composes the AC_BK (control signals and beacon frames) are evaluated in the discussions. Also, it verifies the IM validations propagation network effects, evaluating the RSSI and SNR performances.

All the access classes packets are sent by the nodes in broadcast mode up to half of the experiment duration having as 250 ms of the sample interval. The access classes messages present varied sizes according to payload, presenting from 14 bytes to 8 Kbytes of size, approximately.

After half of the experiment duration, the transmission is composed only by a video streaming classified as AC_VI ToS, in that the size of video frames received by nodes is verified. Video streaming is composed of frames of MPEG-4 video of 637.7 Kbytes of size. The video resolution has 352 X 288 using 30 frames per second with 65 kbps of bit rate. The video could be send up to 5 times by each node.

The separation of AC_VI from the other types of service is relevant to get more specific validations, in this important type of service applied by search and rescue missions. The Evalvid (KLAUE; RATHKE; WOLISZ, 2003) tool is employed to provide service of sending video frames between nodes, to evaluate the AC_VI (video access class) type of service message.

MAC and PHY results are generated by metrics collected at the running time of the experiment. Since this is also composed of ACK-type packets coming from the beacon frames received by the nodes, these samples are collected at intervals of 1 ns depending on the spectral sensing events. Thus, to facilitate the understanding of the results, they were standardized in aggregated sample sets.

All of the experiments were performed using heterogeneous interfaces; that is, using the proposed IM with two (IM-2Int), three (IM-3Int), four (IM-4Int), or five (IM-5Int) wireless communication interfaces. For propose a comparison all the interfaces used in IM settings were performed in homogeneous way.

The interfaces used in the experiments were:

- IM-2Int: IEEE 802.11n 2.4 GHZ and IEEE 802.11p 5.9 GHz. The first one was applied with non-overlap channel 6 (2426–2448 MHz) and 22 MHz of bandwidth, while the second one was in channel 172 (5860–5870 MHz), which is a safety channel with 10 MHz bandwidth, used as a data priority to send messages without association, based on node distance. These configuration are the same as employed in the other experiments.
- IM-3Int: Both interfaces described before plus IEEE 802.11ac 5 GHz. This interface uses channel 42 (5170–5250 MHz) reduced to 20 MHz of bandwidth with four spatial antennas and a short guard interval of 400 ns. The HT (High-Throughput) data rate was also applied, which means it was possible to achieve more than 300 Mbps. These antenna settings and short guard interval of OFDM are defined by the IEEE protocol standard setting for this device.
- IM-4Int: All the interfaces described before plus IEEE 802.11ax 2.4 GHz. This interface uses channel 1 (2401–2423 MHz) with 20 MHz of bandwidth, with four spatial antennas and an OFDM short guard interval of 800 ns. The HE (High-efficiency) data rate is enabled, in order to configure nodes when using this device, to allocate the whole channel to a single client node at a time or partition a channel to serve multiple users simultaneously.
- IM-5Int: At least one experiment used all communication interfaces described

before plus IEEE 80211 ax 5 GHZ. This interface uses channel 42 (5170–5250 MHz) reduced to 20 MHz with 800 ns guard interval, and all of the other IEEE 802.11ax 2.4 GHz settings. These settings were installed by default, when IEEE 802.11ax is configured as per the standard in NS-3. The IEEE 802.11ax has been marketed as Wi-Fi 6 (2.4 GHz and 5 GHz) by the Wi-Fi Alliance (ALLIANCE, 2000).

Table 6 presents relevant configuration parameters used in all scenarios. The Friis free-space propagation model was used, in the simulation, as a signal attenuation model. However, to include signal fading effects, the Nakagami statistical shading model was applied using a Rayleigh distribution, considering variations in signal strength due to multi-path fading, once the nodes could not be in LOS (*line-of-sight*) of each other, as seen in (RIBEIRO, Laura Michaella Batista; MÜLLER; BUSS BECKER, 2021).

The OLSR (Optimized Link State Routing) protocol was used, in order to reduce the message overhead, using link state information only in the case of network changes (i.e., adding/removing a node) and, thus, minimizing the number of control messages in the network.

The performance of each set of experiments is compared and discussed in this section, in order to describe in which aspects the use of heterogeneous communication can be favorable, as well as which configuration provides the best performance in these networks. The experimental duration varied for each scenario: around 132 s maximum for scenario 1 (three nodes), 140 s maximum for scenario 2 (five nodes), and 150 s maximum for scenario 3 (eight nodes). These durations correspond to the NS-3 simulation time, as it used the metrics of evaluation in its execution logs on the order of *ns*.

IM validation (switchings) for each experiment occurred at 1 s intervals, using the average of the condition decisions from buffers containing at least 10 samples, collected every 100 ms. This avoided instantaneous value fluctuations. All the IM validations is present in the Table 12 in Appendix A.

7.1.1 Application Results

Figure 30 shows the number of packets received by the network, in terms of different ToS, for each experimental scenario. This metric was chosen to evaluate the network productivity when sending different types of services between nodes and, consequently, the effective capacity of the network to exchange these different types of service packets during the flight.

In order to validate the performance of the IM experiments, *MTxP*(*network*) (i.e., the maximum capacity for transmitting packets over the network) was calculated, without inclusion of distance variation between nodes. Ideally, to determine *MTxP*, it is necessary to know the maximum network data rate (50 *Mb*/*s*, according to Table 5).

Thereby *MTxP* can be calculated as shown in Equation (6):

$$\begin{aligned} TxP(second) &= \left(\frac{MaximumDataRate(bps)}{packetSize(bits) * N}\right) \\ MTxP(network) &= \left\{ TxP * \left[\frac{duration(s)}{2} + 1.0\right] \right\}, \end{aligned} \tag{6}$$

where $T_X P$ is the packet transmission rate per second and N is the number of nodes in the network. Thus, in this work, the *MTxP* was composed by the *TxP* multiplied by $duration(s)/2$. As it was defined in all scenarios, three ToS (AC_BE, AC_BK and AC_VO) were sent and validated by all nodes for up to half of the maximum duration plus 1 s (safety time to start and end communication by sink node); for example, in the three-node scenario, considering the maximum data rate adopted by network, Equation (6) results in: $MT_X P(network) = [(50000000(bps)/((1500 * 8) * 3)] * ((132/2) + 1)$. In this way, we obtained 93,055.55 (9.30 Mb/s) as the MTxP of the network for the three-node scenario, 59,166.66 (5.9 Mb/s) for the five-node scenario, and 39,583.33 (3.96 Mb/s) for the eight-node scenario.

For the three-node scenario (Figure 30(a)), the experiment IM-4Int performed best, with a greater number of successful AC_BK (12,918) and AC_VO (13,996) packets. In terms of AC_BE ToS, IM-2Int presented the best performance, achieving 338 packets. The second-best performance was the IM-3Int experiment, with 4307 and 4418 for AC_BK and AC_VO, respectively. In general, the addition of interfaces in IM implies different ToS packets propagated by the network. However, the IM-5Int experiment (which added a communication interface operating in the 5 GHz band, IEEE 802.11ax 5 GHz) generated an increase of packet loss in all ToS packets, when analyzed implicitly against the IM-4Int and IM-5Int experiments.

A possible cause for this is the use of IEEE 802.11ax in the same channel as IEEE 802.11ac, causing possibilities of co-channel interference; that is, if another node within the communication range is using the 802.11ac interface. All communication interfaces applied in the experiments used unlicensed frequency bands, meaning they do not guarantee channel allocation, thus potentially generating this type of interference. An alternative to minimize this problem is to use dynamic channel assignments, in an attempt to minimize the effects of co-channel existence.

Analyzing Figure 30 (a2) for the three-node scenario, which presented the performance of interfaces applied in a homogeneous manner, IEEE 802.11p showed the best performance for all access classes, with 197 AC_BE, 15,595 AC_BK, and 16,739 AC_VO. This means that the feature of short-time node association and the lower header inserted by 802.11p WAVE protocol are likely very favorable to ensure packet productivity in multi-UAVs networks. The interface 802.11n presented the worst performance for all access classes, correlating with both performances (homogeneous and heterogeneous). The worst performance of 802.11n obtained in a homogeneous situation reflects the worst performance obtained by the IM-2Int experiment, in which the IM used 802.11n and 802.11p in its decisions. The number of AC_BK and AC_VO packets obtained by interfaces applied in homogeneous mode presented the best performance against the IM experiments. In terms of AC_BE packets, the IM experiments presented the best performance, with 135 more packets received than homogeneous experiments. Therefore, in terms of packets up to 144 bytes, the IM experiments presented the best performance. This means that the IM is less susceptible to noise and interference from medium and fading effects, where this type and size of packet is very likely to be affected under these conditions. Furthermore, the volume of packets for the homogeneous experiment was better, presenting a higher capacity of the network; however, it is not sufficient to define the efficiency of a network, as these packets can present errors in data recovery or may comprise duplicate transmissions. So, the end-to-end delay, latency, and PDR are important network evaluation metrics to define the quality of packet reception. End-to-end-delay and latency have special place in multi-UAV network QoS evaluation, mainly when the mission includes shared tasks and goals, and where the reception time is a critical factor during the mission execution.

For the five-node scenario, the experiments IM-3Int and IM-4Int performed better, with a greater number of AC_BK (8366 and 6781, respectively) and AC_VO (8622 and 7095, respectively) packets. In this case, the IM-4Int experiment presented the best performance, in terms of AC_BE packets. In this scenario, with the exception of the IM-2Int experiment, the performance of the other IM experiments presented similar behavior, varying between 4751 (IM-2Int) to 8366 (IM-3Int) for AC_BK and 4683 (IM-2Ínt) to 8622 (IM-3Int) for AC_VO packets. The IM-5Int performance did not present the best performance, however, but was third in terms of AC_BK and AC_VO ToS, and the worst in terms of AC_BE ToS. Therefore, in the five-node scenario, more communication interfaces does not necessarily imply the best performance but, with a major density of nodes, the performance of the IM experiments presented similar results.

Figure 30(b2) presents the performance of interfaces applied in a homogeneous manner. In this case, with an increase in the number of nodes and closer UAV paths, the interfaces using 802.11n and 802.11p presented the best performances, with 11,682 (AC_BK) and 14,567 (AC_VO) for 802.11n, and 22,950 (AC_BK) and 24,180 (AC_VO) for 802.11p. For AC_BE, 802.11n presented the worst performance, with 257 received packets. In this case, 802.11p used in homogeneous mode implied three times more packets received than the best performance verified in the IM experiments (IM-3Int). Therefore, in terms of data transmitted volume, 802.11p applied homogeneously could provide a good interface to be used for signals, control, and voice transmissions. Once more, the IM experiments presented better performance, in terms of short-packet (AC_BE), reaching approximately two times more packets received.

The 802.1ac, 802.11ax 2.4GHz, and 802.11ax 5GHz experiments presented similar performance as the IM combination experiments for AC_BK and AC_VO.

For the eight-node scenario, the IM-2Int experiment presented better performance, considering AC_BK and AC_VO packets, while the IM-5Int experiment was best for AC_BE packet. The other experiments varied between 557 (IM-3Int) and 623 (IM-5Int) for AC_BE; for AC_BK, between 37,509 (IM-2Int) and 11,473 (IM-5Int); and, for AC_VO, between 38,210 (IM-2Int) and 12,076 (IM-5Int).

This scenario presented more spatial UAVs routes and a higher density of nodes, which generated more transmission requests, composed of signaling short-packets (between 66 and 144 bytes) of the AC_BE packet type. For this reason, a larger number of request and ack packages were generated than in other scenarios. The same happened with other ToS packets, having a higher number of packets.

Analyzing the homogeneous IEEE standard performance in the eight-node scenario, all of the IM combinations presented better performance, reaching up to three times more packets received. The best performance IM combination (IM-2Int) presented very close performance to 802.11p, with 600 AC_BE, 37,509 AC_BK, and 38,210 AC_VO packets against 544 AC_BE, 37,374 AC_BK, and 39,441 AC_VO packets, respectively. Therefore, in fact, the IM made decisions considering the best interface to apply in these scenarios.

In this scenario, the co-channel interference may also be applied in this case, as the best efficiency in packet transmissions came from the experiment considering the IM with only two interfaces (IEEE 802.11n 2.4 GHz and IEEE 802.11p 5.9 GHz). This can be justified by the adaptability of the 802.11p protocol in sparse environments, with a theoretical range of communication of about 1 km without an RSU (Road Side Unit).

Thus, the scenarios that presented more than three nodes had similar performance behavior, in terms of the number of packets received for the different types of service packets. However, the best performance was reached in each scenario by IM-4Int (three-node scenario), IM-3Int (five-node scenario), and IM-2Int (eight-node scenario), having performances up to 2 times better. In the homogeneous case, 802.11p presented the best performance in all scenarios, representing a better option for AC_BK and AC_VO data in high mobility networks. Another conclusion was that 802.11n 2.4 GHz presented bad performance in scenarios up to three nodes, as seen in IM-2Int and 802.11n in Figures 30(a) and (a2), with an increase in the number of nodes increasing its performance, being part of the best combination in IM experiments (IM-2Int).

In general, the IM combinations were less susceptible to interference than the interfaces applied homogeneously, which can be seen in the eight-node scenario, with a high volume of packet transmitted/received in a high-frequency concurrency scenario.

The combination of interfaces applied to the IM which showed the best performances demonstrated that a greater number of interfaces applied in IM does not imply

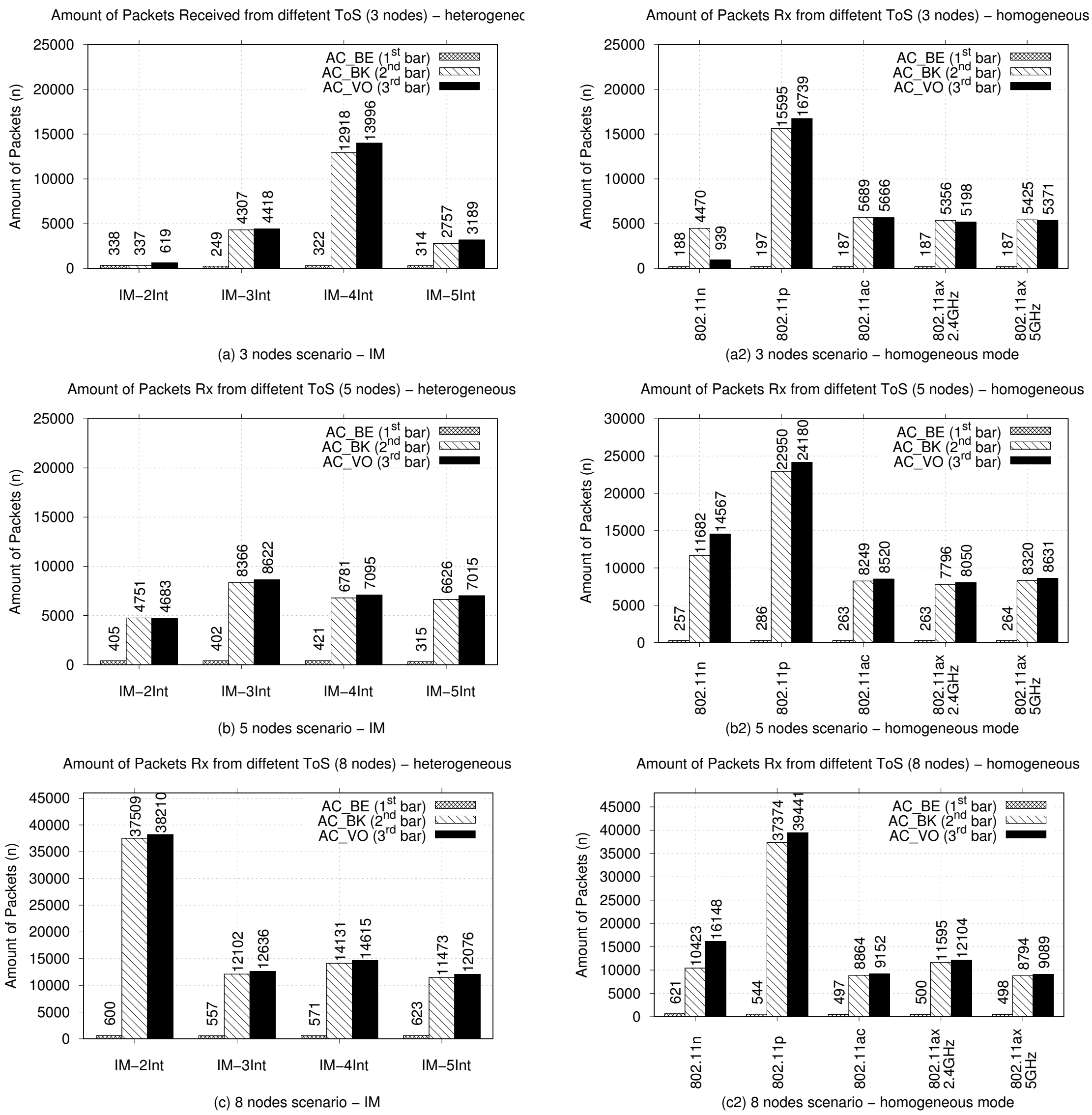


Figure 30 – Number of different ToS packets received by network: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

better performance; instead, the performance was defined by which interfaces were defined to be used, which frequencies and channels were set and, finally, the scenarios and type of services were applied in a certain mission.

