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Evaluation of VoIP QoS Performance in Wireless Mesh Networks

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Abstract: The main focus of this research article is the evaluation of selected voice over Internet protocol (VoIP) solutions in wireless mesh network (WMN) scenarios. While WMNs have self-healing, self-forming, and dynamic topology features, they still pose challenges for the implementation of multimedia applications such as voice in various scenarios. Therefore, various solutions to make WMN more suitable for VoIP application have been proposed in the scientific literature. In this work, we have extensively explored a set of applicable scenarios by conducting experiments by means of a network simulator. The following scenarios were selected as the most representatives for performance evaluation: first responders, flooded village, remote village, and platoon deployment. Each selected scenario has been studied under six sub-scenarios corresponding to various combinations of the IEEE 802.11g, 802.11n, 802.11s, and 802.11e standards; the G.711 and G.729 codecs; and the ad hoc on demand distance vector (AODV) and hybrid wireless mesh protocol (HWMP) routing protocols. The results in terms of quality of service (measured with the mean opinion score rating scale), supported by the analysis of delay, jitter and packet loss, show that 802.11g integration with both VoIP codecs and AODV routing protocol results in better VoIP performance as compared to most other scenarios. In case of 802.11g integration with 802.11s, VoIP performance decreases as compared to the other sub-scenarios without 802.11s. The results also show that 802.11n integration with 802.11e decreases VoIP performance in larger deployments. We conclude the paper with some recommendations in terms of combinations of those standards and protocols with a view to achieve a higher quality of service for the given scenarios.

Keywords: wireless network; VoIP communication; mesh; QoS; MOS; delay; jitter; packet loss

1. Introduction

Wireless mesh networks (WMNs), which are defined in standards such as IEEE 802.11s for Wi-Fi [1], IEEE 802.15.4 for Bluetooth [2] and IEEE 802.16j for WiMAX [3], are suitable platforms for many critical and non-critical services. Such types of networks own high availability features, self-formation and self-organization capabilities [4]. They are also considered self-healing and dynamic types of networks. WMNs can provide solutions for various applications including emergency relief efforts, urban, rural, military fields [5], mines and temporary setups [6], etc. In most of such applications, implementing a wired infrastructure or traditional wireless solution is either too expensive or is challenging due to environmental issues and/or the scenarios' specific requirements. There might even be cases for which other traditional solutions would be infeasible (in terms of e.g., air-to-air communication, mobility, right of way, immediate deployments, high availability, etc.).

There are various standards and technologies available that can be used to form WMNs, in particular, WLAN and WPAN are mostly used to form client mesh networks and WiMAX mesh is used to establish infrastructure mesh network using wireless routers. The focus of this research paper is on the IEEE 802.11 standard (i.e., the Wi-Fi technology) using client nodes to form a mesh networks called client or ad hoc mesh network. WMNs could be one of three types, namely, backbone mesh, clients mesh, or a mix thereof [7,8].

The first type, backbone mesh [9], is formed by connecting at least three routers with each other in such a way that each mesh router has a direct path to the other two routers, as shown in Figure 1a. If a path through one router fails, each router has the possibility to send traffic through the other available routers in the network topology. A backbone mesh is usually formed by WiMAX technology, which uses the IEEE 802.16 standard, especially in large installations mainly due to interference, long range features and frequency allocation issues. A Wi-Fi backbone mesh of routers, which uses the IEEE 802.11 family of standards, could also be used in small/medium scale installations where interference is not a major concern, e.g., in remote areas where these bands are not crowded. In this type of mesh topology, the backbone mesh routers are responsible for providing redundant backbone paths to their clients. Usually, backbone mesh routers are considered as fixed network components. In this case, the wireless clients are not forming a mesh topology; instead, they are only serviced by mesh routers in an infrastructure-based wireless network using dual radio links.

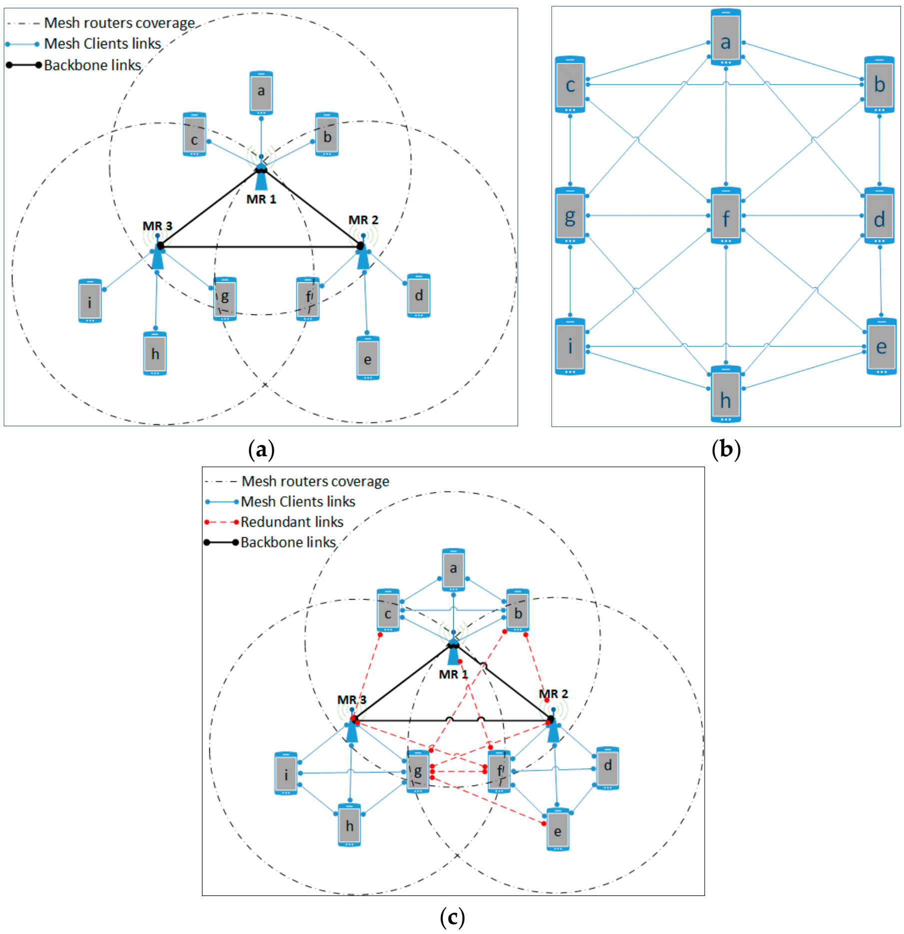


Figure 1. Three types of wireless mesh networks: (**a**) Backbone mesh with each router supporting a separate service set and clients connected in infrastructure mode with the routers; (**b**) ad hoc or clients mesh (MANETs), where the network is formed without dependency to any wireless router or access point; (**c**) backbone and clients mesh in which nodes can roam and connect to any available mesh node or router in any cell.

The second type of WMN is the clients mesh. In this type of topology, all the clients form the mesh network; they all participate in the formation of the mesh network backbone and are usually referred to as mesh nodes/points; the type of topology is then called ad hoc, as shown in Figure 1b where the nodes a, b, c, . . . , i form a mesh network without any wireless router or access point's help. This type of network can use the IEEE 802.11 and 802.15 standards. In such types of mesh networks, each mesh node can act as a client, server and router. Each node's role can change based on the type of service offered over the WMN, but the nodes will always have to play either a client or a router role, while the server's role depends on the type of application offered using such network platforms. Ad hoc network with mobile nodes are usually referred to as mobile ad hoc networks (MANETs) [10,11].

The third type of WMN is a mixture of the first and second types, which comprises a mesh of wireless routers that form the backbone and a mesh of clients that form the access layer of a hierarchical network, as shown in Figure 1c. In this type of network, the nodes can form a mesh network among themselves and the mesh router could be a supportive component of the mesh network to connect mesh nodes to external networks. This type of network is called heterogeneous mesh (HetMesh) [7] and requires the mesh routers to be equipped with dual radio links in order to establish and maintain redundant links with the mesh routers and to service the mesh clients as their gateways to other mesh segments or external networks, e.g., the Internet.

Since ad hoc networks increase delay, jitter, and packet loss, VoIP services offerings in such networks are challenging [12,13]. There are several methods to investigate and measure the performance of VoIP and its service quality. In [14] methods such as mathematical proofs, real implementation and simulation are discussed to evaluate the performance of scenarios that involves multiple variables. The author uses OMNet++ simulation software to measure multiple variables which involves a wide range of parameters across multiple OSI model layers. There exist several network simulators such as OMNet++, NS-2, NS-3, EstiNet, QualNet, OPNET modeler, and JSim [15]; in this research we use the QualNet simulation software in order to evaluate the performance of VoIP in various scenarios using multiple types of parameters for the reasons given below.

The QualNet simulation software enables us to conduct experiments that are almost identical to real-life scenarios [16]. It also saves time in configuring, experimenting, collecting data and analyzing multiple scenarios using various parameters. Among several features for configuring VoIP profiles, generating VoIP traffic and evaluating the service performance, the configuration of the "Total VoIP loss probability" percentage parameters enables us to set the estimated VoIP loss probability percentage to mimic a real network scenario. This parameter's setting directly affects the mean opinion score (MOS) rating scale values obtained in simulation results. The MOS rating scale is defined by ITU-T as a 5-point rating scale where 5 is rated as "Excellent", 4 as "Good", 3 as "Fair", 2 as "Poor" and 1 as "Bad" [17].

The motivation behind this research is to provide an insight into VoIP application with recommendations on the best ways to combine standards, protocols and codecs to improve VoIP quality in various scenarios considering ad hoc mesh network implementations using selected IEEE 802.11 standards. Since ad hoc networks are self-formed and do not require any prior setup nor existing infrastructure, this makes it an interesting type of network compared to the first and third types explained above. On the other hand, one of the challenges in this research domain is the applicability of VoIP on wireless mesh networks and how it could be offered with improved service quality. Below we highlight our contributions towards this challenge:

- We integrate and experiment 802.11g/n with 802.11s/e IEEE standards together with G.711 and G.729 voice codecs using AODV and HWMP routing protocols in order to extensively evaluate how VoIP service performs, which can help us to make informed choices about standards, codecs and protocols in WMN implementations. To the best of our knowledge, research dealing with the combination of these standards, codecs, and protocols in the specific type of scenarios considered in this work has not been reported before.
- We investigate the performance of VoIP deployment in five main scenarios (three scenarios with mobility and two scenarios with no mobility). We evaluate how the mobility models

(e.g., waypoint mobility and random waypoint mobility) and different area sizes can affect the VoIP performance. For evaluating how the integration of standards and protocols can affect the VoIP performance, we further define six sub-scenarios for each main scenario and experiment with changing standards and protocols.

- Finally, by conducting experiments and extensively evaluating the VoIP performance based on above mentioned points, our research findings show that IEEE 802.11g without being integrated with IEEE 802.11s standard using G.711 and G.729 voice codecs, along with the AODV routing protocol, results in better VoIP performance as compared to the integration of IEEE 802.11g with IEEE 802.11s using the HWMP routing protocol. Similarly, the integration of 802.11n standard using G.711 and G.729 voice codecs, along with the AODV routing protocol, shows poor VoIP performance as compared to the other scenarios. In general, our results show that scenarios with IEEE 802.11g using AODV routing protocol show better VoIP performance as compared to scenarios with IEEE 802.11n using the same routing protocol.

The remainder of this paper focuses on WMN applications and scenarios where VoIP could be offered as a critical service using a self-formed, self-healed, survivable and easy to setup communication network (Section 2). This is followed by the selection of a few scenarios and performing experiments using different IEEE 802.11 standards, voice codecs and protocols (Section 3). Our focus is mainly on integrating standards and protocols to facilitate an improved voice communication in emergency scenarios, isolated villages, and small-scale military operations. The results are presented and analyzed in Section 4. Finally, Section 5 concludes the paper.

2. VoIP Application and Scenarios

VoIP service offerings over IP networks have turned into a most wanted service over wired and infrastructure-based wireless networks in most network installations of various sizes [18]. Fixed equipment like VoIP phones, switches, access points, and routers can guarantee VoIP quality and they can very well support VoIP services. This better quality is usually achieved by reducing the number of hops, delay, jitter and packet loss using routing policies, traffic engineering, traffic shaping, QoS features configuration techniques on infrastructural devices, or networking equipment. However, if such networks are affected by either natural or man-made disasters, the supporting infrastructure for VoIP is equally affected [19]; this then limits affected people's access to emergency services and hence puts their lives in danger. A backup or supportive, self-forming and self-healing network for emergency situations using mobile phones with Wi-Fi capability can respond to such scenarios [20]. There are also other scenarios where the wired network is non-existent or even not possible and traditional wireless networks cannot respond, for example in mobility scenarios, rural areas, isolated areas, hard-to-reach villages, mines, perimeter security, military fields, temporary deployments, etc. A report on community networks [21] has studied such networks across the globe, where Wi-Fi and mesh technologies have been used, among other technologies, to facilitate the development of networks that are for public use in rural and urban installations.

2.1. VoIP Application in WMNs

VoIP is commonly used as a critical service in modern communication networks. Today, people often prefer making VoIP calls instead of using PSTN services, GSM phones [22], texting or sending emails due to their low cost, wide range of supported features, and ease of use. Studies also show that VoIP usage is increasing in countries where mobile operator call tariffs are higher [23]. On the other hand, there are specific scenarios where only voice calls are feasible and/or the preferred means of communication. VoIP services offering with acceptable or improved quality with the consideration of the MOS rating scale is very much important in cases of emergency networks, which has been studied in, e.g., [24]. For example, in the case of natural or man-made disasters, people who are affected and people who approach the affected area are turning to voice calls to reach each other. In scenarios where the main communication mediums through wired or infrastructure-based wireless network are affected by natural or man-made disasters, building a temporary or long-lasting network using the available mobile devices on the scene can save lives and makes it possible to communicate, coordinate, assist, locate, send help, and provide the affected people with the necessary support services and medical care.

2.2. VoIP Implementation Scenarios

VoIP applications in WMNs are challenging due to the VoIP traffic sensitivity to delay, jitter and packet loss [13]. WMNs implementation varies based on each scenario requirements and as a result these factors are also affected differently. These factors are considered and measured in a technical context, but from the user's perspective the main measurement factor is his/her satisfaction with the voice call quality. Hence, the user's perceived VoIP quality is not directly measured in terms of delay, jitter, and packet loss, but by the MOS rating scale defined by ITU-T [25].

A VoIP application in any type of network requires the necessary components to be in place so that the calling party (call initiator) and the called party (call receiver) can have a voice conversation for as long as they desire. In order to establish a VoIP call between the two parties, they both have to be registered with a call registrar. The call registrar requires a special protocol such as session initiation protocol (SIP) or H.323 to register all VoIP nodes in a client and server architecture [26]. These protocols are not only used for call registration, but also for call establishment, maintenance, termination, authentication, authorization, proxying, forking, redirection, and as call gateways to external phone systems. However, VoIP protocols cannot function alone and they are used with other protocols such as real-time transport protocol (RTP) for transporting VoIP traffic; real time control protocol (RTCP) for transporting control messages to support RTP; real-time streaming protocol (RTSP) as a control protocol for providing client/server and multimedia services by the support of RTP and RTCP services; session description protocol (SDP) for multimedia services session management; user datagram protocol (UDP) for best effort delivery services; and other OSI layer protocols, such as IP and so on.

Researchers have proposed solutions such as admission control, load aware mobility management, routing protocols, packet aggregation, gateway placement and priority schedulers, to name a few, which can contribute to the VoIP quality improvement to some extent [27]. These solutions have been studied in detail and each solution's limitation and contribution have been analyzed in [27,28]; a summary thereof is presented in Table 1. The review of the literature in this domain shows that there is still a clear need for further research in order to propose feasible, practical, and low-cost approaches for successful VoIP implementation in WMNs [27].

Table 1. Advantages and limitations of existing QoS solutions for VoIP over WMNs.

Solution Name	Advantages	Limitations
IEEE 802.11s [1]	EDCA, differentiated service and access categories, own routing mechanism using HWMP	Not well supported and VoIP performance is not improved significantly
Admission Control QoS [29]	Channel reservation for multimedia traffic	Only solves the problem of access to the medium
Routing Protocols [30]	Better usage of resources with reactive routing and better performance with the proactive routing with the cost of using more resources	Reactive routing is slow, proactive routing is resource hungry. Slow routing results in excess delay and use of more resources consumes lots of device processing power and battery life
IEEE 802.11e [31]	EDCA function and good for infrastructure wireless network	Not developed for WMNs
Codec compression [32]	Choice of high quality codec can improve voice quality	Codec delay is only one small portion of the whole problem and high quality codec increases codec delay and generates large VoIP packets

Table 1. *Cont.*

Solution Name	Advantages	Limitations
Packet aggregation [30]	Avoids redundant packet headers, improves VoIP quality to some extent in special cases	Packetization and de-packetization delay is added. Takes more time to route large packets. Packetizing the packets travelling to different destinations is difficult in the relay nodes
Priority schedulers [33]	Improves VoIP performance to some extent	In case of a continuous flow, creates problem for low priority packets; does not work well for high loads
Load-aware mobility [10]	Load balancing of mesh nodes	Association phase gets delayed; does not perform well for high loads
Gateway placement [34]	Improves performance for a limited number of hops and if the nodes are communicating to external nodes	Does not solve the problem of mesh nodes communicating internally.
Traffic allocation for delay variation optimization (TADVO) [35]	Improves the delay factor using multiple paths and preferring paths with least amount of delay	This type of routing adds extra load. Puts route under continuous computation process
QoS Aware routing [36]	Prefers routes with least amount of load	Segmentation and use of several routing protocols adds to network complexity. May not work with high number of nodes due to multicasting function
Secure routing with QoS amplification SRQA [37]	Solves interference issues	Only addresses signal to noise ratio
Local packet recovery [38]	Recovering sporadic and link failure packet loss	Only addresses packet loss factor

VoIP service configuration and quality also depends on the type of codec. There are a number of codecs available, each having its own features and use cases. Some of the common VoIP codecs are G.711, G.729, G.722, G.723, and G.726. VoIP codecs performance has been studied in, e.g., [11], which uses G.711, G.729, and G.723 in an indoor environment; the results show that G.711 outperforms the other two due to A-law/µ-law algorithmic properties related to compression and high bandwidth usage features.

In our experiments, we have investigated VoIP applications in various scenarios and identified the challenges that VoIP applications face and the possible ways for improving VoIP quality of service. The G.711 and G.729 codecs are used in our experiments since they are commonly used for providing better call quality and better bandwidth usage, respectively. In [24,39] VoIP codecs have been used in various scenarios and G.711 and G.729 are considered as the most widely used.

2.2.1. Emergency Relief Deployment

In case of emergency situations, the most vital means of communication is voice communication [40]. In such cases, affected people and those who approach them to provide help, directly turn to voice calls [41]. In some countries and regions, VoIP services must be connected with the emergency services like in the USA (911), Europe (112 [42]), or the United Kingdom (999 [43]). Hence, all public and private computer network installations with the need for voice communication should provide VoIP services with integration to the emergency services.

VoIP could be the main means of communication or the backup system to an existing wired connection; in case of large-scale disasters, regular communication systems are also damaged and not responsive, as happened during Hurricane Katrina in the United States [44]. Security of the WMN in case of disaster is also a concern and various security solutions are reviewed in [40]; however, this aspect is not in the scope of this paper. In most emergency cases, the terrain, distance among nodes and number of nodes make each scenario different. Some main emergency scenarios are explained in detail in next paragraphs. The only challenging issue with VoIP over IP networks is the nodes location reporting, which is not directly provided to the emergency services and requires the caller to report its location to the emergency team verbally. Alternatively, the service could be integrated with GPS and the exact location could be reported via purpose-built applications for disaster relief situations [45].

First Responders

Every emergency relief starts with a group of people reaching the affected area after the incident. The first responders need to communicate among themselves to locate people, move medics, send support teams, and coordinate their efforts [46]. They also need to send and retrieve data to/from a central command. In case of large-scale multinational emergency response efforts, the communication becomes more difficult since teams may use different communication technologies [19]. In such cases, a unique communication system through which first responders, rescue teams, and affected people could get connected and communicate is very much important in order to save lives, protect public infrastructure and coordinate efforts in a timely and efficient way.