Figure 31 describes the average latency obtained by the networks and the amount of successful flow messages. The flow of messages is defined in terms of the successful links established between nodes to send packets.

From Figure 31(a), it is possible to see that the IM-4Int experiment also presented the best performance, considering the relationship between average latency and flow of message, presenting 0.69 ms of latency per 45 effective messages delivered. The

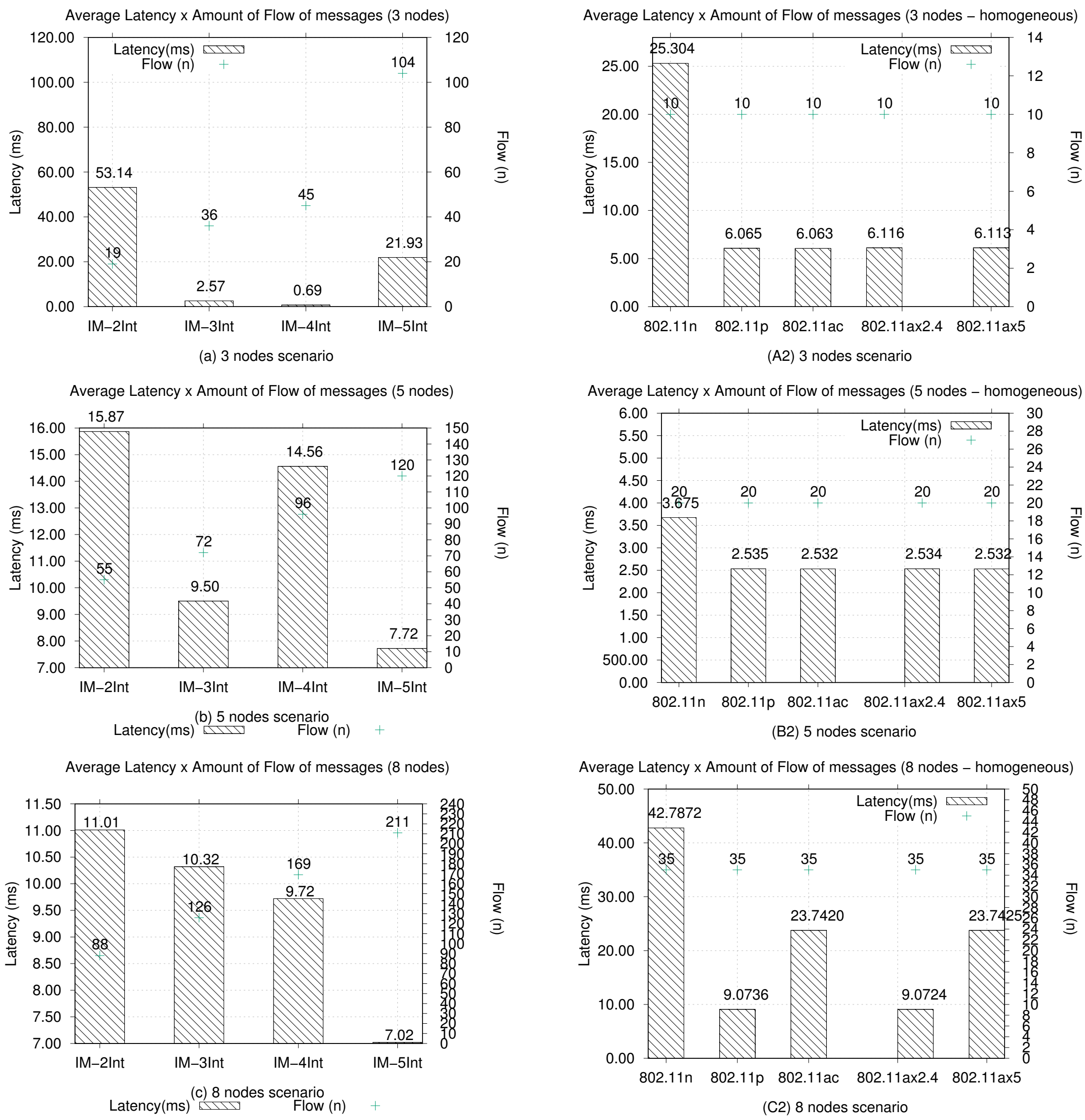


Figure 31 – Average Latency and number of flow messages transmitted by network in IM and homogeneous experiments: (A) Three-node scenario; (A2) three-node scenario (homogeneous); (B) five-node scenario; (B2) five-node scenario (homogeneous); (C) eight-node scenario; and (C2) eight-node scenario (homogeneous).

greatest number of flow messages was determined in the experiment IM-5Int but, as seen in Figure 30 (a), this does not imply a higher reception of ToS packets, as a message flow could consist only of acknowledgment messages from beacon frames. For homogeneous experiments (Figure 31(A2)) the best performance was obtained by 802.11ac, with 6.063 ms of average latency per 10 messages delivered. 802.11 n presented the worst performance, with 25 ms of latency for the same number. This performance reflected the performance obtained in the IM-2Int experiment (which was the worst performance obtained in the IM setting).

All of the interfaces applied homogeneously presented the same amount of flow obtained during the mission, in all scenarios. The latency variance presented in homogeneous experiments highlights the intrinsic difference in protocols; in this case, IM-4Int presented a four-fold higher flow of messages delivered in the lowest amount of time. This describes the benefits of heterogeneous communications, used to dynamically adapt to a network with medium conditions.

Figure 31(b) shows IM-5Int, which presented the best performance, considering the proportion of average latency obtained (7.72 ms per 120 flow messages). In this case, evaluating this proportion plus the number of packets received by the different types of service, as seen in Figure 30(b), this experiment presented the best performance for the five-node scenario, as it represents the nodes communicating more frequently, with lower latency and quantities similar to other packet reception experiments using different types of services. Analyzing the interfaces applied in a homogeneous manner, the 802.11p 5.9 GHz presented performance close to that of 802.11ax 2.4 GHz; this is interesting, as they use different frequency bands. Meanwhile, 802.11ac 5 GHz presented equal performance to 802.11ax 5 GHz; in this case, both presented the same frequency band and channel. These performances indicate that that MAC and PHY layers of these interfaces present some common compositions.

In the eight-node scenario, presented in Figure 31(c), IM-5Int showed the best performance, considering the proportion of average latency obtained (7.02 ms per 211 flow messages). However, considering the number of packets received, as shown in Figure 30(c), the IM-5Int experiment was much lower than the best performance of IM-2Int, such that this larger number of flow may only be composed of requests and responses from nodes or the establishment of links, without sending relevant payloads. In this case, evaluating both Figures, the best performance was still obtained from the IM-2Int experiment, followed by the IM-4Int experiment. For homogeneous performance, the best performance was that of 802.11p and 802.11ax 2.4 GHz, which presented almost the same performance. In this scenario, the same homogeneous behavior was presented by the five-node scenario, where 802.11p presented very similar performance to 802.11ax 2 GHz and 802.11ac from 802.11ax 5 GHz. Using, as reference, the performance of IM-5Int and 802.11ax 2.4 GHz, the interface manager allowed around six times more number of data flow to be successfully received.

To conclude, as can be verified by comparing Figures 30 and 31, it is not enough to simply establish more communication flows with the nodes with the lowest latency, when dealing with a mission that requires different types of service; it is also necessary to consider the type and amount of payload for each packet received. Furthermore, the best IM settings presented similar performance to 802.11 p, in terms of the number of packets received from different ToS. Thus, IM is capable to achieving the lowest latency with a higher flow of messages (i.e., payload successfully delivered) than all of the interfaces applied in a homogeneous manner.

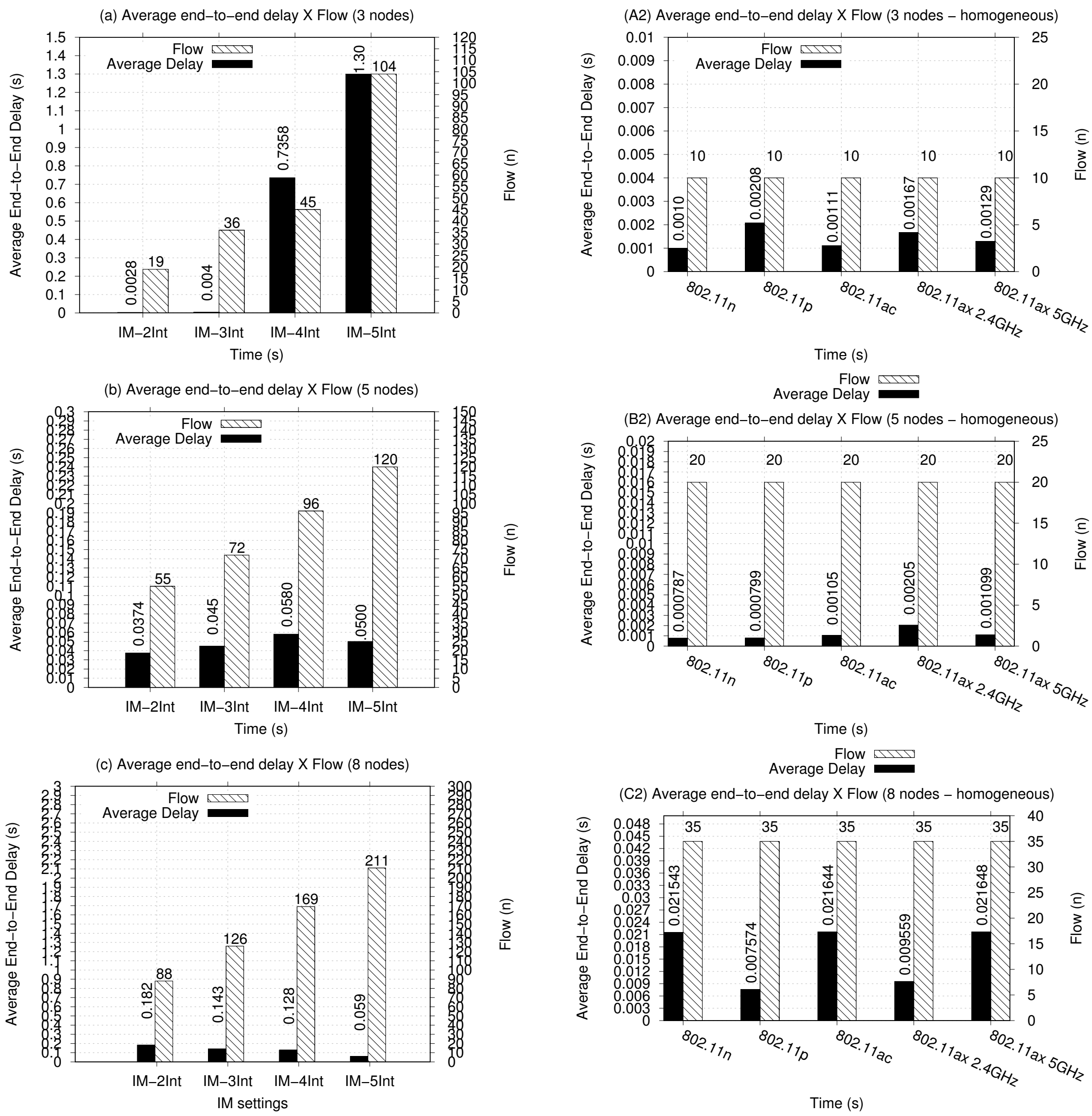


Figure 32 – Average end-to-end delay and number of flow messages received by network per IM and homogeneous experiment: (A) Three-node scenario; (A2) three-node scenario (homogeneous); (B) five-node scenario; (B2) five-node scenario (homogeneous); (C) eight-node scenario; and (C2) eight-node scenario (homogeneous).

Another important consideration is the heuristic of sum of points used by the IM, applying equal weights to the evaluation metrics, does not allow the algorithm to be biased towards missions where greater performance in the flow of data is needed, in terms of more flow messages (i.e., establishing links) or seeking the lowest latency at any cost. This can be the subject of future research.

In this way, evaluating the results together allows for more precise conclusions. Figure 32 presents the performance of delay compounded by the preparation for sending message time in the source node, including the IM decision time, up to the reception procedure in the sink node. According to Figures 32(a–c), as expected, with more nodes present in the experiment, a higher flow of messages is received. The same did not occur with the delay and flow, as seen in Figures 32(b) and (c). In this case, lower delay was presented by IM-2Int (with 55 flow) and IM-5Int (with 211 flow). In the five-node scenario, considering time-restricted missions, the best performance was attained by IM-5Int, presenting 0.0500 s of average end-to-end delay and latency of 7.72 ms, as seen in Figure 31(b).

For the eight-node scenario (Figure 32(c)), if the mission also presented time restrictions, IM-5Int presented the best performance, considering the average delay of 0.059 s and latency of 7.02 ms (Figure 31(c)). Considering only the performance of average end-to-end delay for the three-node scenario, the best performance was found in the IM-3Int experiment (0.004 s), but it should be noted that a higher number of data flow was not presented.

Using the roaming delay of the 802.11 standard described in (GEIER, JIM, 2010) as reference, the user generally does not perceives any notable delay in voice over WLAN phone calls if the delay is no higher than 150 ms. Thus, in case of missions with time restrictions and transmissions comprised mainly of voice ToS (AC_VO), the IM-4Int and 5-Int settings for the three-node scenario and IM-2Int for the eight-node scenario will not obtain the best performance.

Evaluating the homogeneous experiments in the three-, five-, and eight-node scenarios (Figures 32(a–c)), in general, the homogeneous experiments presented better performances than IM settings, with lower end-to-end delay. This demonstrates that IM leads to some delay in the sending and receiving of messages, due to its executions; whoever, considering the flow of messages transmitted by the network, and with the exception of the IM-4Int and IM-5Int experiments for the three-node scenario, which presented delays > 150 ms, the IM performances were acceptable when increasing the data flow. Comparing the best delay performances for the three-node scenarios, IM-2Int (IM) and 802.11n (homogeneous), the IM led to around a 1.8 *ms* increase in delay for each message sent. In the same way, comparing the performance of IM-5Int with 802.11n, which had the best performances for the five-node scenario, and IM-5Int in comparison to 802.11p for the eight-node scenario, the IM led to around 0.05 *ms* extra delay when sending messages.

Thus, evaluating all of the experiments presented up to this point, two important verifications are necessary for the use of heterogeneous communications in networks composed of high mobility nodes, such as UAVs: a) Which applied interfaces can provide the best performance, considering the mission application? and b) What are the most important metrics for collaborative mission success? With these questions in mind, the use of different weights for the most important metrics could provides a good basis for designing a UAV network.

Figure 33 describes the throughput and PDR (Packet Delivery Rate). One can

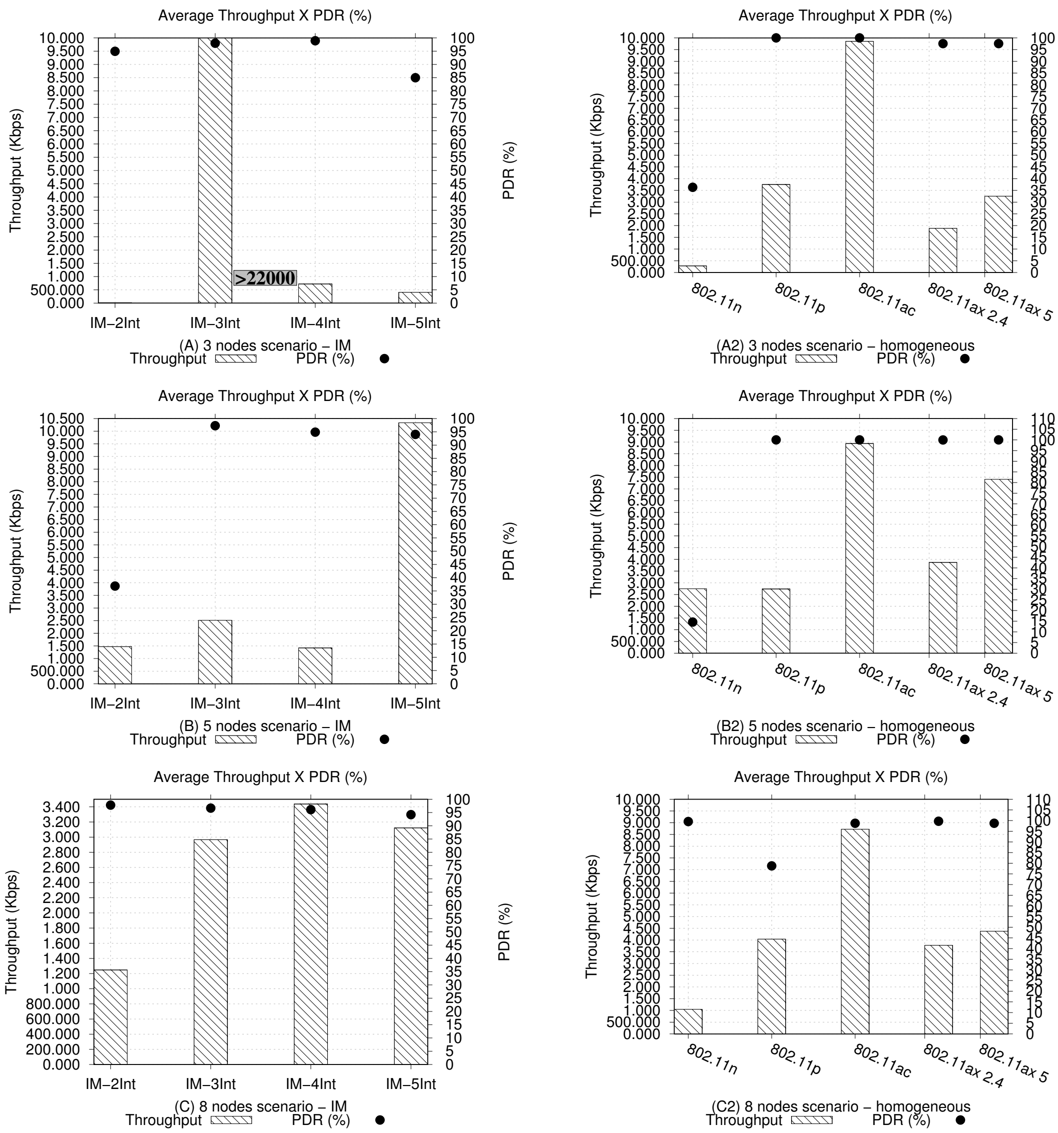


Figure 33 – Average throughput and PDR obtained by IM experiments: (A) Three-node scenario; (B) five-node scenario; and (C) eight-node scenario.

see that the PDR presents different behavior than the throughput. Throughput refers to how fast data is transmitted from source to sink node, through a link successfully established between them. PDR refers to quality of data delivered in this transmission, as many packets can be sent but not received, due to the 802.11 standard multipath transmission technologies, noise, and background interferences, as well as losses related to the attenuation generated as a function of the distance.

In these terms, for the three-node scenario, the IM-2Int experiment presented a throughput of 18.0863 Kbps with 94% PDR, the IM-3Int experiment presented 22460 Kbps of throughput and 97% PDR, the IM-4Int presented 722.11 Kbps of throughput and 98% PDR, and the last one, IM-5Int, presented 407.84 Kbps of throughput and 84% PDR. In this case, the experiment that presented the best performance, in terms of throughput and PDR analyzed together, was IM-3Int. In comparison with the homogeneous experiments presented in Figure 33(A2), all of the interfaces presented better performances than IM-2Int, IM-4Int, and IM-5Int, in terms of average throughput, with the exception of 802.11n, which had 280 Kbps and 36% PDR. The best performance and throughput, obtained by IM-3Int, were twice that of 802.11ac (the best homogeneous performance).

For the five-node scenario, the IM-2Int experiment presented a throughput of 1473.26 Kbps with 36% PDR, the IM-3Int experiment presented 2516.20 Kbps of throughput and 97% PDR, the IM-4Int presented 1418.36 Kbps of throughput and 94% PDR and the last one, IM-5Int, presented 10332.44 Kbps of throughput and 94% PDR. In this case, the experiment that presented the best performance, in terms of throughput and PDR analyzed together, was IM-5Int; which, if we consider the performance obtained in all the other metrics seen before (even those not presented)—for example, the best performance in terms of number of packets Figure 30(B) and average end-to-end delay Figure 32(B)—was the best when we analyze the set of APP metrics together.

Analyzing the homogeneous performance for the five-node scenario seen in Figure 33(B2), all of the interfaces presented better performance than those of the IM settings. The exception was IM-5Int, which present 1.200 Kbps more than the 802.11ac, which had the best homogeneous performance.

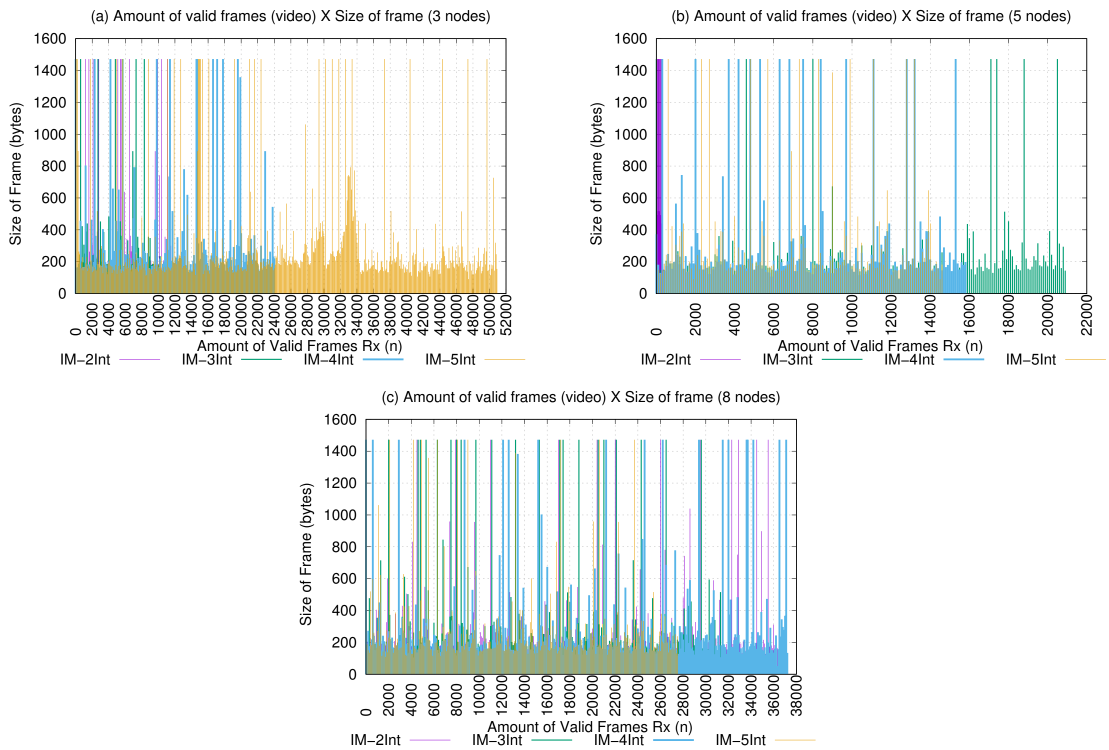


Figure 34 – Number of video frames successfully received by the network, considering the size of frames per each IM experiment: (A) Three-node scenario; (B) five-node scenario; and (C) eight-node scenario.

For the eight-node scenario, the IM-2Int experiment presented a throughput of

1247 Kbps with 97% PDR, the IM-3Int experiment presented 2967.02 Kbps of throughput and 96.67% PDR, the IM-4Int presented 3436.37 Kbps of throughput and 96.10% PDR and the last one, IM-5Int, presented 3122.05 Kbps of throughput and 94.21% PDR. In this case, the experiment that presented the best performance, in terms of throughput and PDR analyzed together, was IM-4Int; however, this experiment was not the best in several other metrics, as can be seen in Figures 30(c), 31(c), and 32(c).

Regarding homogeneous performances (Figure 33(C2)), all of the interfaces presented better performances than in IM settings. The best one, 802.11ac, presented 8700 Kbps, which was almost three times higher than IM-4Int (with the best throughput performance). So, for the eight-node scenario, the use of IM does not imply better throughput than the interfaces applied homogenously. In these scenarios, the IM increased end-to-end delay, directly affecting the throughput.

When analyzing according to the mission application, if the number of quality packets delivered is the most important feature, all the IM settings and (with the exception of 802.11p) all the interfaces applied homogeneously presented good performances; however, if it is necessary to find a configuration with higher throughput, IM-3Int (for a three-node scenario), IM-5Int (for a five-node scenario), and 802.11ac (for all scenarios) would be the best IM settings and interfaces to apply. An important observation is that, although 802.11p presented the best performance, in terms of number received of different ToS, delay, and latency, it did not present better throughput and PDR, as can be seen from Figure 33(C2). This highlights the importance of the definition of metric requirements in network deployment.

Figure 34 presents the number of valid frames (sent by the source node and confirmed by the sink node) by the size of frames. Thus, in this experiment, only the AC_VI ToS was propagated by the APP layer in the network and the nodes send video frames continuously, compounded as a video trace file. For the three-node scenario, the number of frames obtained under IM-5Int was higher than in the other experiments, with more than 50,000 frames arriving, which describes a higher volume of data propagated in this experiment. The other experiments presented similar performance, in descending order (from the largest to the smallest volume): IM-5Int, IM-4Int, IM-3Int, and IM-2Int. In this case, the use of IEEE 802.11ax interfaces in IM (5Int, 5 GHz; and 4Int, 2.4 GHz) presented higher frame volumes.

For the five-node scenarios, the experiments sorted in descending order (from the largest to smallest volume of frames propagated) were as follows: IM-3Int, IM-4Int, IM-5Int, and IM-2Int. In this case, the use of IEEE 802.11ac interfaces (IM-3Int) in IM-2Int (the worst performance) led to an increase of 200 times the number of valid frames received, reaching the best performance. This validates the idea that it is not enough to just add more interfaces but, instead, to evaluate which ones might actually be useful to increase the reliability and quality of network transmissions.

Finally, in the eight-node scenario, the descending order was as follows: IM-4Int, IM-2Int, IM-3Int, and IM-5Int. Here, once more, IM-5Int was not the best but, instead, the worst-case for video frame transmissions, highlighting the conclusion obtained for the five-node scenario.

Thereby, two set of conclusions were obtained from these experiments: a) To establish a network with reliable connections and reliable message delivery in UAV networks, it is necessary to verify which metric will be used to analyze the quality of message transmissions and receptions (presented in this work as number of packets and PDR), as well as which type of service will be shared by the nodes of the network (presented in this work as the number of packets, classified into access classes); b) Taking into consideration the mission requirements, such as delay tolerance (end-to-end delay, in this work), what are the limits of latency for a good transmission without generating continuous disconnections (latency), and how often do the nodes need to communicate (flow of messages, in this work)?

7.1.2 MAC and PHY Results

Figure 35 presents the results of the performance experiments, considering the average latency obtained under distance variation. For this experiment, the delay measurements occurred until the maximum distance possible between nodes was reached. The x-axis presents the number of samples obtained (network productivity) during the experiment, versus the average distance reached between the UAV nodes. Thus, more dots in the curve, indicates more packets propagated by the network using a determined IM setting.

For the three-node scenario IM performance, the IM-4Int experiment presented the best performance, in terms of productivity versus distance reached by nodes. Of course, if the distance increases, the delay also increases, considering the free-space propagation delay. The IM-4Int experiment remained between 200–250 ms, when a 300 ms of delay peak is verified with 100 m distance. The reception of some ToS packets could be affected with a delay greater than 200 ms (reached at 70 m); for example, for high quality video transmissions, the maximum delay is 150 ms, as mentioned previously. The worst case was IM-2Int, because the delay performance was close to 250 ms with a smaller number of samples.