Earthquake/Flooding/Cyclones/Fires

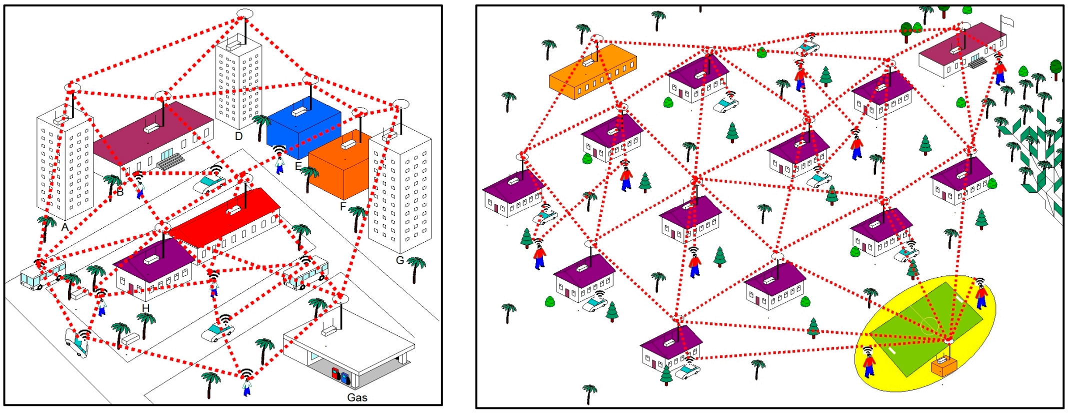
Earthquakes of high magnitude, large-scale flooding, cyclones, and fires destroy cities, damage infrastructure and forests, and put people's lives in danger. Large-scale natural disasters usually affect existing wired and wireless communication infrastructure [47]. Survivors of such large-scale disasters and rescue teams need to communicate with each other frequently using battery-powered mobile devices until the proper infrastructure is rebuilt or fixed. As an example, Figure 2 shows a small village affected by flooding where the existing communication infrastructure was damaged.

Figure 2. Flooded village [38] scenario where the fixed communication infrastructure is affected and WMNs could be used to establish connectivity among affected people and first responders.

2.3. Urban and Rural Deployment

There have been successful municipal Wi-Fi installations for public services like in Tallinn, Mountain View, and Kuala Lumpur [48], which are examples of urban deployments. Many other countries have also started to provide similar services for the public in many cities. Municipal Wi-Fi installations can be supported by a WMN backbone. These installations are cost effective and highly available for many services including VoIP services [49]. While using mesh technologies for providing backhauling to the mesh clients is very effective and improves the network's availability factor, the same solution could be used among the mesh clients to improve the network's coverage and connection areas where backbone WMN equipment cannot provide adequate coverage or where the installation of backbone equipment is not cost-effective. An example of an urban mesh network is shown in Figure 3a (adapted from [50]).

Usually, rural areas do not benefit from the many services that modern communication technology can offer. This is the case in many undeveloped and developing countries [51]. Wi-Fi mesh can solve this problem to an extent by enabling people in rural areas to communicate among themselves, call local offices like the police station, firefighting teams, hospitals, etc., even if they are not connected to the Internet or to call gateways to make long-distance calls, as shown in Figure 3b.

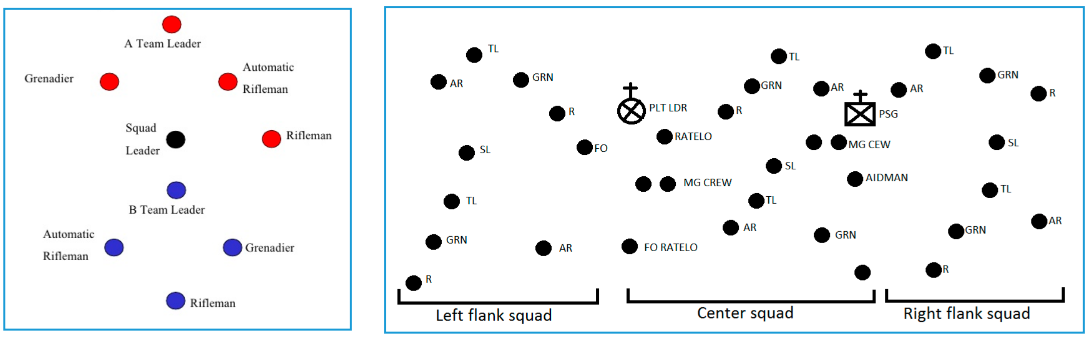


(**a**) (**b**)

Figure 3. Examples of urban and rural mesh network deployments: (**a**) urban mesh network where homes, public buildings, and private offices could be serviced by WMNs and the network can adapt based on nodes addition and removal; (**b**) a rural area where homes, police, hospitals, and schools could be connected with WMNs.

2.4. Military Operations Deployment

Military operations need a stable, highly available, dynamic, and isolated communication system to connect military personnel. Although a military typically has its own means of communication, mesh networks could still be used for military units as a primary or backup means of communication [52]. In cases where there are high chances of military radio system failure or interference to the main communication channel on small- or large-scale military operations, then Wi-Fi mesh could be a suitable choice. The use of Wi-Fi and wireless mesh for military purpose is presented in [53] for Wi-Fi and in [54] for wireless mesh, but there are still some security concerns about the use of Wi-Fi for the military. An example of a squad and a platoon formation where WMN could be used to facilitate military personnel communication is shown in Figure 4a,b.



(**a**) (**b**)

Figure 4. WMN small-scale military operations scenarios: (**a**) Squad line formation, in which a small number of nodes could be used to support a military operation; (**b**) infantry platoon formation, where three squads' communication could be facilitated by WMNs to support a military operation.

3. Experimental Setup

There are several methods to evaluate and measure the performance of services offered over various types of computer networks. These methods and approaches are mainly analytical, real implementation, and network simulation [55]. Among these methods, the use of network simulators for conducting experiments which involve multiple parameters is a workable and preferred method. This method allows us to investigate the configuration of various parameters over different types of network deployments, various communication standards and protocols. In our experiments, we use the QualNet simulation software to simulate VoIP application in various scenarios and to evaluate how a set of standards and protocols integration can affect the VoIP quality in WMNs.

One of the main challenges in VoIP applications in WMNs is the call quality as perceived by the VoIP call initiator (caller) and receiver (listener), which is usually measured with MOS based on the ITU-T standard and E-model [25,39]. The model defines subjective and objective MOS measurement; subjective MOS measurement involves humans, while the objective MOS measurement could be automated using simulation software. Hence, in our research we consider objective MOS values, which are further supported by the analysis of delay, jitter, and packet loss factors. While ITU-T defines the MOS values as integers, measuring with points between the ranges with decimal values is also allowed, as shown in Table 2, and mostly used in simulation tools, as described in [17,56]. The MOS values of the initiating node and receiving node can vary depending on the traffic condition in the network. There are several factors that can affect the MOS factor, but delay, jitter, and packet loss are considered the main factors affecting the MOS values [25]. As discussed in Section 1, the loss incurred by all these factors is called the "VoIP total loss probability" in QualNet simulation software; this indicates the percentage probability of a VoIP application packet being lost during transmission as the result of obstacles and other factors in the real environment and the configuration of this parameter affects the MOS values. In real scenarios, there is always a percentage of such loss that affects the VoIP quality. The VoIP total loss probability range could be any value from 1 (a few minor obstacles) to 100 (many large obstacles). The default value in QualNet simulation software is 5% and the same is used in our simulation scenarios, which is the maximum loss a VoIP application can tolerate [57]. The purpose of considering a 5% total loss probability in our scenarios is to simulate total loss due to various factors including loss incurred by terrain profiles in real scenarios. As a consequence, setting this parameter to 5% yields MOS rating values that are always below the value of 4.

Table 2. MOS rating scale.

Quality Level	MOS
Excellent	4.3–5.0
Very good	4.0–4.3
Good	3.6–4.0
Fair	3.1–3.6
Poor	2.6–3.1
Bad	1.0–2.6

In order to investigate VoIP performance in various WMN scenarios, we have chosen five scenarios from those that were introduced in the previous section. The list of the scenarios selected for our experiments is in Table 3. There are five main scenarios; each of them is investigated under six different sub-scenarios with variations in the physical layer, data link layer, and presentation layer. The main scenarios are different in terms of area size, nodes mobility model, and distance between the nodes. There are two scenarios (First Responders and Platoon) with a waypoint mobility model where the nodes move towards a specific direction with varying mobility speeds. This mobility model is selected since, for example, in an emergency scenario it can happen that an affected area is small and all the first responders move towards that direction. In the case of a platoon, the waypoint mobility simulates the military personnel movement towards a specific direction without major changes in the platoon's formation. In this case, we have considered a platoon line deployment with three squads (left, centered, and right). They move from their initial positions to the final position without changing the platoon's formation using the way-point mobility model.

Table 3. Main and sub-scenarios.

Main Scenarios	Sub-Scenarios Description	Mobility/Speed	Short Name
First Responders	802.11g, 802.11s, Mesh Points, G.711, HWMP	Waypoint	FR1
	802.11g, 802.11, No Mesh Points, G.711, AODV	Waypoint	FR2
	802.11g, 802.11s, Mesh Points, G.729, HWMP	Waypoint	FR3
	802.11g, 802.11, No mesh Points, G.729, AODV	Waypoint	FR4
	802.11n, 802.11e, No Mesh Points, G.711, AODV	Waypoint	FR5
	802.11n, 802.11e, No mesh Points, G.729, AODV	Waypoint	FR6
First Responders-Random Waypoint	802.11g, 802.11s, Mesh Points, G.711, HWMP	Random waypoint, 1.3 m/s	FRW1
	802.11g, 802.11, No Mesh Points, G.711, AODV	Random waypoint, 1.3 m/s	FRW2
	802.11g, 802.11s, Mesh Points, G.729, HWMP	Random waypoint, 1.3 m/s	FRW3
	802.11g, 802.11, No mesh Points, G.729, AODV	Random waypoint, 1.3 m/s	FRW4
	802.11n, 802.11e, No Mesh Points, G.711, AODV	Random waypoint, 1.3 m/s	FRW5
	802.11n, 802.11e, No mesh Points, G.729, AODV	Random waypoint, 1.3 m/s	FRW6
Flooded Village	802.11g, 802.11s, Mesh Points, G.711, HWMP	No	FV1
	802.11g, 802.11, No Mesh Points, G.711, AODV	No	FV2
	802.11g, 802.11s, Mesh Points, G.729, HWMP	No	FV3
	802.11g, 802.11, No mesh Points, G.729, AODV	No	FV4
	802.11n, 802.11e, No Mesh Points, G.711, AODV	No	FV5
	802.11n, 802.11e, No mesh Points, G.729, AODV	No	FV6
Isolated Village	802.11g, 802.11s, Mesh Points, G.711, HWMP	No	IV1
	802.11g, 802.11, No Mesh Points, G.711, AODV	No	IV2
	802.11g, 802.11s, Mesh Points, G.729, HWMP	No	IV3
	802.11g, 802.11, No mesh Points, G.729, AODV	No	IV4
	802.11n, 802.11e, No Mesh Points, G.711, AODV	No	IV5
	802.11n, 802.11e, No mesh Points, G.729, AODV	No	IV6
Platoon	802.11g, 802.11s, Mesh Points, G.711, HWMP	Waypoint	PL1
	802.11g, 802.11, No Mesh Points, G.711, AODV	Waypoint	PL2
	802.11g, 802.11s, Mesh Points, G.729, HWMP	Waypoint	PL3
	802.11g, 802.11, No mesh Points, G.729, AODV	Waypoint	PL4
	802.11n, 802.11e, No Mesh Points, G.711, AODV	Waypoint	PL5
	802.11n, 802.11e, No mesh Points, G.729, AODV	Waypoint	PL6

There is one scenario (First Responders Random Mobility) in which the nodes move using the random waypoint mobility model with a minimum speed of 1.1 m/s and a maximum speed of 1.5 m/s, which simulates pedestrian traffic mobility speed. We have also considered two scenarios (Flooded Village and Isolated Village) with no mobility, where the nodes do not move at all and it is assumed that the mesh nodes are in a fixed installation mode.