Considering the performance achieved by interfaces applied in a homogeneous manner, all the interfaces presented an increase of 250 ms maximum of delay with an increase in distance between nodes. When the nodes reached 70 m, the delay was maintained at this rate, with the exception of the 802.11n interface, which maintain the link between nodes up to 100 m with 350 ms of delay (high delay, unfeasible in multi-UAV scenarios). In this case, the best performance was obtained by 802.11p, which maintained the multi-UAV communication link with 280 ms delay at 70 m between

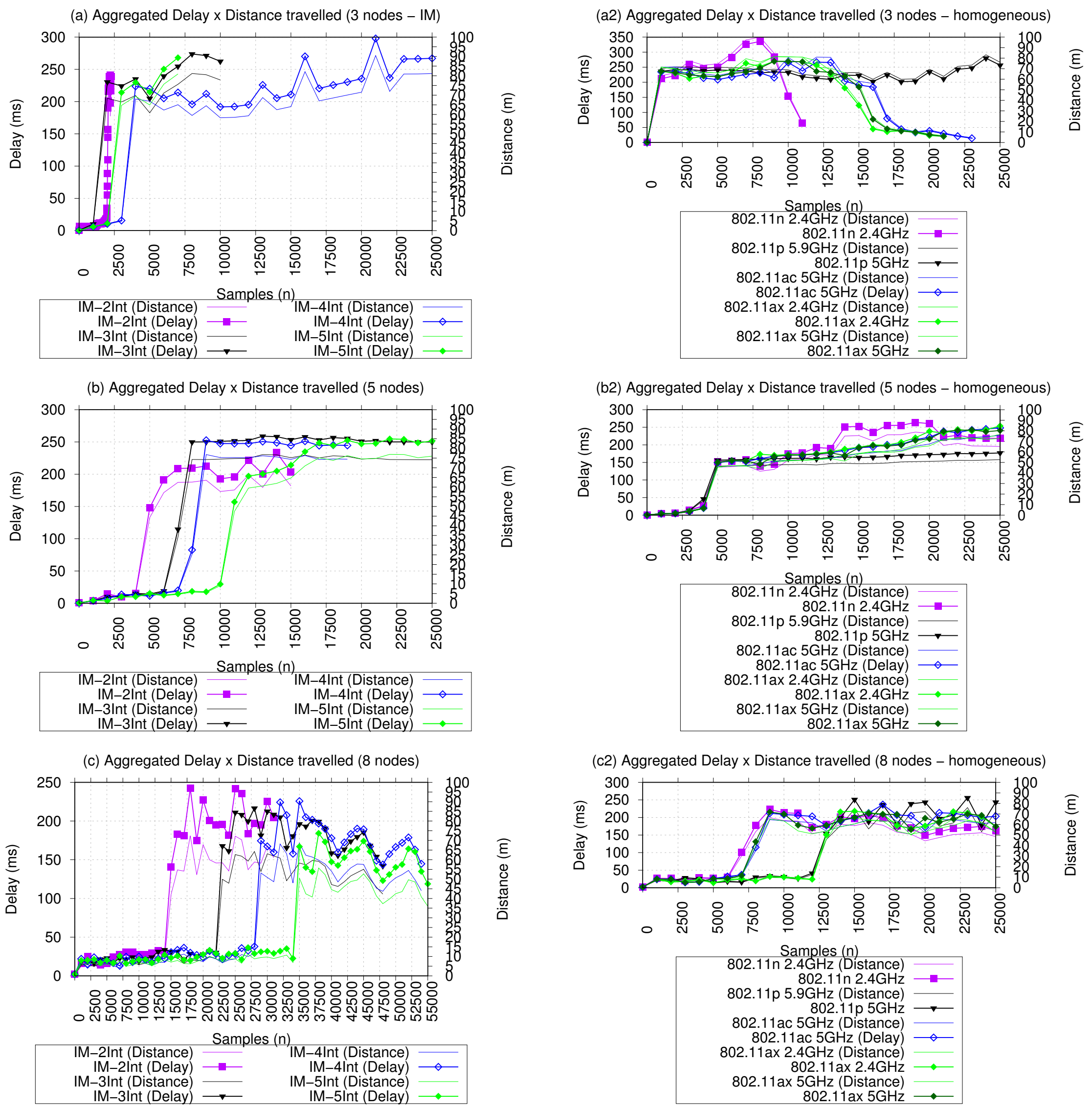


Figure 35 – Aggregated delay and distance traveled by UAVs for each IM experiment: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

nodes, allowing for 25,000 samples to be received. In contrast, the maximum samples received by the other interfaces was around 22,500, with average distance of 60 m. Once more, the worst behavior was that of 802.11n using 2.4 GHz, receiving only 11,000 samples at 260 ms when the distance is 70 m.

In comparison with IM different settings, using the best performance IM-4Int and 802.11p, the IM was capable of maintaining the communication link with a maximum of 260 ms delay up to 80 m distance between nodes, with 25,000 samples.

For the five-node scenario, IM-5Int presented the best performance, with a delay of around 15 ms when the nodes had distance up to 15 m and generating 10,000 samples, with an ascendant curve formed between delay versus distance: the delay reached 250 ms with 10000 samples at 75 m of distance between nodes, allowing for a higher number of samples with lower delay aggregated. The worst case was observed in the IM-2Int experiment, which presented an ascendant curve between 2500 to 5000 samples reaching 200 ms of delay with a maximum number of 15000 samples. A similar performance was obtained by IM-3Int and IM-4Int, highlighting the IM-3Int experiment which started with an increase in delay with 6000 samples reaching 250 ms of delay, maintaining communication up to 84 m.

Figure 35 (B2) presents the homogeneous performance in the five-node scenario. All of the interfaces presented an increase of 150 ms when the distance was more than 50 m between nodes, presenting 5000 samples. In this case, using 50 m as a reference distance, the IM presented performances of 120 ms (IM-3Int), 80 ms (IM-4Int), and 30 ms (IM-5Int) delay, up to 55 m, with > 6000 samples, with the exception of IM-2Int experiment, which presented the worst performance, in terms of number of samples and link maintenance. The 802.11 ac, 802.11 ax 2.4 GHz, and 802.11 ax 5 GHz experiments presented the best performances, reaching 80 m with 250 ms maximum of delay in homogeneous scenarios.

For the eight-node scenario, IM-5Int presented the best performance, in terms of delay reaching 180 ms maximum in 75 m for 37,500 samples; as well as in terms of the number of samples being higher than 55,000. The IM-4Int experiment presented the second-best performance, in terms of the number of samples (53,000). In terms of the delay, this experiment showed two peaks at 225 ms for 32,500 and 35,000 sample, compared to IM-3Int, which presented 210 ms as a maximum delay at 47,500 samples.

Figure 35(C2) presents the homogeneous performance in the eight-node scenario; in which, the interfaces allowed for delay samples up to 70 m of distance between nodes with low delay fluctuations and a maximum of 200 ms delay. The 802.11 p experiment presented peaks at 250 ms up to 70 m. In this context, the interfaces applied in a homogeneous manner presented better performance, in terms of delay (several samples with 200 ms) and communication range between nodes (70 m), than IM interface combinations in more sparse scenarios. The IM allows for a communication range of up to 60 m, presenting some delay peaks of 245 ms, but the adaptability of the IM solution allowed the network to receive around 55,000 samples, compared to 25,000 in homogeneous experiments. This implies more communication time between nodes.

Analyzing the three scenarios, it possible to see that, close to 100 m between nodes, more delay peaks were verified; this could indicate a possible communication range limit of IM employed with the interfaces used by this paper. An interesting phenomenon was also observed, considering the increase of density of nodes in the network. With more interfaces and nodes applied in the scenario, a lower average delay and more samples were achieved, until starting the ascendant curve, as seen when comparing Figure 35(c) against Figure 35(a). The same behavior occurred for the homogeneous experiments.

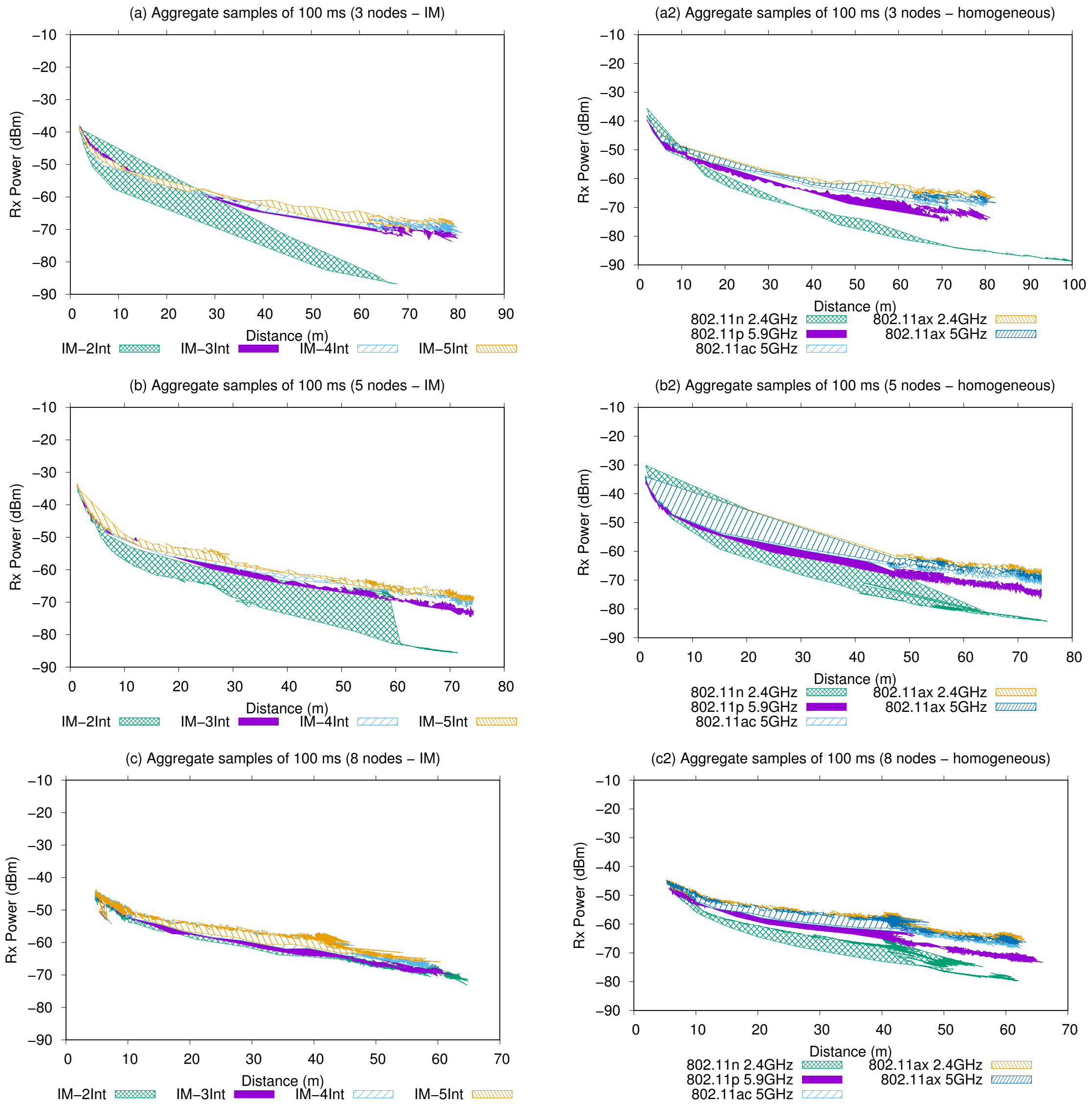


Figure 36 – Aggregated samples of Rx Power performance in intervals of 100 ms for each IM experiment: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

Figure 36 presents the aggregated samples of Rx power obtained by nodes during the trajectories. A sharp curve describes the intensity of samples received of average signal power obtained by the nodes. Of all the scenarios, IM-5Int presented the best performance, maintaining reception between -40 dBm and -70 dBm, which represents a good reception power for 802.11 protocols.

The IM-2Int experiment was the worst combination for three- and five-node scenarios, although presenting -70 dBm to -88 dBm between 30 m to 70 m, with a larger interval of reception of signal packets (the nodes become less time-audible). In this way, the IM-2Int experiment presented a more sparse curve.

The stable behavior obtained from IM-3Int, IM-4Int, and IM-5Int experiments shown in the three-, five-, and eight-node scenarios, with less samples fluctuations, make these set-ups more suitable for networks composed of high-mobility nodes with different speeds, leading to higher reliability in transmissions.

Figures 36(a2–c2) present the performance of IEEE standards applied in a homogeneous manner. These figures highlight the IM attempts to define the best standard to apply, observing that the IM experiments presented more full curves (i.e., more beacon frames received). In terms of range, the IM presented a similar range of communication as homogeneous experiments. This behavior was expected, as the IM preserves the standard protocols in default mode. In case of homogeneous performance, 802.11n presented a high signal degradation above 40 *m* distance between nodes, while the other interfaces were capable of maintaining the reception power between –50 dBm to –70 dBm up to 80 *m* for three-node, up to 75 *m* for five-node, and up to 65 *m* for eight-node scenarios. Therefore, increasing the number of nodes caused a decrease in the communication link intensity.

Figure 37 presents the average aggregated loss obtained by nodes during the trajectories. In this case, a greater number of dots describes a greater amount of loss samples obtained by communication attempts between nodes, reflecting the results shown in Figure 36: for each sample of Rx power, there exists a sample of loss obtained. With the loss results, it is possible to evaluate how much the nodes were inside the communication range, as described by the presence of dots: with more dots present, the lower the quality of the signal received.

For the three-node scenario, IM-2Int presented 60–100 dB of signal attenuation loss, which indicates an excellent performance, up to 100 m of distance between nodes; but at the cost of fewer transmission attempts between them, as identified by the smaller number of dots represented in Figure 37(a). This behavior is not ideal for missions that need to maintain continuous transmissions in the network. In this case, IM-3Int presented the best performance, considering the quality of reception with samples between 50–80 dB, allowing for reception up to 90 m between nodes. For homogeneous experiments (Figure 37(a2)), 802.11n presented the same behavior as IM-2Int, but with more samples received. This indicates that, in fact, the 802.11n standard suffers in high-mobility scenarios, reaching >100 *dB* loss in the three experimental scenarios. 802.11ax 2.4 GHz presented the best performance when evaluating the loss intensity, the amount of loss samples, and the distance reached.

For the five-node scenario IM-3Int, -4Int, and -5Int presented similar performance, highlighting IM-3Int in terms of low density of dots, which represents less lost samples

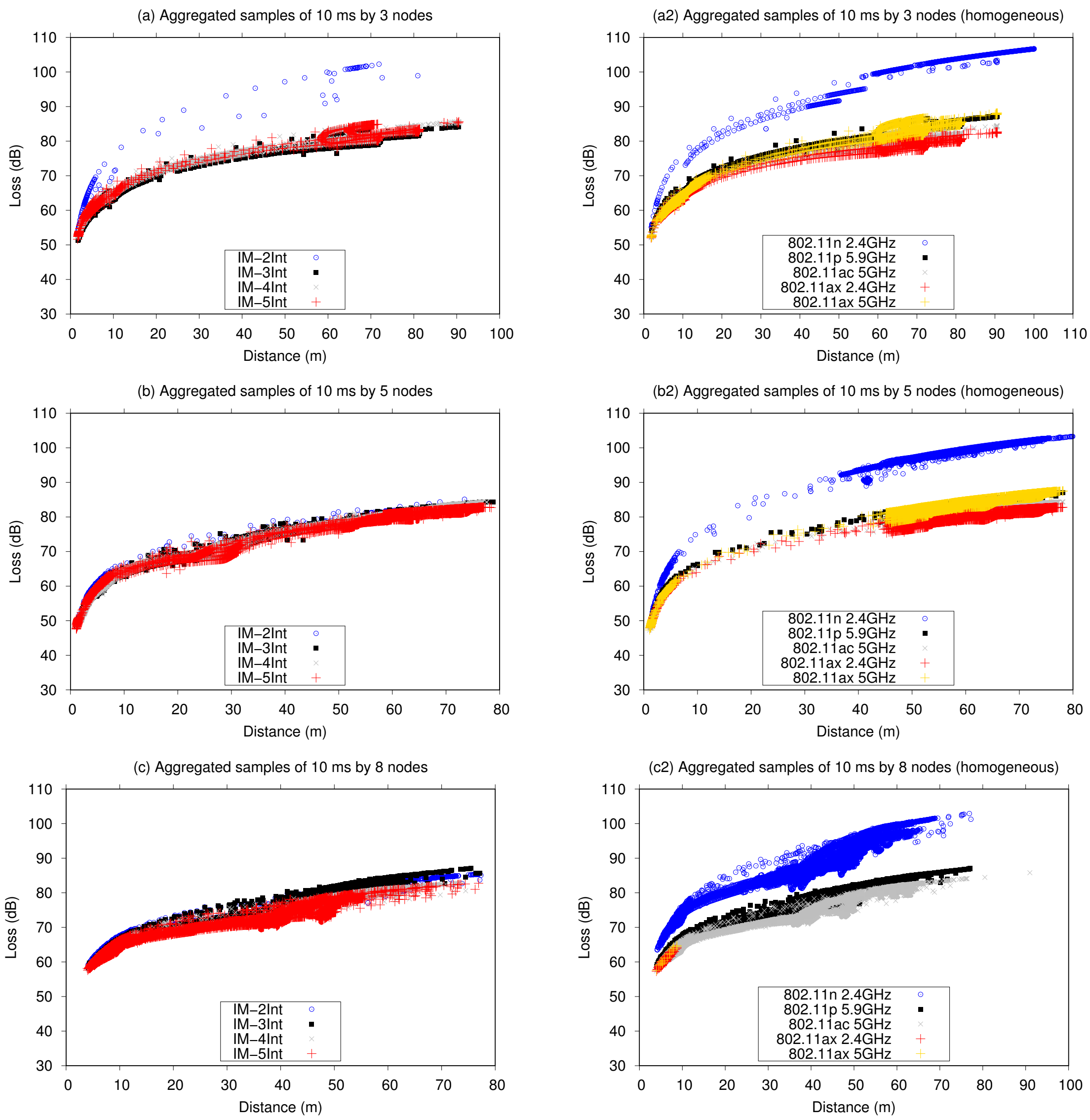


Figure 37 – Aggregated samples of Loss performance in intervals of 10 ms per each experiment: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

received, in terms of the loss indices. In this case, balancing between loss dots and levels, in ascending order of number of samples, we have: IM-2Int, IM-3Int, IM-4Int, and IM-5Int. The same order occurred for the eight-node scenario, indicating that IM-2Int was the best, in terms of loss samples *versus* loss level, allowing for communication up to 78 m while maintaining loss indices up to 80 dB. In this case, 802.11p presented the best performance, in terms of loss intensity and number of samples, considering the homogeneous experiments, as shown in Figure 37(b2). The linear curve presented in the loss experiments represents more stability in the link, maintaining a loss level up to 80 dB (theoretical limit of IEEE standards loss, considering 100 *m* distance between nodes.)

For the eight-node scenario, in terms of homogeneous performance, the interface 802.11ac presented the lowest maximum loss level of 75 dB, while 802.11p presented a more linear curve, with more loss samples received. 802.11 n presented the worst performance, showing fast signal degradation.

It important to note that, for 802.11 communications with up to 100 m between nodes without relays or repeaters in a free-space transmission, the theoretical calculated loss is 80 dB (GEIER, JIM, 2010; RIBEIRO, Laura Michaella Batista; MÜLLER; BUSS BECKER, 2021). Observing all graphs presented in Figure 37, with the exception of the IM-2Int experiment for the three-node scenario, all IM combinations obtained loss values up to theoretical one, but with shorter distances (75 *m*, 60 *m*, and 55 *m* for three-, five-, and eight-node scenarios, respectively.

Figure 38 presents the performance of RSSI and Noise aggregated samples received during the experiments. This result highlights the background noise received by nodes. Here, it is possible to see the time interval in which the signal strength received by the nodes is decreased with increasing distance between them. We use, as reference, the maximum duration of the experiments, considering the trajectory from the departure of the UAVs (start point) up to their arrival, of: 132 s (three nodes), 140 s (five nodes), and 150 s (eight nodes).

Thus, it is clear that, in all scenarios, that if a UAV is closer to their maximum of distance from the base, a significant decrease in RSSI will be observed. In all scenarios, this time interval is approximately half of the experiment, where the RSSI curves describes descendent curves.

For the three-node scenario in Figure 38(a), IM-4Int took longer to suffer the impacts of distance decreasing the RSSI, maintaining -64 dBm after 70 s. The second experiment that took a longer time to present RSSI decrease was IM-3Int (after 60 s). These two experiments also showed a higher sample volume, with thicker lines.

In general terms, all of the experiments presented very good RSSI, in the range of –32 to –68 dBm, for the three-node experiment scenario, with controlled noise in range of –92 to –96 dBm.

For the five-node scenario, in the first half of the simulation, a significant decrease in RSSI was observed also, with IM-2Int, IM-3Int, IM-5Int, and IM-4Int in ascending order of RSSI decrease. For this scenario, IM-4Int maintained the received signal strength in the range –36 to –64 dBm. In this scenario, the presence of intermediary waypoints implied more noise detected after 60 s, as these waypoints cause more concurrence in the frequency spectrum, as the UAVs remained within each others communication range longer, presenting UAV trajectories with 35 m distance between nodes. Furthermore, the noise range obtained did not imply a significant decrease of signal reception.

For the eight-node scenario, the best performance was in the IM-5Int experiment, which presented less fluctuations of the RSSI, ranging from –48 to –64 dBm, thus maintaining communication with an excellent RSSI, even with more noise received (–92 dBm). All of the IM experiments allowed for greater connectivity of the nodes during the flight with an extensive number of samples received.

This suggests the better performance obtained by heterogeneous IM in scenarios with more sparse routes (with distances greater than 35 m between nodes), when we compare the performances under the UAV routes defined in the three- and five-node scenarios. The network is probably more susceptible to co-channel interference or medium sharing background noise under shorter distances.

The intensity of the connection in levels can be verified from the result obtained by the RSSI network minimum, subtracting its average values of –52 dBm (three nodes), –60 dBm (five nodes), and –56 dBm (eight nodes) from the average noise obtained: –94, –92, and –96 dBm, respectively. Therefore, on a scale of 0 to –100 (with 0 meaning the best signal possible and –100 indicating the worst), the IM presented an RSSI value of around 40, which is generally considered excellent for most kind of network ToS.

Regarding the homogeneous performances for three-, five- and eight-node scenarios, it can be seen that a linear and descendent curve of decreasing RSSI was obtained for the five interfaces in the three scenarios. The IM settings allowed for smoothing in the descendent curves, maintaining the connections with –52 dBm and –44 dBm of reception (IM-3Int and IM-4Int experiments, respectively) in the first half of the experiment, compared to –64 dBm for the homogeneous 3-node scenario experiments.

The same behavior was seen in the five- and eight-node scenarios, where the IM setting maintained –48 dBm up to 65 s. In this case, for homogeneous performance within 50 s of the experiment, the RSSI decreased to –68 dBm for the five-node scenario, and within 60 s for the eight-node scenario.

In all experiments, when passing 60 s (i.e., half of the experiment), the video streaming started and the curves presented a rapid decrease of RSSI, reaching between –68 dBm and –72 dBm. In conclusion, the AC_VI ToS packets require more data transmissions per second: the curves present an apparent thickening, which implies more samples of RSSI causing stress in the communications link. This causes degradation of the signal, in terms of coexistence of transmissions, describing also thicker noise curves in the second half of the experiment. The tdicker curves describe more incidence of noise sensed during the experiments. In general, the IM presented lower incidence with lower variations, which can be seen more clearly when comparing the performances for eight-node scenarios up to 20 s.

In general, the Noise was maintained with maximum of –92 dBm, which represents a low incidence of medium noise sensed by the network (considering the –94 dBm noise floor).

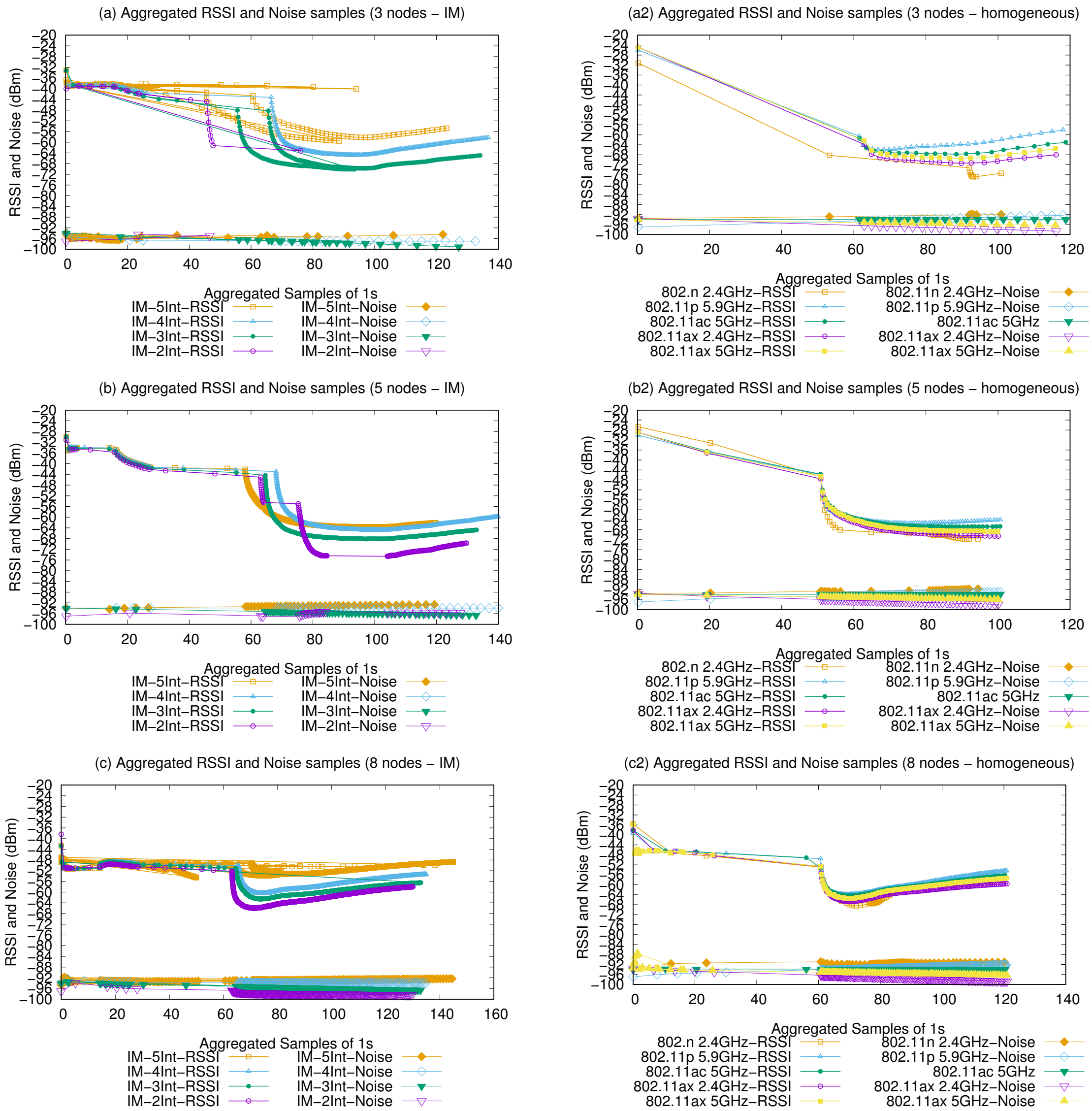


Figure 38 – Aggregated samples of RSSI and Noise performance in intervals of 1 s per each experiment: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

Figure 39 presents the RSSI obtained by IM validations. In this case, the curves represent the RSSI variations when the IM chooses a new communication interface (represented by samples of 0 dBm). Here, it is possible to see the number of IM interventions during the experiment. In this case, this experiment demonstrated which IM experiment led to less changes in the network, and how much this can imply the degradation of network performance. It is noteworthy that these samples were collected only in the IM validation intervals (1 s), and the 0 dBm samples do not represent total disconnection from the network; that is, a user would not be aware of the interface change. Considering the interval of IM switching, and the use of the same IEEE protocol 802.11, the trade-off of a UAV connection timeout and its reload with a new interface is acceptable because the last better performance is kept.

Analyzing all scenarios, the three-node scenario presented a greater number of interface switching, where the IM-2Int experiment required more switching than the IM-5Int experiment. These variations demonstrate that the IM attempts to adjusts the network for better performance, but a greater number of switches could imply less signal samples as *beacon frames*; this type of traffic is composed of short-packets, which means low recovery rate by the node receiver. This behavior can be seen in Figure 38(a), where IM-2Int presents a thinner curve with a broad loss samples interval, as seen in Figure 37(a).

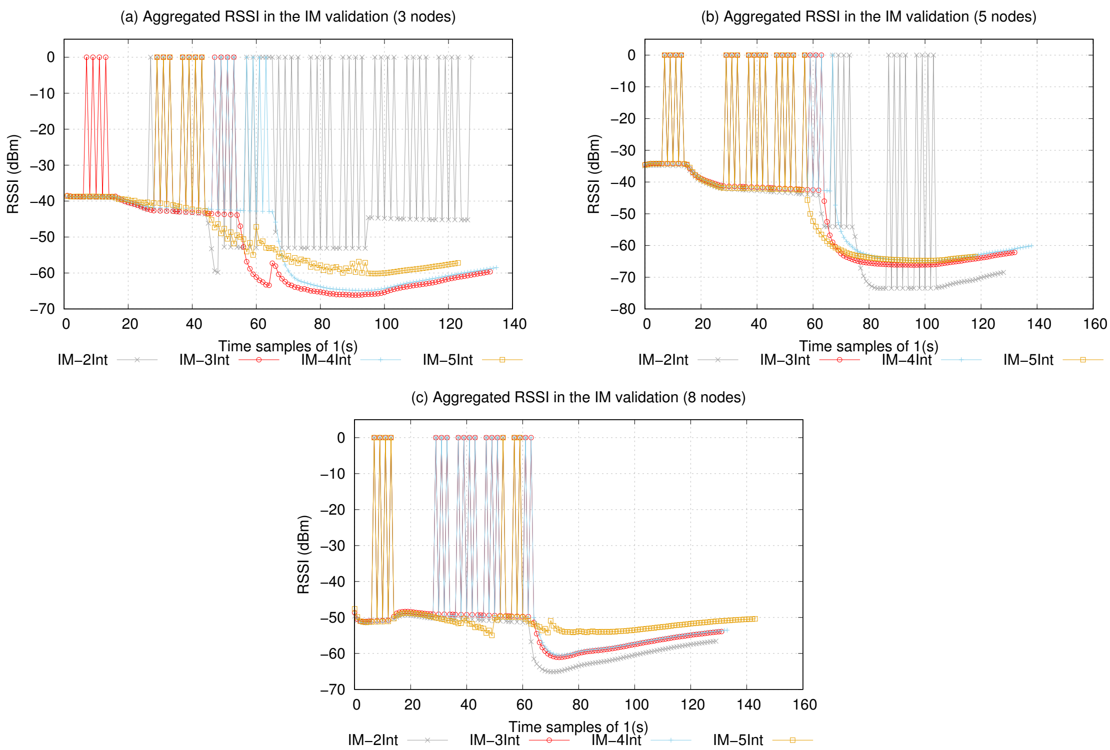


Figure 39 – Aggregated samples of RSSI performance in intervals of 1 s, considering the IM validation effects per each IM experiment: (A) Three-node scenario; (B) five-node scenario; and (C) eight-node scenario.