We have conducted our experiments by combining multiple standards, protocols, and codecs in order to find out how VoIP performance is affected and which combinations would be the best in consideration of specific scenarios. We have limited our research to the choice of two common codecs, namely G.711 and G.729. The G.711 requires higher bandwidth, while G.729 requires lower bandwidth. The routing protocol type for all the scenarios without the IEEE 802.11s standard is AODV, which is a light-weight routing protocol commonly considered in WMNs as protocol of choice in real experiments and focused research activities, as presented in [58–62]; in [58] a real world evaluation of the AODV is presented in an industrial setup and the rest are AODV usage and its comparison in various mesh network scenarios. For scenarios with IEEE 802.11s, the routing protocol choice is HWMP, which is a built-in path selection protocol as part of the IEEE 802.11s standard [1]. The reason for choosing these two protocols is that AODV operates at the network layer while HWMP operates at the data link layer; HWMP is also called a path selection protocol. The comparison of these two protocols' performance can help us make informed choices in WMNs implementations.

As discussed previously, VoIP implementation requires a signaling protocol to work. We have chosen the SIP signaling protocol for our experimental scenarios because of its good performance and low resource usage features, and its commonality of use in VoIP implementations. Node 11 has been configured as the SIP server in all scenarios. In a distributed system such as a WMN, a central VoIP server can create a single point of failure and VoIP calls may not happen if the connectivity to the SIP server is not established. There are solutions like the SIP clustering presented in [63], which could be used in mesh networks to turn every node into a SIP server. However, such exploration is outside the scope of this work and in our experimental scenarios all nodes were able to connect to the SIP server during the entire simulation time.

In order to simulate VoIP conversations, we have used the QualNet Simulator and its VoIP traffic generator to simulate a human conversation for 180 s; all calls start 30 s after the simulation starts and end after 300 s of simulation time have elapsed. There are 31 nodes in all scenarios. As reported in [63], with 32 nodes the probability of finding a destination is almost 80% and the data delivery ratio is almost 84%, which is very good for WMNs. Although this may vary based on the type of scenario, we experimented with a fixed number of nodes (30 nodes, of which 15 are VoIP call initiators and 15 are receivers; plus one node as a SIP server) in all scenarios for better comparison of the results. This setup reflects typical real-life cases such as a first responder team with around 30 nodes, a rural area/campus/school/hospital with around 30 nodes, and a platoon with around 30–35 nodes. The receiving nodes are configured to "Accept Call" states. The whole simulation time configured for each scenario is 500 s with the consideration of some buffer in case the call extends beyond 300 s.

Configuration Parameters

The technologies and standards configuration details are important for understanding how these simulations scenarios were set up and configured. In most cases the default parameters have been used; we have only configured specific parameters in scenarios where they are required for the technology and protocol to work. The configured parameters for IEEE 802.11g/n standards are given in Table 4.

Table 4. IEEE 802.11g/n physical configuration parameters.

Parameters	Values		Remarks
	802.11g	**802.11n**	
Phy-model	Phy802.11g	Phy802.11n	Common 802.11 standards
Transmit power (dBm)	20	20	Max transmit power for a node
Phy802.11-frequency-band	2.4	2.4	Used instead of 5 GHz, better coverage
Phy802.11-20MHz-channel-index	6	6	Operating channel

The configured parameters for IEEE 802.11, 802.11e and 802.11s are described in Table 5. The IEEE 802.11 MAC is the generic MAC for IEEE 802.11g. IEEE 802.11e is configured due to the constraint of the simulation tool, since we are only allowed to use IEEE 802.11e for the 802.11n PHY to work; however, the parameters for IEEE 802.11e MAC used in our simulation scenarios are the same as the IEEE 802.11 generic MAC given in Table 5. Furthermore, the VoIP-only traffic is simulated without any background traffic in all scenarios including the IEEE 802.11n/e scenarios in order to compare it with the IEEE 802.11g/s VoIP-only scenarios, since this is the focus of our work. Thus no different access categories were configured. On the other hand, IEEE 802.11s parameters are different and the HWMP parameters are also described under the 802.11s column since HWMP is configured as part of the IEEE 802.11s MAC protocol feature in on-demand mode. The configured parameters for the AODV routing protocol are given in Table 6.

Table 5. IEEE 802.11/e/s and HWMP MAC configuration parameters.

Parameters	Values			Remarks
	802.11	**802.11e**	**802.11s**	
MAC-PROTOCOL	**MACDOT11**	**802.11e**	**MACDOT11**	
MAC-dot11-short-packet-transmit-limit	7	7	7	Default
MAC-dot11-long-packet-transmit-limit	4	4	4	Default
MAC-dot11-RTS-threshold	0	0	0	No limit
MAC-dot11-stop-receiving-after-header-mode	No	No	No	Default
MAC-dot11-association	None	None	Dynamic	Required for 802.11s
MAC-dot11-directional-antenna-mode	No	No	No	Not used
MAC-dot11-ssid	N/A	N/A	meeran	Required for 802.11s

Table 5. *Cont.*

Parameters	Values			Remarks
	802.11	802.11e	802.11s	
MAC-PROTOCOL	**MACDOT11**	**802.11e**	**MACDOT11**	
MAC-dot11-ap	N/A	N/A	No	Not required
MAC-dot11-scan-type	N/A	N/A	Active	Required for 802.11s
MAC-dot11-sta-ps-mode-enable	N/A	N/A	No	Default
Dummy-MAC-dot11-set-mesh-parameters	N/A	N/A	Yes	Required for 802.11s
MAC-dot11s-mesh-id	N/A	N/A	meeran1	Required for 802.11s
MAC-dot11s-path-protocol	N/A	N/A	HWMP	Required for 802.11s
MAC-dot11s-hwmp-active-route-timeout	N/A	N/A	5 s	Default
MAC-dot11s-hwmp-my-route-timeout	N/A	N/A	10 s	Default
MAC-dot11s-hwmp-reverse-route-timeout	N/A	N/A	5 s	Default
MAC-dot11s-hwmp-route-discovery-type	N/A	N/A	Expanding-ring	Set for on demand mode
MAC-dot11s-path-metric	N/A	N/A	Airtime	Default metric for 802.11s
MAC-dot11s-link-setup-rate-limit	N/A	N/A	1	Default
MAC-dot11s-net-diameter	N/A	N/A	7	Default
MAC-dot11s-node-traversal-time	N/A	N/A	100 ms	Default
MAC-dot11s-portal-timeout	N/A	N/A	10 s	Default
MAC-dot11-directional-antenna-mode	N/A	N/A	No	Not required

Table 6. AODV parameters.

Parameters	Values	Remarks
Network Diameter	35	Default
Node Traversal Time	40 ms	Default
Active Route Timeout Interval	3 s	Default
My Route Timeout Interval	6 s	Default
Maximum RREQ Retries	2	Default
Route Deletion Constant	5	Default
Maximum Number of Buffered Packets	100	Default
Maximum Buffer Size	0	Default
TTL Start	1	Default
TTL Increment	2	Default
TTL Threshold	7	Default

4. Results and Analysis

During the experiments, all the required data such as delay, jitter, packet loss, and other statistical information were collected in order to correlate them for analysis purposes. However, to make the results more readable, we only present the MOS values for each scenarios analysis, which is derived considering the delay, jitter and packet loss values using the QualNet simulation software. We also present delay, jitter, and packet loss analyses for all scenarios for better interpretation of the results. As stated in Section 2, in order to simulate a realistic scenario in all simulation cases, we have configured a VoIP total loss probability of 5 percent. For scenarios where the MOS values are lower as compared to other sub-scenarios, we have looked at other factors to identify possible causes of QoS degradation. In the remainder of this section, we present our research findings for each scenario separately in terms of the obtained MOS values for the VoIP initiators and VoIP receivers; in the analysis summary of all scenarios, we also present the delay, jitter, and packet loss analysis for the VoIP initiators and VoIP receivers.

4.1. First Responders with Waypoint Mobility

This scenario considers 31 first responders approaching a disaster-affected site with an area of 400 × 600 m. The mobility pattern for each node is the waypoint mobility model. This mobility model reflects that the responders move to specific positions in order to approach the affected site and to provide the necessary help and support to people in the area. In QualNet, the movements and positions of nodes are based on their initial position and their next moves within the terrain. The nodes start moving at time 0 to position x and y. A node's movement speed is determined by the simulation tool in a way that it reaches next position x and y at the configured time slot. For example, if Node 1 is in position x = 276, y = 17 at time 0 s, and Node 1's next move is to reach position x = 243, y = 184 at time 60 s, this means that Node 1 moves 33 m along the x-axis and 167 m along the y-axis, so the node's movement is towards the y-axis. This gives an average speed of 2.7 m/s. Some nodes reach their final position after 240 s in four moves and some nodes reach it in eight moves. For nodes with four moves, the configured time for each movement is 60 s. For nodes with eight moves, the configured time for each movement is 30 s. For example, if Node 4's movement from its initial position at time 0 is x = 147, y = 27, this node's movement to the final position of x = 232, y = 336 at time 240 is configured with 8 moves, then the configured time for next movement is in 30-s time slots.

A screenshot of a scenario with the mobility pattern is shown in Figure 5. The flags with dotted lines show the positions to which the nodes move; the dotted lines connected to a cloud show the IPv4 subnet association. The solid lines show VoIP peers. The figure also shows the nodes' initial positions, waypoints/paths, and the nodes' final positions.