For the five-node scenario, IM-2Int also presented more interface manager switchings, describing attempts to maintain the RSSI at satisfactory levels (up to –70 dBm). The performance, in terms of signal frames, is verified in Figure 37(b). The best performances in these scenario, sorted in descending order of RSSI performance, were: IM-4Int, which allowed communication up to 141 s with average RSSI of –65 dBm; followed by IM-3Int, with the same RSSI average up to 134 s; and, finally, the IM-5Int experiment, which kept the RSSI at –62 dBm up to 121 s.

For the eight-node scenario, the best performances were in the order of: IM-5Int, as it preserved the RSSI level up to 141 s at –50 dBm; while IM-4Int and IM-3Int presented similar performance, maintaining the RSSI level of –55 dBm up to 130 s. The worst case was also verified in the IM-2Int experiment, reaching –65 dBm up to 126 s. In terms of number of IM interventions (switches) in all scenarios, the IM-2Int experiment presented more impacts in the aggregated RSSI during its switches and the IM-5Int implied less effects. In this case, more interfaces implied a lower number of network interventions.

Table 12 of Appendix A shows the IM-aggregated decisions with interval of 1 s. The IM decisions are composed of the aggregated average of decisions, of which the aggregate decision is composed, with IM considered in most decisions.

Figure 40 presents the SNR obtained by the IM experiments for the three experimental scenarios by simulation duration. The SNR indicates the effective signal sensed by receiver nodes. For the three-node experiment, the best IM performance was obtained by IM-3Int, reaching 0.7 when the ToS changed to video streaming (60 s). In this scenario, with the exception of the 802.11n 2.4 GHz experiment, which presented 0.75 at 50 s, all other interfaces presented an increase, with peak of 0.7 at 60 s. The homogeneous performances in this scenario presented a faster increasing of SNR than the IM experiments, but at the cost of smaller volume of samples (slimmer curves).

For the five-node scenarios, the SNR reached 0.78% of signal effective SNR in 80 s, against 0.75% obtained by 802.11n 2.4 GHz in the homogeneous experiments. Furthermore, the homogeneous interfaces presented SNR > 0.5 earlier than the IM experiments; once more, the number of samples obtained in the IM experiments (more thicker curves) were higher than those in the homogeneous performances. The SNR was calculate per sample, such that the behavior of IM experiments could have been affected by the volume of samples.

For the eight-node scenarios, all of the IM settings presented a decrease of 0.025 between 0 s and 20 s; where, according to Table 12 of Appendix A, the IM switched sometimes from IEEE 802.11p 5.9 GHz to interface 802.11ax 2.4 GHz. However, after 60 s, an increase by 0.25% occurred when the IM choose IEEE 802.11p for the most of nodes, in order to maintain this rate. A similar behavior occurred in five-node scenarios when IM-5Int had an early increase of SNR in the 60 s sample; additionally, according to Table 12, the interface manager switched between these same interfaces. For both scenarios, the best performance was obtained with IM-2Int, which reflects the performances of 802.11n and 802.11p, as seen in Figures 40(b2) and (c2). The worst performance was obtained by IM-5Int in all experiments, which presented very high fluctuations in the IM setting experiments. This could represent that the interface added in this IM setting inserts more instability in the signal caused by shared medium with other interfaces operating at the same frequency. But, this behavior was also seen between 0–20 s in the eight-node scenario homogeneous performance for 802.11 ax 5 GHz and 802.11 ac 5 GHz, which could represents a protocol feature in node association of these protocols. These curves are both plotted in the same color, in order to clearly verify the co-channel interference and show that the 802.11ax 5 GHZ interface presented more susceptibility to interferences than 802.11ac 5 GHz, which presented more stable behavior.

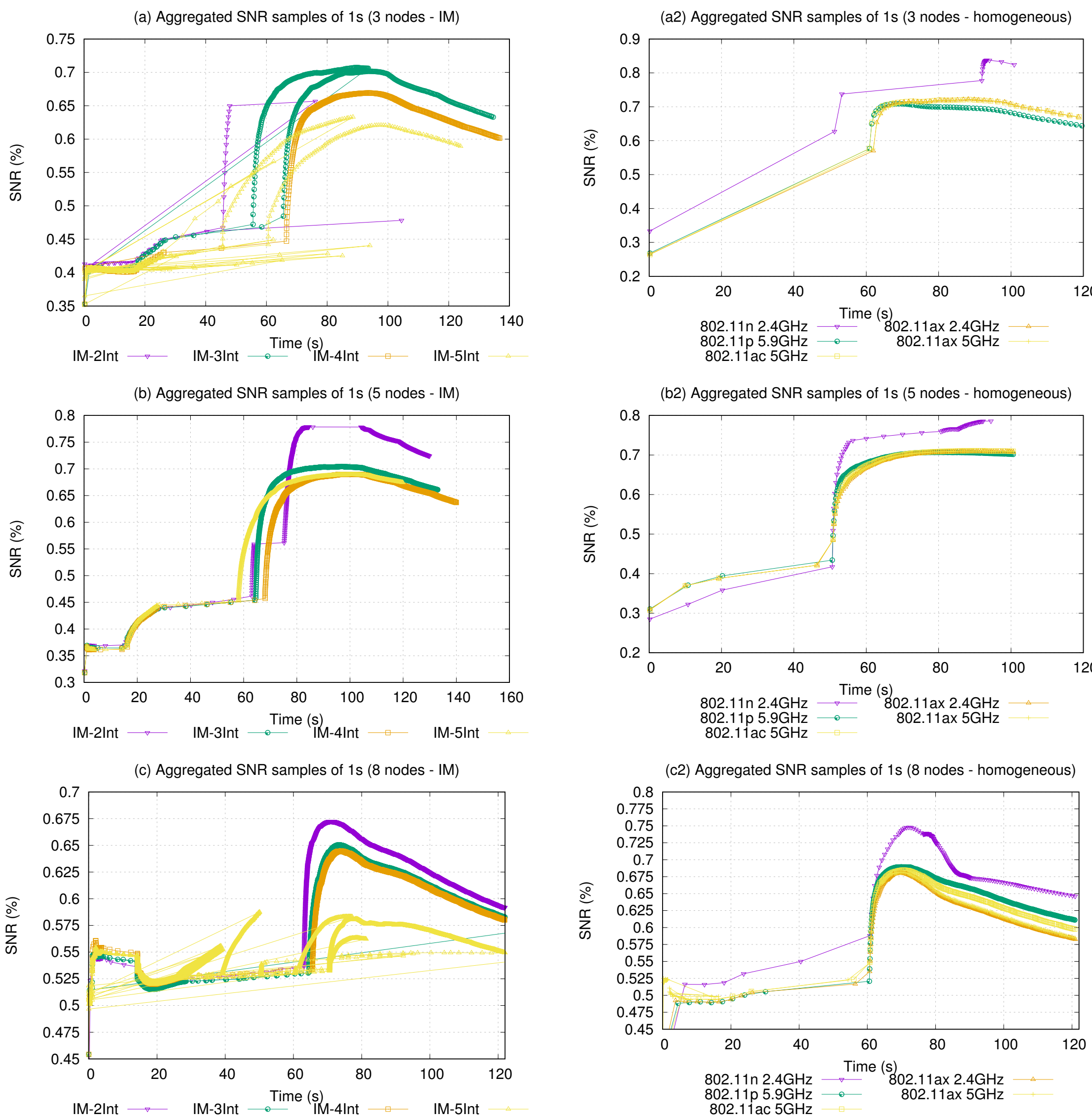


Figure 40 – Aggregated samples of SNR performance in interval samples of 1 s per each experiment: (A) Three-node scenario IM performances; (A2) three-node scenario homogeneous performances; (B) five-node scenario IM performances; (B2) five-node scenario homogeneous performances; (C) eight-node scenario IM performances; and (C2) eight-node scenario homogeneous performances.

The interfaces 802.11p 5.9 GHz and 802.11ac 5 GHz presented good SNR performances in these homogeneous scenarios, as well as when used in heterogeneous

IM combinations, providing better signal reception efficiency. Thus, these combinations of interfaces could be favorable for better transmission rates, considering similar application scenarios. Such switches are a very powerful feature of heterogeneous networks to maintain or increase the communication intensity, especially if the IM or a software-defined radio has different frequencies available as a resource. In terms of the number of samples, packets, and flow of messages, the IM was capable of presenting better performance, improving or maintaining the network connectivity to avoid load fluctuations and signal interruptions.

7.2 FINDING IM CONSTRAINTS

This section present the results obtained by scenario with 2 UAVs, where one stay around of start point and the other reach up to 1 km of distance from this point, as seen in Section 5.2.2 in the Figure 17.

Figure 41 shows the reception power (Rx Power) per distance reached between UAVs during their paths. This Figure also describes the communication range maximum obtained by IM , using the interfaces applied.

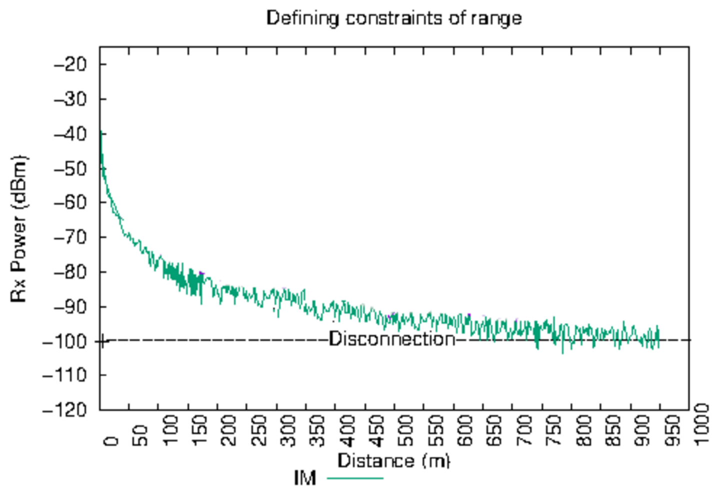


Figure 41 – Rx power (dBm) per distance reached between nodes, defining communication range constraints.

In this one, using the classification of received signal intensity for Wi-Fi interfaces, it means that a signal received between –30 dBm to–60 dBm describes the best performance possible, and level signals with values < –90 dBm represents total disconnection or a communication drowning in the noise floor.

In this case the IM was verified using the five interfaces (IM-5Int). In this one, the IM presents a very good signal reception up to 100*m*, with curve between –60 dBm to –70 dBm of rx power. Analysing the interval of distance between 100*m* up to 200*m*, the IM performance reach –90 dBm, which means basic connectivity with high rate of packet loss.

The stretch between 200 and 450*m* represents the attempts of IM to recovery the traffic searching to get –80dBm at least of reception. The IM experiment reached –90 dBm in 300 *m* which represents several intervals of disconnection. After 500 *m* the IM presents some intervals of reception of beacon frames up to 750 *m*, where it is not possible to get any guarantees of transmission, reaching the level of total disconnection in 550 *m*.

Some signal is sensed after 600 *m* by IM experiment but basically compound by noise. So, the IM have a constraint of 250 m of distance between nodes. After that there are no guarantees of service. The interface 802.11 p (one of used in IM-5 Int set) present the theoretical range of up to 1 km in V2V communication, but clearly it is not verified in this scenario.

Figure 42 presents the loss caused by FSL (Free Space Loss) during the experiments. The performance describe the direct proportion of increase the loss per increase of distance between nodes, highlighting the communication range limits of the solution proposed by this thesis.

In the sample of 500 m is reached 100 dB of signal loss, considering that the transmission power of nodes is about 16.02 dBm, this loss will imply in –83.98 dBm of theoretical reception power calculated by subtraction of tx power and loss at determinate sample. Using the Figure 41 as reference to validate the rx power at 500 m sample, IM and IM+Naive present around –95 dBm of reception. This describes that the communication link between nodes is affected by other losses than FSL, like coexistence of beacons from the other interfaces that is not in use.

This brings as conclusion that the IM ausing the WLAN interfaces applied allow a connectivity with minimum requirements up to 400 m as the maximum distance between nodes, and to give better results with QoS guarantee up to 250 m. After 400 m, the QoS and connectivity are very affected between nodes, and the packet delivery reliability is affected having any guarantee of service.

Other metrics that highlight the capacity of communication of the network is verified in Figure 43. This Figure shows the delay calculated by each amount of 1000 packets received. In this one, it is very clear that the delay increase with the distance between nodes, and after 600 m the delay obtained is not viable for this context. So, in the Figure also is possible to see the interruption point of the communication at 420 m reaching 1500 ns of delay. Probably, this is the constraint of delay that allows some valid communication. After this point, the IM experiment presents a more sparse interval of reception delivering 800 samples presenting delay of 3500 ns, approximately.

In general terms, the IM presents good performances up to 250 m of the distance between nodes and up to 400 m with some restrictions on real-time transmissions (voice and video), with these interfaces defined. This represents more than twice the performance obtained by the same interfaces applied in a homogeneous way.

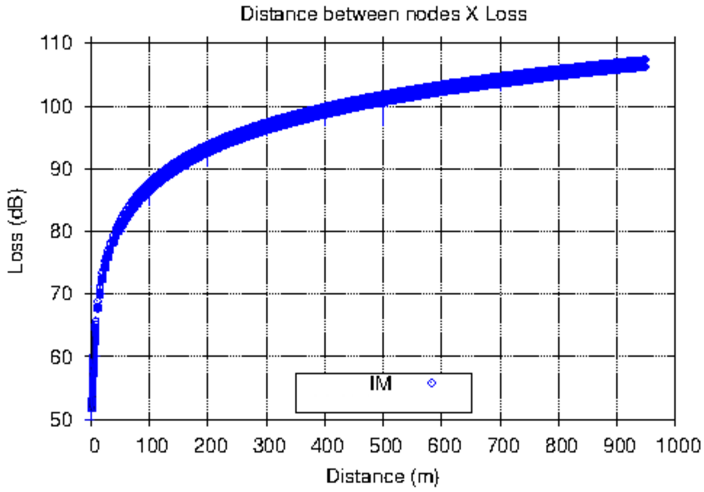


Figure 42 – Loss versus distance between nodes.

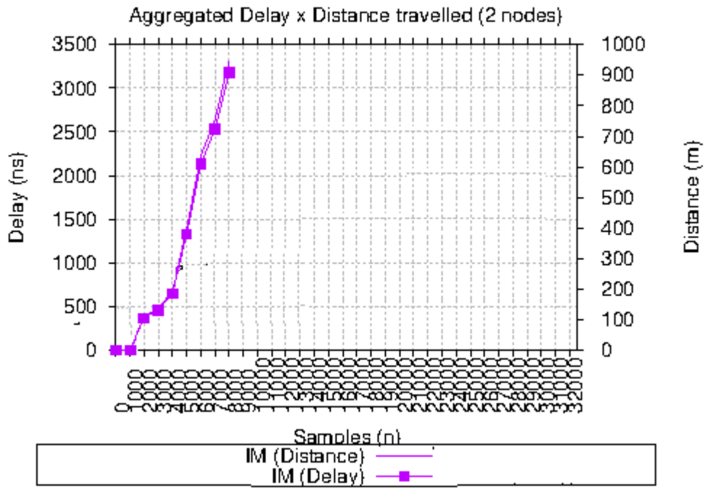


Figure 43 – Delay (ns) measured by packets samples in relation to distance between nodes.

7.3 FINAL REMARKS

This chapter presented an extensive analysis of different communication interfaces combinations applied in a heterogeneous interface manager. An use of a heterogeneous communication presented best performances in terms of improved reliability and quality of communication for UAV networks.

In order to propose a validation regarding the type of service, packages composed of different classes of service were sent throughout the execution of the experiments, to provide analysis regarding the different types of service that can be applied in these networks to meet the objectives of a mission.

The main conclusion is that depending on the type of service to be carried by the network, different network requirements are necessary and, to meet these requirements with reliable connections and quality of service, it is necessary to validate which are the main network metrics (latency, throughput, rx power) that will culminate in the best performance of transmission.

The IM is capable to maintain the link quality up to 250 m of the distance between nodes, and up to 420 m with some uncertain of delivery using the interfaces defined in this work. Of course, if other interfaces these constraints can change.

Another important conclusion is that, depending of interfaces applied in a heterogeneous communication, a greater number of interfaces added to nodes does not imply in better performances, but which combinations can be more propitious for a given transmission considering the mission constraints.

The next chapter will present the general conclusions obtained by this thesis, highlighting the main contributions and presenting future directions.

8 CONCLUSIONS

Collaborative missions or missions with shared tasks that employ wireless multi-UAV networks require higher link stability and special attention to the reliable delivery of messages. An important part of this challenge relates to the wireless interface technology that is used. Studies were conducted to make comparisons of some wireless interfaces performances in UAV networks, evaluating behavioral characteristics of each protocol, including the definition of most important metrics to validate the reliability and quality of communication. These studies highlight the different performances obtained by interfaces for different access classes services (AC_BK, AC_VI, AC_VO, AC_BE).

In this Ph.D. thesis, a heterogeneous distributed network solution was presented as a contribution to improve the U2U connectivity and message delivery reliability. The solution was capable of dynamically define the best communication interface to be used when more than one option is available, working by dynamically evaluating parameters collected from the medium.

Studies were also performed to define and evaluate several evaluation networks metrics from PHY, MAC, and Application layers, where the IM has been present as a suitable behavior to compose an adaptive solution. Different combinations of wireless interfaces commonly applied in UAV networks were employed to evaluate and highlights the performance differences according to network traffic. Based on the performed studies it was observed that more interfaces do not imply better results, but what interfaces were applied according to requirements of each type of service (data, voice, and video) needed by the mission.

Some close-to-reality simulation scenarios were constructed with the use of different simulation tools, compounding 2 D and 3 D experimental setups. These experimental scenarios integrate tools usually used in MANET and VANET scenarios, allowing the definition of multi-UAV networks.

In this context tree main contributions were proposed including i) the proposal of a heterogeneous distributed network for missions composed by multi-UAV shared tasks, ii) the use of a decision heuristic that employs dynamically sensed and calculated evaluation metrics , and iii) the validation of the interface manager as a modular solution, allowing the insertion of several WLAN interfaces.

Initially, a decision tree using a sum of point heuristic was proposed, presenting low computational cost and dynamically evaluate conditions, using two WLAN interfaces which have different frequency bands 2.4 GHz and 5.9 GHz. From obtained results, the proposed IM presented a lower performance fluctuation in the network flow, even with the increase in the number of nodes, presenting good reception of a signal by nodes during all missions, with fewer communication interruptions. The IM was able to maintain the link between –60 and –75 dbm, with a distance of up to 100 m between the nodes, with the lowest signal loss indexes (80 dB to 85 dB), and with SNR up to 0.7. And also, the use of these solutions promotes higher link stability, enabling the dynamic selection of interfaces to adjust the network to the conditions of the medium and to promote U2U communication with increased reliability. The IM enabled almost twice the sum of the average throughput from both interfaces applied homogeneously.

Once the proposed method was finished, it was possible to validate if this solution is modular, which means to allow add and remove interfaces without more changes in the proposed architecture. As result, the solution allowed to add more three interfaces expanding the IM decision for five communication interfaces. To add more interfaces than five will require some changes in the architecture that will need to get points from two or more decision-tree compound local decisions. But, considering that most parts of common devices have no more than three interfaces this study is out of the scope of this thesis.

So, in the second moment, a set of five wireless local interfaces are used compounding different interfaces combinations applied to IM to highlight the performance of IM using the most common interfaces available for UAV platforms. In general terms, it was observed that a previous definition of the mission application and the communication metrics requirements is very important in the definition of which set of interfaces should be applied in the system. This holds because the performance obtained from the traffic of different access classes packets even considering the use of more than one communication interface could be worst in some evaluation metrics.

For example, regarding the number of packets from different access classes from different IM interfaces combinations, the use of more interfaces implies more frequency coexistence in the unlicensed spectrum, which depends on the number of nodes this could cause more effects in the network traffic.

Another question is about of general settings of interfaces employed, if they use the same frequency band, some separation of frequency channels or dynamic channels assignments reduces the co-channel interferences incidence. Because of the co-channel interference, the IM with only two interfaces in an 8-node scenario (the scenario with more nodes) presents a better performance in the amount of different ToS packets received by the network.

In opposite that, the IM with five interfaces presents the best average latency per-flow of messages ratio in all scenarios, reaching 0.03 ms per 211 successfully flow of messages in the 8-node scenario, which represents that this interference impacted the amount of payload delivery, but not in the maintenance of connectivity between nodes.

As main conclusions from these experiments are: the importance of the definition of application of a multi-UAV mission-related with a combination of communication interfaces that will be used, and what is the most important networks metrics requirements for the kind of network traffic to get a collaborative mission success. These conclusions brought the idea of to apply different weights to the most important evaluate metrics according to each type of traffic, could improve the IM performance, it will be a near-future study object.

The IM allowed a communication up to 450 m of distance between nodes sensing about –70 dBm of rx power, –93.5 dBm of noise level and reaching 80-85 dBm of signal loss. In this way, this is the IM constraints with QoS guarantee. But, it was surrounding some traffic at 600 m of distance between nodes, sensing about –90 dBm of rx power, –94 dBm of noise level, and reaching 100-105 dBm of loss, so these are the maximum constraints of communication distance between nodes reached by this thesis solution. In this case, without guarantees of communication (without QoS).

The developed algorithm, 2 D and 3 D proposed scenarios, and the steps to integration of tools are available on https://github.com/LAURAMICHAELLA/NS3-SUMO-EVALVID (2 D scenarios), https://github.com/LAURAMICHAELLA/HetMUAVNet (3 D scenarios), and https://github.com/ LAURAMICHAELLA/HeterWIrelessMUAVNet (IM with five interfaces).

In general, the proposed solution cause significant increasing in the reliability, and connectivity between multi-UAV networks, maintaining the communication in considerable distances employing WLAN interfaces on-the-shelf, without any intermediary nodes, relays or gateways, this could helps several kinds of low costs multi-UAVs missions allowing more division of tasks along the flight with quality of service.

8.1 FUTURE WORKS

In the following a list of possible future works related to this thesis, is proposed:

- Use of more evaluation conditions in decision-tree as delay, latency, packet interval rate and etc, generating real-time video camera traffic in Gazebo. This will provide more interfaces validations to define the best interface.
- Improve the interoperability between ns-3 and gazebo, allowing to construct the application service out of these tools, using the ns-3 and gazebo like add-ons of communication and mobility. It will allow to conduce more experiments, as seen the UAV as agents, for example. This will allow to validate the IM as a middleware solution.
- Design new heuristics or algorithms that considers different classes of messages for decision-making communication interface. For example, using machine learning techniques like reinforcement learning or deep learning algorithms to propose IM comparisons.
- Provide an adaptive solution to define dynamically the IM execution time according to medium sensing conditions, avoiding unnecessary IM switches.

- Create scenarios with some obstacles and other kind of coexistent networks to validate this thesis solution, when the unlicensed spectrum present high concurrence (public areas) and environment signal losses.
- Evaluate the IM performance using WWLAN interfaces as LTE 5 GHz, considering the IM modular feature. Currently, the IM uses communication interfaces with 1 km of theoretical communication range, so the use of WWLAN will allow to extends for metropolitan network range(>50 km).
- Design others heterogeneous communication academic approaches using the same simulated experimental environment proposed by this thesis to compare performances.
- Evaluate the IM in a real testbed using sparse and dense UAV trajectories.
- Verify the energy consumption of the IM in a real testbed, using several UAV platforms.
- Design a Multi-UAV simulator with visual interface, allowing the user chosen which communication interfaces will be used in a heterogeneous or homogeneous network, experimentation scenarios, trajectory coordinates, and some other decision algorithms.

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Appendix

APPENDIX A – INTERFACE MANAGER DECISIONS DURING MISSION TIME (TWO INTERFACES)

Tables 9, 10, and 11 describe the IM decisions obtained during the three scena–rios defined for 3 D experiments, where the UAVs sent CBR data transmissions. These results were described in Chapter 6.

The experiment present an overall of 108 samples for the 3-node experiment, which present 1080 s (18 min) of duration, 540 samples for the 5-node experiment with 5400 s (1 h 30 min) of duration, and 720 samples for the 8-node experiment with 7200 s (2 h) of duration, using Gazebo time clock (real duration).

However, for 5-node and 8-node experiments, just until the 443 sample was described in Table 11, because the last IM decision is maintained equals for the following samples. In this way, for 5-node experiment the decision for interface IEEE 802.11p is maintained after the 296 sample, and after the 419 sample for 8-node experiment, according to medium sense conditions.

The interfaces shown in the Table are the most adopted in UAVs by local decisions in each sample interval. This means that the samples represent the interface more chosen in each sample interval. The IM employed two interfaces, IEEE 802.11 p and 802.11 n for making decisions.

Table 9 – IM interface decisions for 3-nodes, 5-nodes and 8-nodes scenario at a sample interval of 10 s - Part 1

Sample	3-node scenario	5-node scenario	8-node scenario
1	n	n	n
2	p	n	n
3	n	n	n
4	p	n	n
5	p	n	n
6	n	n	p
7	n	n	p
8	n	n	p
9	p	n	n
10	p	n	n
11	n	n	p
12	p	n	n
13	p	n	n
14	p	n	n
15	p	n	p
16	p	n	n
17	n	n	p
18	p	n	p
19	n	n	n
20	n	n	n
21	p	n	p
22	p	n	p
23	n	n	n
24	n	n	p
25	n	n	p
26	n	n	n
27	n	n	n
28	p	n	n
29	p	n	n
30	n	n	p
31	n	n	p
32	p	n	n
33	n	n	p
34	n	n	n
35	n	n	n
36	n	n	n
37	p	n	n
38	p	n	p
39	n	n	n
40	p	n	n
41	n	n	p
42	n	n	p
43	n	n	n
44	n	n	p
45	n	n	n
46	n	n	p
47	p	n	n
48	n	n	p
49	n	n	p
50	p	n	p
51	p	n	p
52	p	n	p
53	n	n	n
54	n	n	p
55	n	n	n
56	n	n	n
57	n	n	n
58	n	n	n
59	n	n	p
60	p	n	n
61	n	n	p
62	p	p	n
63	p	p	p
64	p	p	n
65	p	p	n
66	p	p	p
67	n	n	n
68	n	n	n
69	n	n	p
70	p	p	n
71	n	p	n
72	n	n	n
73	n	n	p
74	n	n	n
75	n	n	n
76	n	n	p
77	n	p	p
78	n	p	n
79	n	n	p
80	n	n	n
81	n	n	n
82	n	n	p
83	n	n	n
84	n	n	n
85	n	p	p
86	p	n	p
87	n	p	p
88	n	n	n
89	n	n	p
90	n	n	n
91	n	n	p
92	n	n	p
93	n	p	n
94	n	p	p
95	n	n	n
96	n	n	p
97	n	n	p
98	n	n	n
99	n	n	n
100	p	n	n
101	p	n	n
102	n	n	p
103	n	n	n
104	n	n	n
105	n	n	n
106	n	n	p
107	n	n	p
108	p	n	n
109	-	n	n
110	-	n	n
111	-	n	n
112	-	p	n
113	-	p	n
114	-	n	p
115	-	n	p
116	-	n	n
117	-	n	n
118	-	n	n
119	-	n	n
120	-	n	n
121	-	n	p
122	-	n	n
123	-	n	n
124	-	p	n
125	-	p	n
126	-	n	n
127	-	n	n
128	-	n	n
129	-	n	n
130	-	n	n
131	-	n	p
132	-	n	n
133	-	n	n
134	-	p	n
135	-	n	n
136	-	n	n
137	-	n	n
138	-	n	n
139	-	n	n
140	-	n	p
141	-	n	n
142	-	n	n
143	-	p	n
144	-	n	n
145	-	n	n
146	-	n	n
147	-	n	p

Table 10 – IM interface decisions for 3-nodes, 5-nodes and 8-nodes scenario at a sample interval of 10 s - Part 2

Sample	3-node scenario	5-node scenario	8-node scenario
148	-	n	n
149	-	p	p
150	-	p	n
151	-	n	p
152	-	n	n
153	-	n	p
154	-	n	n
155	-	n	p
156	-	n	p
157	-	n	p
158	-	n	p
159	-	n	n
160	-	n	n
161	-	n	p
162	-	n	n
163	-	n	p
164	-	p	n
165	-	n	p
166	-	n	n
167	-	n	n
168	-	n	p
169	-	n	p
170	-	n	p
171	-	p	p
172	-	n	n
173	-	n	p
174	-	n	p
175	-	n	n
176	-	n	p
177	-	n	n
178	-	p	n
179	-	n	n
180	-	n	n
181	-	n	p
182	-	n	n
183	-	n	n
184	-	p	n
185	-	p	n
186	-	n	n
187	-	n	n
188	-	n	n
189	-	p	n
190	-	p	n
191	-	n	n
192	-	n	p
193	-	n	n
194	-	n	n
195	-	n	n
196	-	n	n
197	-	p	p
198	-	p	n
199	-	n	n
200	-	n	n
201	-	n	n
202	-	n	n
203	-	n	n
204	-	p	p
205	-	n	n
206	-	n	n
207	-	n	n
208	-	n	n
209	-	n	n
210	-	n	n
211	-	p	n
212	-	p	n
213	-	n	n
214	-	n	n
215	-	n	n
216	-	n	n
217	-	n	n
218	-	n	n
219	-	n	n
220	-	p	p
221	-	n	n
222	-	n	n
223	-	n	n
224	-	n	n
225	-	n	n
226	-	n	n
227	-	p	n
228	-	p	n
229	-	n	p
230	-	n	n
231	-	n	p
232	-	n	n
233	-	n	n
234	-	n	n
235	-	p	p
236	-	p	n
237	-	n	n
238	-	n	p
239	-	n	p
240	-	n	n
241	-	n	n
242	-	n	n
243	-	n	p
244	-	n	n
245	-	n	p
246	-	n	p
247	-	n	p
248	-	n	n
249	-	n	p
250	-	n	p
251	-	n	n
252	-	n	p
253	-	n	p
254	-	n	n
255	-	n	p
256	-	n	p
257	-	n	p
258	-	n	n
259	-	n	p
260	-	n	p
261	-	n	p
262	-	n	p
263	-	n	p
264	-	p	p
265	-	n	n
266	-	n	p
267	-	n	p
268	-	n	p
269	-	p	p
270	-	n	p
271	-	n	p
272	-	n	p
273	-	n	p
274	-	n	p
275	-	n	p
276	-	n	n
277	-	n	p
278	-	n	n
279	-	n	n
280	-	n	p
281	-	n	p
282	-	n	p
283	-	p	n
284	-	p	p
285	-	n	n
286	-	n	p
287	-	n	p
288	-	n	p
289	-	n	n
290	-	n	n
291	-	n	p
292	-	n	p
293	-	n	p
294	-	n	p
295	-	n	p