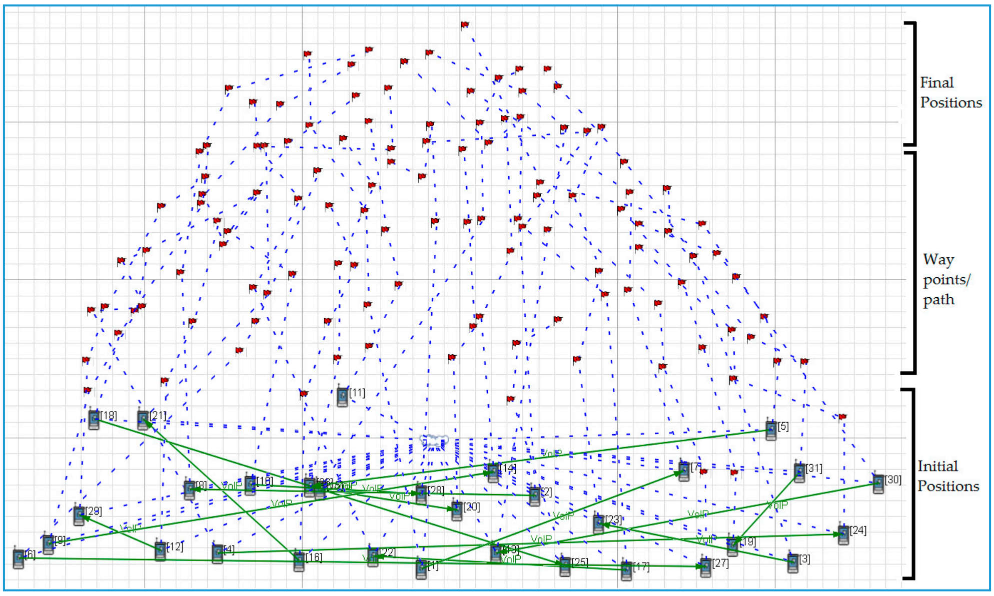
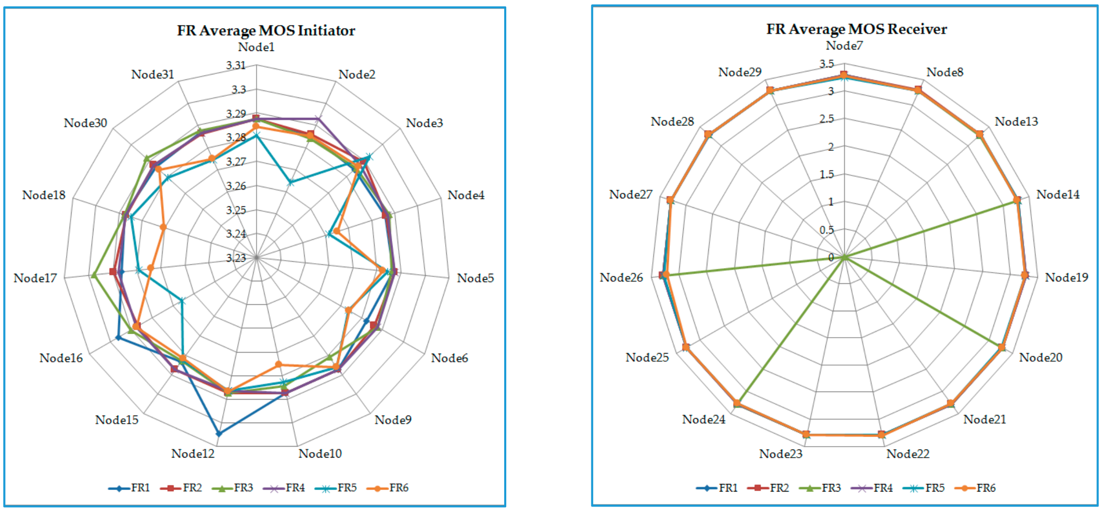


Figure 5. First responders with waypoint mobility. The flags with dotted lines show the positions to which the nodes move, the dotted lines connected to a cloud show the IPv4 subnet association. The solid lines show VoIP peers.

The main scenario of first responders with waypoint mobility has been tested in various sub-scenarios, as explained in Section 2. For ease of data representation, we named each sub-scenario FR1, FR2, etc. and these short names are mapped to the full scenario names in Table 3.

We have analyzed the MOS values of each sub-scenario. Among the six sub-scenarios, FR1 is the best performing scenario with the integration of IEEE 802.11g, 802.11s and G.711. FR5 which uses the IEEE 802.11n, 802.11e standards, and G.711 codec is the worst as compared to other sub-scenarios, as shown in Figure 6a for VoIP Initiators and in Figure 6b for VoIP receivers, respectively. The analysis shows that FR5 sub-scenario performance degradation is due to the 802.11n and IEEE 802.11e standards integration with the G.711 codec and AODV since FR6, which also uses same configuration parameter except the G.729 codec, is also not performing better as compared to other sub-scenarios that use the IEEE 802.11g standard.

From the analysis of the first responders' scenario, we can conclude that in sub-scenarios where the IEEE 802.11g standard is integrated with IEEE 802.11s, the MOS values show increased VoIP performance as compared to other sub-scenarios, while sub-scenarios with IEEE 802.11n show decreased VoIP performance.



(**a**) (**b**)

Figure 6. First responders with waypoint mobility MOS values for VoIP initiators and receivers: (**a**) VoIP initiator; (**b**) VoIP receiver.

4.2. First Responders with Random Mobility

In this scenario, it is assumed that the first responders are approaching a disaster-affected site using a random waypoint mobility model as shown in Figure 7. The dotted lines connected with a cloud show nodes association with an IPv4 subnet and the solid lines show VoIP peers. In this model, all nodes are configured with a minimum mobility speed of 1.1 m/s and a maximum mobility speed of 1.5 m/s, which is a typical mobility speed for pedestrian traffic.

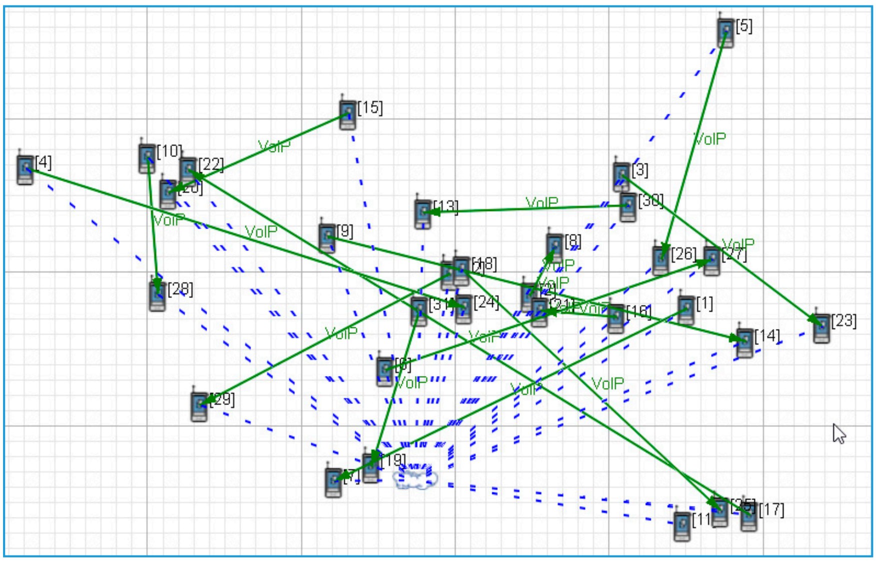


Figure 7. First responders with random waypoint mobility (captured during simulation).

The achieved MOS values in all the sub-scenarios are presented in Figure 8a for VoIP initiators and Figure 9b for receivers. The analysis shows that FRW4 is the best performing sub-scenario in which the IEEE 802.11g, IEEE 802.11, G.729, and AODV have been integrated. The FRW5 is the worst performing sub-scenario in which the IEEE 802.11n, IEEE 802.11e, G.711, and AODV have been integrated.

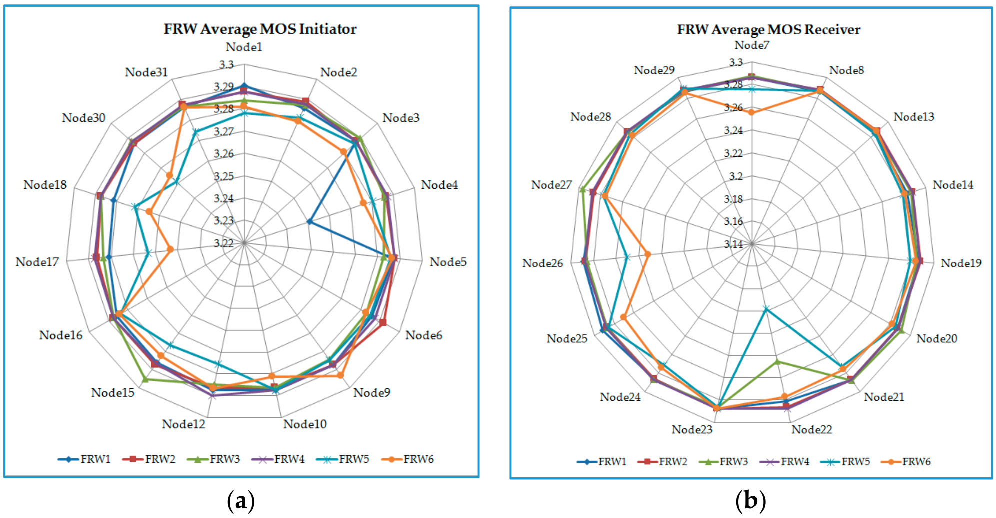


Figure 8. First responders with random waypoint mobility MOS values: (**a**) VoIP initiators; (**b**) VoIP receivers.

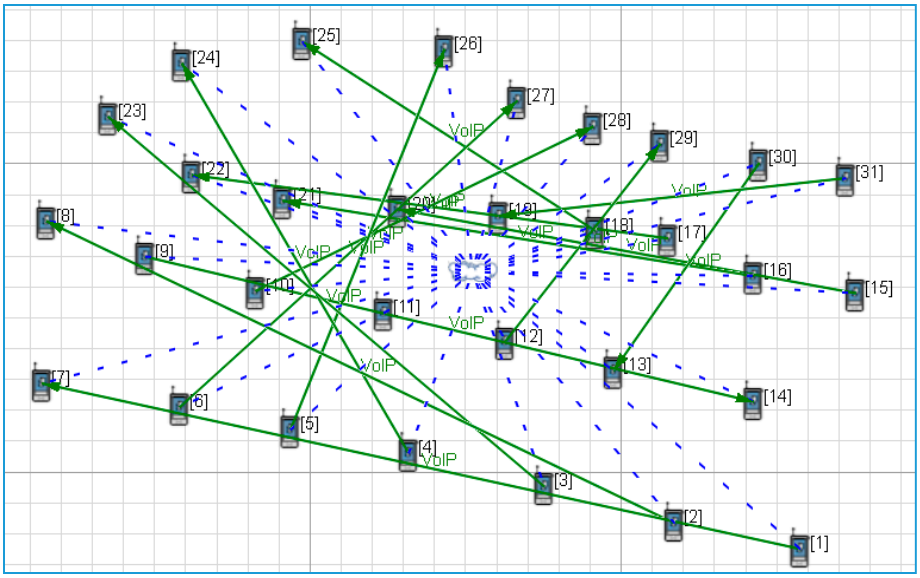


Figure 9. Flooded village scenario.

4.3. Flooded Village

In this scenario, a small village with 31 houses that has been affected by a flood is simulated, as shown in Figure 9. The dotted lines connected with a cloud show the nodes' association with an IP subnet and the solid lines show VoIP peers. As for the other previous two scenarios, the main scenario is experimented with six sub-scenarios. The terrain size is 300 × 300 m. All the nodes in the sub-scenarios are stationary and the nodes' configuration parameters are shown in Table 3. The analysis of this scenario shows that FV2 is the best performing sub-scenario in which IEEE 802.11g, 802.11, G.711 and AODV are integrated. The worst performing sub-scenario is FV6, in which IEEE 802.11n, 802.11e, G.729, and AODV are integrated, as shown in Figure 10a for the VoIP initiators and Figure 10b for the receivers.

By analyzing all sub-scenarios, we can conclude that IEEE 802.11g with AODV in the case of FV2 and FV4 without the IEEE 802.11s integration show better performance as compared to the other sub-scenarios.

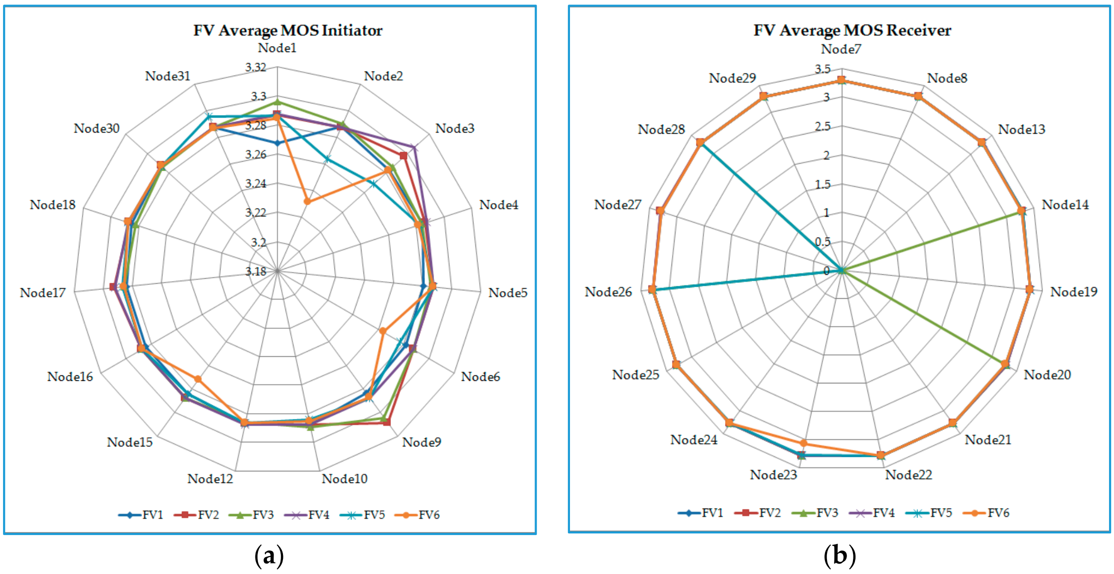


Figure 10. Flooded village MOS values for VoIP initiators and receivers: (**a**) VoIP initiators; (**b**) VoIP receivers.

4.4. Isolated Village

In this scenario, an isolated village in a remote area is considered. The terrain size for this simulation is 1500 × 1500 m. All the mesh nodes are stationary, as shown in Figure 11. The dotted lines connected with a cloud show the nodes' association with an IP subnet and the solid lines show VoIP peers.

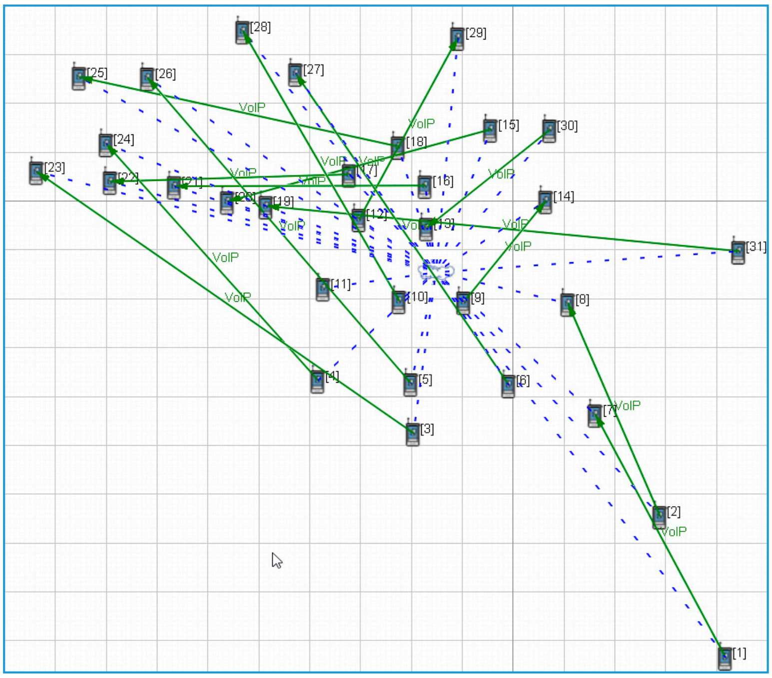
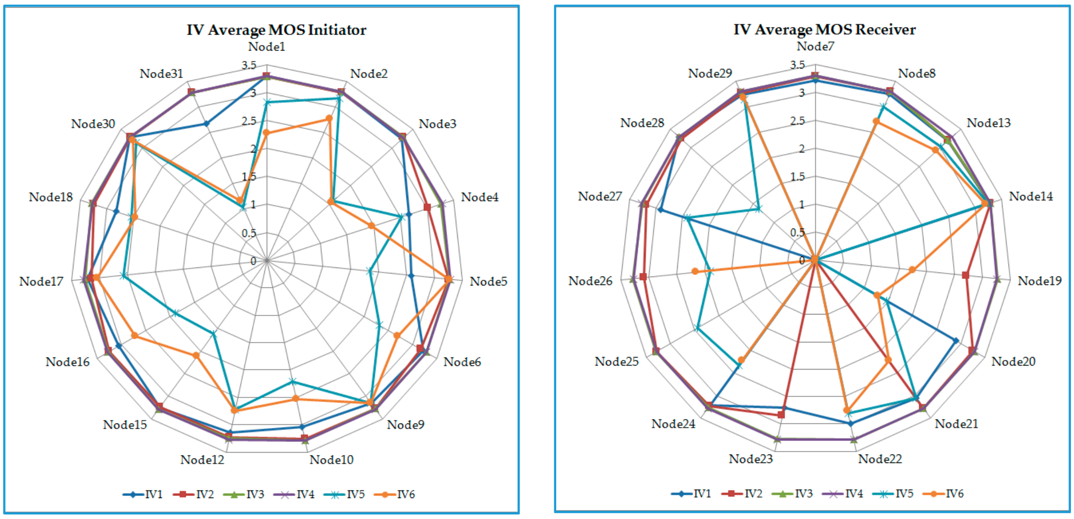


Figure 11. Isolated village scenario.

This main scenario is experimented under six sub-scenarios. The analysis of sub-scenarios shows that IV4 is the best performing sub-scenario, in which IEEE 802.11g, IEEE 802.11, G.729 codec, and AODV have been integrated. The worst performing sub-scenario is IV5, in which IEEE 802.11n, IEEE 802.11e, G.711 codec, and AODV have been integrated, as shown in Figure 11a for VoIP initiators and Figure 12b for the receivers.



(**a**) (**b**)

Figure 12. Isolated village MOS values for VoIP initiators: (**a**) VoIP initiators; (**b**) VoIP receivers.

The overall analysis of the sub-scenarios shows that IEEE 802.11g with AODV routing protocol without IEEE 802.11s integration results in better VoIP performance and IEEE 802.11n with AODV shows the worst VoIP performance.

4.5. Platoon

In this scenario, a platoon with 31 military personnel is considered in a line deployment in a terrain size of 400 $\times$ 600 m, as shown in Figure 13. This main scenario is experimented under six sub-scenarios. The nodes are configured with waypoint mobility. This mobility model makes the nodes move in a particular direction in order to keep the platoon's formation intact, while the nodes are moving.

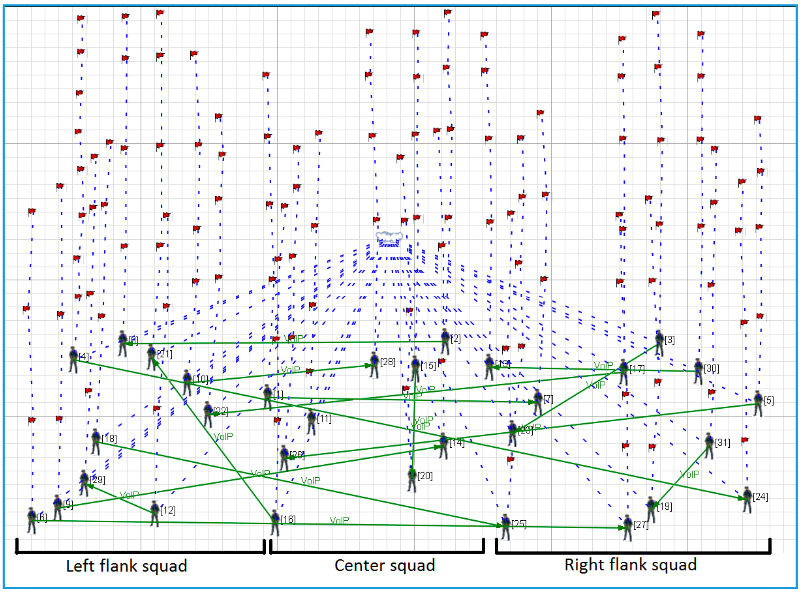
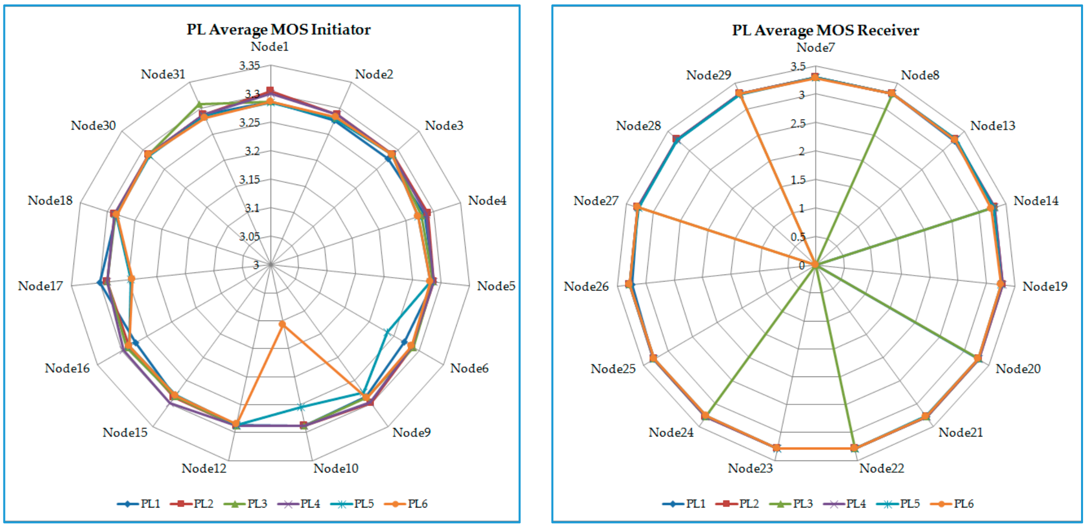


Figure 13. Platoon scenario line deployment.