Table 11 – IM interface decisions for 3-nodes, 5-nodes and 8-nodes scenario at a sample interval of 10 s - Part 3

Sample	3-node scenario	5-node scenario	8-node scenario
296	-	p	p
297	-	p	p
298	-	p	n
299	-	p	p
300	-	p	p
301	-	p	p
302	-	p	p
303	-	p	n
304	-	p	p
305	-	p	p
306	-	p	p
307	-	p	p
308	-	p	p
309	-	p	n
310	-	p	p
311	-	p	p
312	-	p	p
313	-	p	p
314	-	p	p
315	-	p	p
316	-	p	p
317	-	p	p
318	-	p	p
319	-	p	p
320	-	p	p
321	-	p	p
322	-	p	n
323	-	p	p
324	-	p	n
325	-	p	p
326	-	p	p
327	-	p	p
328	-	p	p
329	-	p	n
330	-	p	p
331	-	p	p
332	-	p	p
333	-	p	p
334	-	p	p
335	-	p	p
336	-	p	n
337	-	p	p
338	-	p	p
339	-	p	p
340	-	p	p
341	-	p	p
342	-	p	p
343	-	p	p
344	-	p	p
345	-	p	n
346	-	p	n
347	-	p	p
348	-	p	n
349	-	p	p
350	-	p	n
351	-	p	p
352	-	p	p
353	-	p	p
354	-	p	p
355	-	p	p
356	-	p	p
357	-	p	p
358	-	p	n
359	-	p	p
360	-	p	p
361	-	p	p
362	-	p	p
363	-	p	p
364	-	p	p
365	-	p	p
366	-	p	n
367	-	p	p
368	-	p	p
369	-	p	p
370	-	p	n
371	-	p	p
372	-	p	p
373	-	p	n
374	-	p	p
375	-	p	n
376	-	p	n
377	-	p	p
378	-	p	p
379	-	p	p
380	-	p	p
381	-	p	p
382	-	p	n
383	-	p	n
384	-	p	p
385	-	p	p
386	-	p	p
387	-	p	p
388	-	p	p
389	-	p	p
390	-	p	p
391	-	p	n
392	-	p	p
393	-	p	p
394	-	p	p
395	-	p	p
396	-	p	p
397	-	p	p
398	-	p	p
399	-	p	p
400	-	p	p
401	-	p	n
402	-	p	p
403	-	p	n
404	-	p	p
405	-	p	p
406	-	p	p
407	-	p	p
408	-	p	p
409	-	p	p
410	-	p	p
411	-	p	n
412	-	p	n
413	-	p	n
414	-	p	p
415	-	p	p
416	-	p	n
417	-	p	p
418	-	p	n
419	-	p	p
420	-	p	p
421	-	p	p
422	-	p	p
423	-	p	p
424	-	p	p
425	-	p	p
426	-	p	p
427	-	p	p
428	-	p	p
429	-	p	p
430	-	p	p
431	-	p	p
432	-	p	p
433	-	p	p
434	-	p	p
435	-	p	p
436	-	p	p
437	-	p	p
438	-	p	p
439	-	p	p
440	-	p	p
441	-	p	p
442	-	p	p
443	-	p	p

APPENDIX B – INTERFACE MANAGER DECISIONS DURING MISSION TIME - (SEVERAL INTERFACES)

Table 12 describes the IM decisions from the three proposed experiments, where the UAVs send different ToS during the execution mission. These results were presented in Chapter 7. The interfaces shown in the Table are the most adopted in nodes by local decisions, using sample intervals of 1 s of NS-3 clock reference. The IM has been employed with four different interfaces combinations:

- IM-2Int: IEEE 802.11 n 2.4 GHz and 802.11 p 5.9 GHz;
- IM-3Int: IEEE 802.11 n 2.4 GHz, 802.11 p 5.9 GHz and 802.11 ac 5 GHz;
- IM-4Int: IEEE 802.11 n 2.4 GHz, 802.11 p 5.9 GHz, 802.11 ac 5 GHz, and 802.11 ax 2.4 GHz;
- IM-5Int: IEEE 802.11 n 2.4 GHz, 802.11 p 5.9 GHz, 802.11 ac 5 GHz, 802.11 ax 2.4 GHz, and 802.11 ax 5 GHz;

Table 12 – IM validations for 3-nodes, 5-nodes and 8-nodes scenario by 1 s sample interval

Scenario	3-node scenario				5-node scenario				8-node scenario			
Time	IM-2Int	IM-3Int	IM-4Int	IM-5Int	IM-2Int	IM-3Int	IM-4Int	IM-5Int	IM-2Int	IM-3Int	IM-4Int	IM-5Int
1	p	n	p	p	p	n	ax2_4	ax5	p	n	ac	ax5
2	p	n	p	p	p	n	ax2_4	ax5	p	n	ac	ax5
3	p	n	ac	n	p	n	ax2_4	ax5	p	n	ac	ax5
4	p	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
5	p	p	ac	n	p	n	ax2_4	p	p	n	ac	ax5
6	p	p	ac	n	p	n	ax2_4	p	p	n	ac	ax5
7	p	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
8	p	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
9	n	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
10	n	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
11	n	p	p	p	p	n	ax2_4	p	p	n	ac	ax5
12	n	n	p	p	p	n	ax2_4	p	p	n	n	ax5
13	n	n	p	p	p	n	n	p	p	n	ac	ax5
14	n	n	p	p	p	n	n	p	p	n	ac	ax5
15	n	n	p	p	p	n	ax2_4	p	p	n	ac	ax5
16	n	n	p	p	p	n	ax2_4	p	p	n	ac	ax5
17	n	ac	p	p	p	n	ax2_4	p	p	n	n	ax5
18	n	ac	p	p	p	ac	ax2_4	p	p	n	n	ax5
19	n	p	p	p	p	ac	ax2_4	p	p	n	ac	ax2_4
20	n	p	ac	ax2_4	p	ac	ax2_4	ax5	p	n	ac	ax2_4
21	n	ac	ac	ax2_4	p	n	ax2_4	ax5	p	n	ac	ax2_4
22	n	ac	ac	ax2_4	p	n	ax2_4	ax5	p	n	ac	ax2_4
23	n	ac	ac	ax2_4	p	ac	ax2_4	ax5	p	n	ac	ax2_4
24	n	ac	ac	ax2_4	p	ac	ax2_4	ax5	p	n	ac	ax5
25	n	p	ax2_4	ax2_4	p	n	n	ax5	p	n	ac	ax5
26	n	ac	p	p	p	n	n	ax5	p	n	ac	ax5
27	n	ac	ax2_4	ax5	p	n	ax2_4	ax5	n	n	ac	ax5
28	n	p	p	p	p	n	ax2_4	ax5	n	n	ac	ax5
29	n	p	p	p	p	n	ax2_4	ax2_4	n	n	ac	ax5
30	n	p	ax2_4	n	p	n	ax2_4	ax2_4	n	n	ac	ax5
31	n	ac	ax2_4	n	p	n	ax2_4	ax5	n	n	ac	ax5
32	n	ac	ax2_4	n	p	n	ax2_4	ax5	n	n	ac	ax5
33	n	p	ax2_4	n	p	n	ax2_4	ax5	n	n	ac	ax5
34	n	p	p	p	p	n	ax2_4	ax5	n	n	ac	ax5
35	n	ac	ax2_4	n	p	n	ax2_4	ax5	n	n	ac	ax5
36	n	ac	ax2_4	n	p	n	ax2_4	ax5	n	n	ac	ax5
37	n	ac	p	p	p	n	ax2_4	ax5	n	n	ac	ax5
38	n	ac	p	p	p	n	ax2_4	ax5	n	n	ac	ax5
39	n	p	p	p	p	n	ac	ax5	n	ac	ac	ax2_4
40	n	ac	p	p	p	n	ac	ax5	n	ac	p	ax2_4
41	n	ac	p	p	p	ac	ac	ax2_4	n	ac	p	ax2_4
42	n	p	p	p	p	ac	ac	ax2_4	n	n	p	ax2_4
43	n	p	p	p	p	ac	ac	ax5	n	n	ac	ax2_4
44	n	p	ax2_4	ax5	p	ac	ac	ax5	n	ac	ac	ac
45	n	ac	p	p	p	ac	ac	ax5	n	ac	ac	ac
46	n	ac	ax2_4	ax5	p	ac	ac	ax5	n	ac	ac	ac
47	n	p	p	p	p	ac	ac	ax5	n	ac	ac	ac
48	n	p	p	p	p	ac	ac	ax5	n	ac	ac	ac
49	n	ac	ax2_4	ax2_4	p	ac	ac	ax5	n	ac	ac	ac
50	n	ac	ax2_4	ax2_4	p	ac	ac	ax5	n	ac	ac	ac
51	n	ac	ax2_4	ax2_4	p	ac	ac	ax5	n	ac	ac	ac
52	n	ac	ax2_4	ax2_4	p	ac	ac	ax5	n	ac	ac	ax2_4
53	n	p	p	p	p	ac	ac	ax5	n	ac	ac	ax2_4
54	n	p	ax2_4	p	p	ac	ac	ax5	n	ac	ac	ax2_4
55	n	p	ax2_4	ax5	p	ac	ac	ax2_4	n	ac	ac	ax2_4
56	n	p	p	ax5	p	ac	ac	ax2_4	n	ac	ac	ax2_4
57	n	ac	p	p	p	ac	ac	p	n	ac	ac	ac
58	n	ac	p	p	p	ac	ac	ax2_4	n	ac	ac	ac
59	n	p	p	p	p	ac	ac	p	n	ac	ac	ac
60	n	p	p	p	p	ac	ac	ax2_4	n	ac	ac	ac
61	n	ac	p	p	n	ac	ac	p	n	ac	ac	ax2_4
62	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
63	n	ac	ax2_4	p	n	ac	ac	p	n	ac	ac	ax2_4
64	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
65	n	ac	ax2_4	n	n	ac	ac	ax2_4	n	ac	ac	ax2_4
66	n	p	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
67	n	ac	p	ax5	n	ac	ac	ax2_4	n	ac	ac	ax2_4
68	n	ac	ax2_4	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
69	n	ac	ax2_4	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
70	n	p	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
71	n	p	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
72	n	p	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
73	n	ac	p	n	n	ac	ac	p	n	ac	ac	ax2_4
74	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
75	n	p	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
76	n	p	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
77	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
78	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
79	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
80	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
81	n	ac	p	p	n	ac	ac	p	n	ac	ac	ax2_4
82	n	ac	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
83	n	ac	p	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
84	n	p	ax2_4	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
85	n	p	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
86	n	p	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
87	n	p	ax2_4	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
88	n	ac	ax2_4	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
89	n	ac	ax2_4	p	n	ac	ac	p	n	ac	ac	ax2_4
90	n	p	ax2_4	p	n	ac	ac	p	n	ac	ac	ax2_4
91	n	p	p	p	n	ac	ac	p	n	ac	ac	ax2_4
92	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
93	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
94	n	ac	p	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
95	n	ac	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
96	n	ac	ax2_4	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
97	n	ac	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
98	n	ac	ax2_4	p	n	ac	ac	p	n	ac	ac	ax2_4
99	n	p	p	ax5	n	ac	ac	ax2_4	n	ac	ac	ax2_4
100	n	ac	ax2_4	p	n	ac	ac	p	n	ac	ac	ax2_4
101	n	ac	p	ax5	n	ac	ac	ax2_4	n	ac	ac	ax2_4
102	n	p	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
103	n	p	ax2_4	ax5	n	ac	ac	ax2_4	n	ac	ac	ax2_4
104	n	p	p	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
105	n	ac	ax2_4	p	n	ac	ac	ax2_4	n	ac	ac	ax2_4
106	n	ac	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
107	n	p	p	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
108	n	p	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
109	n	ac	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
110	n	ac	ax2_4	ax2_4	n	ac	ac	p	n	ac	ac	ax2_4
111	n	ac	ax2_4	ax2_4	n	ac	ac	n	n	ac	ac	ax2_4
112	n	ac	ax2_4	ax2_4	n	ac	ac	ax2_4	n	ac	ac	ax2_4
113	n	ac	ax2_4	p	n	ac	ac	n	n	ac	ac	ax2_4
114	n	ac	ax2_4	p	n	ac	ac	n	n	ac	ac	ax2_4
115	n	p	p	p	n	ac	ac	n	n	ac	ax2_4	ax2_4
116	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ax2_4	ax2_4
117	n	ac	p	p	n	ac	ac	n	n	ac	ax2_4	ax2_4
118	n	ac	p	p	n	ac	ac	ax2_4	n	ac	ax2_4	ax2_4
119	n	p	p	p	n	ac	ac	n	n	ac	ax2_4	ax2_4
120	n	p	p	p	n	ac	ac	p	n	ac	ax2_4	ax2_4
121	n	p	p	ax5	n	ac	ac	p	n	ac	ax2_4	ax2_4
122	n	ac	p	p	n	ac	ac	-	n	ac	ax2_4	ax2_4
123	n	ac	ax2_4	ax5	n	ac	ac	-	n	ac	ax2_4	ax2_4
124	n	p	p	p	n	ac	ac	-	n	ac	ax2_4	ax2_4
125	n	p	ax2_4	p	n	ac	ac	-	n	ac	ax2_4	ax2_4
126	n	ac	p	ax5	n	ac	ac	-	n	ac	ax2_4	ax2_4
127	n	ac	p	-	n	ac	ac	-	n	ac	ac	ax2_4
128	n	ac	ax2_4	-	n	ac	ac	-	n	ac	ac	ax2_4
129	n	ac	ax2_4	-	n	ac	ac	-	n	ac	ax2_4	ax2_4
130	n	ac	ax2_4	-	n	ac	ac	-	n	ac	ax2_4	ax2_4
131	n	ac	ax2_4	-	n	ac	ac	-	n	ac	ax2_4	ax2_4
132	-	ac	ax2_4	-	-	n	ac	-	-	ac	ax2_4	ax2_4
133	-	p	ax2_4	-	-	n	ac	-	-	ac	ax2_4	ax2_4
134	-	p	ax2_4	-	-	ac	ac	-	-	ac	ax2_4	ax2_4
135	-	p	p	-	-	-	ac	-	-	-	ax2_4	ax2_4
136	-	p	p	-	-	-	ac	-	-	-	ac	ax2_4
137	-	-	p	-	-	-	ac	-	-	-	-	ax2_4
138	-	-	p	-	-	-	ac	-	-	-	-	ax2_4
139	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
140	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
141	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
142	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
143	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
144	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
145	-	-	-	-	-	-	ac	-	-	-	-	ax2_4
146	-	-	-	-	-	-	ac	-	-	-	-	ax2_4