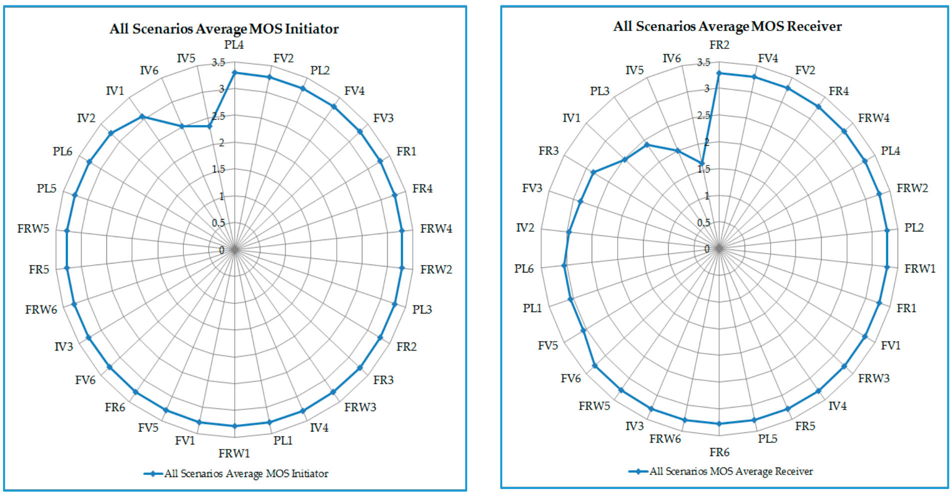
The analysis of this scenario and its sub-scenarios shows that the best performing scenario is PL4 in which IEEE 802.11g, IEEE 802.11, G.729 codec, and AODV have been integrated, as compared to other sub-scenarios. The worst performing sub-scenario is PL6, in which IEEE 802.11n, IEEE 802.11e, G.729, and AODV have been integrated, as shown in Figure 14a for VoIP initiators and Figure 15b for receivers.

The overall analysis of all sub-scenarios shows that IEEE 802.11g with AODV without the IEEE 802.11s integration results in better VoIP performance and IEEE 802.11n with AODV resulted in the worst VoIP performance.



(**a**) (**b**)

Figure 14. Platoon MOS values for VoIP initiators and receivers: (**a**) VoIP initiators; (**b**) VoIP receivers.



(**a**) (**b**)

Figure 15. All scenarios' MOS values comparison for: (**a**) VoIP initiators; (**b**) VoIP receivers.

4.6. Analysis Summary

In order to analyze how the nodes performed in terms of the VoIP quality considering the MOS values, delay, jitter, and packet loss in all scenarios, we have compared all scenarios' performance for VoIP initiators and receivers based on each scenario's results, as shown in Figure 15a for VoIP initiators and Figure 16b for receivers.

The analysis shows that the following scenarios with the mentioned choice of IEEE 802.11 standard(s), voice codec and routing protocol are the best performing ones for VoIP initiators based on the analysis of the MOS values (Figure 15), end-to-end delay (Figure 16), jitter (Figure 17), and packet loss (Figure 18):

- PL4 = Platoon, waypoint mobility, 802.11g, G.729 codec, AODV
- FV2 = Flooded village, no mobility, 802.11g, 802.11, G.711, AODV
- PL2 = Platoon, waypoint mobility, 802.11g, 802.11, G.711, AODV
- FV4 = Flooded village, no mobility, 802.11g, 802.11, G.729, AODV
- FV3 = Flooded village, no mobility, 802.11g, 802.11s, G.729, HWMP

For VoIP receivers, the following scenarios show the best VoIP performance:

- FR2 = First responders, waypoint mobility, 802.11g, 802.11, G.711, AODV
- FV4 = Flooded village, no mobility, 802.11g, 802.11, G.729, AODV
- FR4 = First responders, waypoint mobility, 802.11g, 802.11, G.729, AODV
- FRW4 = First responders, random waypoint mobility, 802.11g, 802.11, G.729, AODV
- PL4 = Platoon, waypoint mobility, 802.11g, , 802.11, G.729 codec, AODV

The analysis also shows that the following scenarios with the mentioned choice of IEEE 802.11 standard(s), voice codec and routing protocol result in the worst VoIP performance for VoIP initiators:

- IV5 = Isolated village, no mobility, 802.11n, G.711 codec, AODV
- IV6 = Isolated village, no mobility, 802.11n, G.729 codec, AODV
- IV1 = Isolated village, no mobility, 802.11g, 802.11s, G.711 codec, HWMP
- IV2 = Isolated village, no mobility, 802.11g, 802.11, G.729 codec, AODV
- PL6 = Platoon, waypoint mobility, 802.11n, G.729 codec, AODV

For VoIP receivers, the following scenarios show the worst VoIP performance:

- IV6 = Isolated village, no mobility, 802.11n, G.729 codec, AODV
- IV5 = Isolated village, no mobility, 802.11n, G.711 codec, AODV
- PL3 = Platoon, waypoint mobility, 802.11g, 802.11s, G.729 codec, HWMP
- IV1 = Isolated village, no mobility, 802.11g, 802.11s, G.711 codec, HWMP
- FR3 = First responders, waypoint mobility, 802.11g, 802.11s, G.729, HWMP
- FV3 = Flooded village, no mobility, 802.11g, 802.11s, G.729, HWMP
- IV2 = Isolated village, no mobility, 802.11g, 802.11, G.729 codec, AODV
- PL6 = Platoon, waypoint mobility, 802.11n, G.729 codec, AODV
- PL1 = Platoon, waypoint mobility, 802.11g, 802.11s, G.711 codec, HWMP
- FV5 = Flooded village, no mobility, 802.11n, G.711 codec, AODV

Considering the obtained results from the experiments and analysis of each scenario, the following conclusions can be drawn with regard to the VoIP initiators and receivers:

- Integrating the IEEE 802.11g, 802.11s standards with both voice codecs decreases the VoIP performance in scenarios with waypoint mobility and no mobility;
- Integrating the IEEE 802.11n with both voice codecs decreases the VoIP performance in scenarios where the nodes are distant from each other.

The MOS values for VoIP initiators and receivers are analyzed and compared in Figure 19. Although in most scenarios the MOS values for the initiator and receiver are the same, there are a few scenarios where the VoIP initiators have better performance compared with the VoIP receivers.

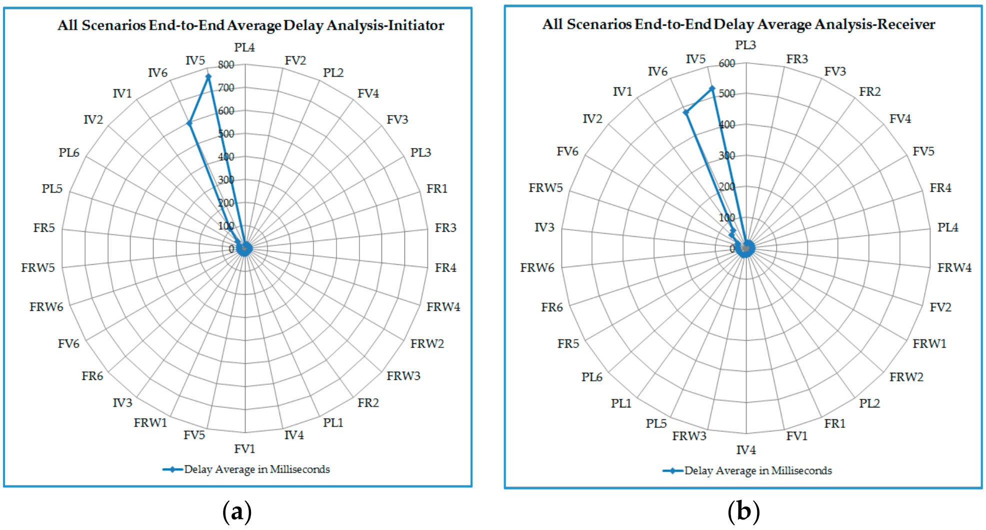


Figure 16. All scenarios' end-to-end average delay comparison for: (**a**) VoIP initiators; (**b**) VoIP receivers.

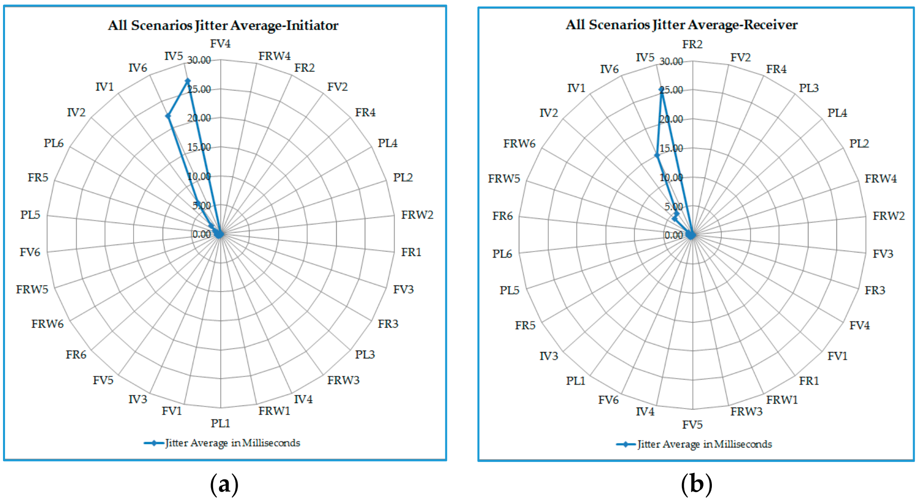


Figure 17. All scenarios' average jitter comparison for: (**a**) VoIP initiators; (**b**) VoIP receivers.

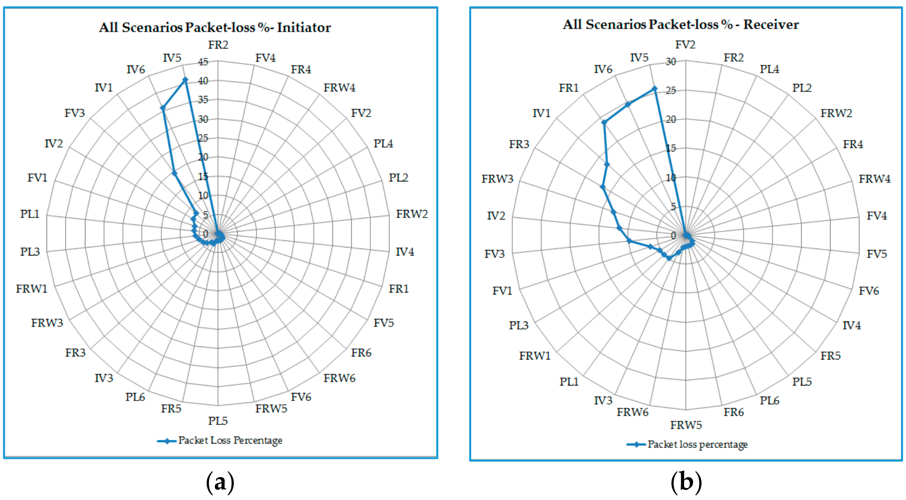


Figure 18. All scenarios' packet-loss % comparison for: (**a**) VoIP initiators; (**b**) VoIP receivers.

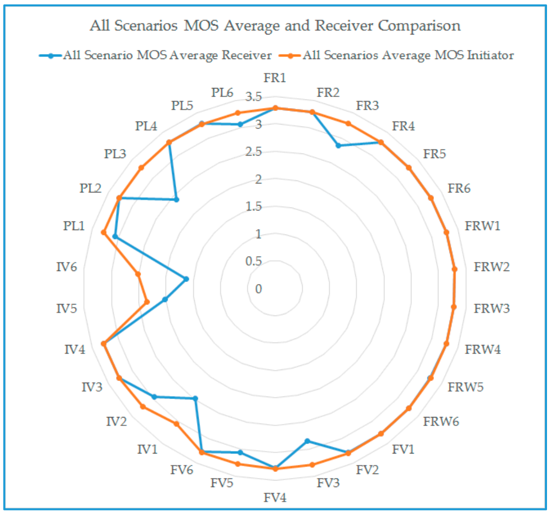


Figure 19. MOS values average comparison for VoIP initiators and receivers.

In order to draw a holistic conclusion from our experiments, we have identified the scenarios with best MOS values and the scenarios with the worst MOS values, as presented in Figure 20. The analysis shows that the following scenarios have the best MOS values (above 3.2) (highest first):

- PL4 = Platoon, waypoint mobility, 802.11g, G.729 codec, AODV
- FV2 = Flooded village, no mobility, 802.11g, 802.11, G.711, AODV
- FV4 = Flooded village, no mobility, 802.11g, 802.11, G.729, AODV
- PL2 = Platoon, waypoint mobility, 802.11g, 802.11, G.711, AODV
- FR2 = First responders, waypoint mobility, 802.11g, 802.11, G.711, AODV
- FR4 = First responders, waypoint mobility, 802.11g, 802.11, G.729, AODV
- FRW4 = First responders, random waypoint mobility, 802.11g, 802.11, G.729, AODV

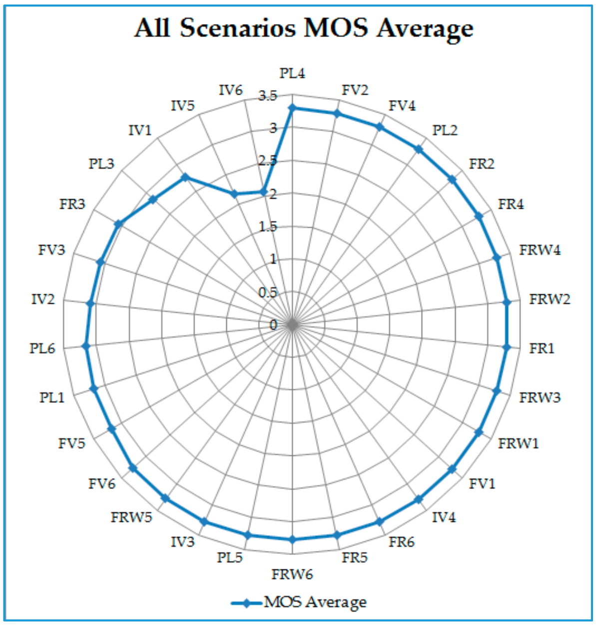


Figure 20. Average MOS values in all scenarios.

The following scenarios produce the worst MOS values in the listing order (lowest first) below 3.1 (fair), which is falling below the acceptable quality threshold:

- IV6 = Isolated village, no mobility, 802.11n, G.729 codec, AODV
- IV5 = Isolated village, no mobility, 802.11n, G.711 codec, AODV
- IV1 = Isolated village, no mobility, 802.11g, 802.11s, G.711 codec, HWMP
- PL3 = Platoon, waypoint mobility, 802.11g, 802.11s, G.729 codec, HWMP
- FR3 = First responders, waypoint mobility, 802.11g, 802.11s, G.729, HWMP
- FV3 = Flooded village, no mobility, 802.11g, 802.11s, G.729, HWMP
- IV2 = Isolated village, no mobility, 802.11g, 802.11, G.729 codec, AODV

Additionally, the analysis of the scenarios in terms of the standards, codecs and protocols integration is presented in Figure 21. The analysis of the results shows that IEEE 802.11g without the IEEE 802.11s integration along with G.711 and G.729 codecs and AODV routing protocol results in achieving better VoIP performance, followed by the IEEE 802.11g integration with IEEE 802.11s using the same codecs and HWMP protocol. While the IEEE 802.11n with the same voice codecs and AODV routing protocol result in poor VoIP performance, the analysis also shows that scenarios with mobility mostly result in producing better MOS scores as compared to scenarios with no mobility.

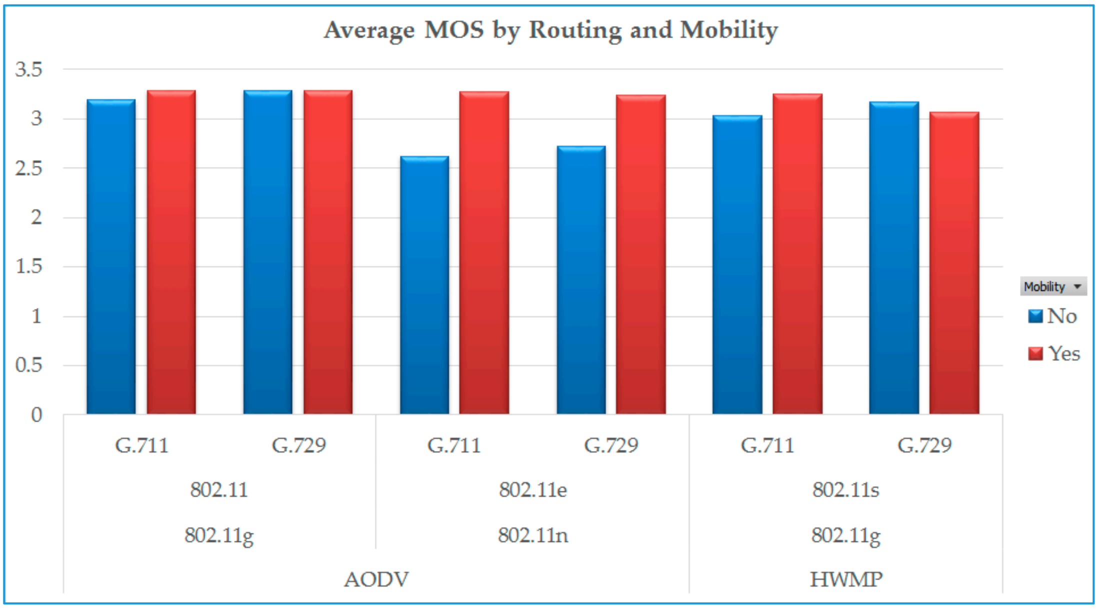


Figure 21. Average MOS by routing and mobility.

5. Conclusions

This research work considered various scenarios in which WMNs could be implemented, specifically the scenarios where VoIP applications are mostly preferred. Emergency relief efforts in case of earthquake, flooding, cyclones, fires, etc. have been discussed and identified as the scenarios where WMNs and VoIP applications could be used to save lives and help affected people.

From those many cases of VoIP implementation in WMNs, we selected five scenarios for our experimental research, namely first responder with waypoint mobility, first responders with random waypoint mobility, flooded village, isolated village, and a platoon deployment with waypoint mobility. Each scenario has been tested under six sub-scenarios with the integration of IEEE 802.11g, 802.11n, 802.11s, 802.11e, AODV, and HWMP routing protocols, G.711 and G.729 codecs. Call duration was 180 s and the simulation time was 500 s.

The analysis of the results shows that integration of IEEE 802.11g, 802.11s standard with G.711 and G.729 codecs using HWMP routing protocol decreases the VoIP quality as compared to scenarios without the IEEE 802.11s integration using AODV routing protocol. Moreover, using G.711 and G.729 codecs with the IEEE 802.11n standard using AODV routing protocol in WMNs installations where the distances between the nodes are greater can result in decreased VoIP performance as compared to scenarios with IEEE 802.11g using the same codecs and same routing protocol. In general, scenarios with IEEE 802.11g standard without integration of IEEE 802.11s result in better VoIP quality followed by the scenarios with IEEE 802.11s integration, while IEEE 802.11n showed decreased performance in all scenarios.

This research's scope involved IEEE 802.11g/n/e/s standards using HWMP hybrid path selection protocol and AODV reactive routing protocol, along with high bit rate (G.711) and low bit rate (G.729) voice codecs on selected WMN scenarios. Our future efforts will focus on the inclusion of at least one proactive routing protocol, a medium bit rate codec, and scenarios with no-mobility, partial mobility and full mobility. Additionally, we will also propose approaches that can lead to improvement of VoIP QoS in WMN scenarios. Focused research efforts on IEEE 802.11n/ac standards integration with 802.11s, codecs of variable bit rates, different type of WMN routing protocols could be considered valuable contributions in this domain.

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