BALKAN JOURNAL OF ELECTRICAL & COMPUTER ENGINEERING, Vol. 10, No. 2, April 2022

A Dual-Radio Hybrid Mesh Topology for Multi-Hop Industrial IoT Networks in Harsh Environments

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***Abstract*—Industrial Internet of things (IIoT) is a paradigm that changes the way people interact with infrastructures by enabling ubiquitous connection to the Internet. It allows to design connected infrastructures in industrial environments, e.g., factories, in order to support innovative services and improve efficiency. While the advantages of IIoT are numerous, it has some fundamental issues such as propagation of signal through metallic obstacles, i.e., walls in industrial environments. To address this issue, we propose a hybrid wired-wireless mesh node and network topology called hybrid mesh network (HMN), enabling the signal to cross over the metallic obstacles in harsh environments. The proposed hybrid mesh node utilizes dual-radio feature of IEEE 802.11 Wi-Fi standard to improve the performance of the proposed HMN further considering multi-hop communications. The effects of the packet size and different fading channels on the performance of the proposed HMN are investigated through various simulations. In addition, the performance of the proposed HMN is compared with that of conventional wireless mesh network (WMN). The results reveal that the proposed HMN outperforms conventional WMN and the proposed topology is promising for the implementation of high performance wireless mesh networks in harsh environments.**

***Index Terms*—Wireless mesh networks, harsh channel environments, multi-hop communications, industrial internet of things (IIoT).**

I. Introduction

WITH the recent explosive interests in the Internet of Things (IoT), the researchers have started to focus on wireless connectivity. Various wireless connectivity options are available, especially for Industrial IoT (IIoT) applications [1]. These options include IEEE 802.15.4 based technologies (e.g., Zigbee, 6LoWPAN), Wi-Fi, and Bluetooth Low Energy (BLE) [2], [3]. Among these options, Zigbee [4], 6LoWPAN [5] and Wi-Fi are promising technologies due to their supports of wireless mesh network (WMN) topology.

IEEE 802.11s standard specify the WMN topology for Wi-Fi networks [6]. This technology enables clients to support multiple connections. In other words, it is not necessary that clients connect to only one of the other clients on the network, but also communicate with multiple clients simultaneously. Even if any of the nodes become inoperable, the other nodes can communicate directly with each other or indirectly through each other. Therefore, WMNs are more practical and robust than other types of wireless networks.

Note that the WMNs can consist of mesh points, mesh routers, mesh gateways and mesh clients depending on the type of WMN topology. The characteristic features of WMNs are dynamic configuration and ability of self organization, quick detection of link errors, error-tolerant connection and back-up option on the network, expandable coverage with multi-hop architecture [7]. Moreover, the performance degradation of network, use of management protocols, applicability of different types of wireless networks and mesh topology are corresponding to the scalability, ease of use, collaborative and accessibility parameters respectively as the critical design requirements for WMNs.

One of the main challenges of WMNs in the harsh environments, such as industrial areas (e.g. factories), is covering large areas using closely spaced mesh nodes, e.g. IIoT devices. Especially, the penetration of the signal through metallic walls and obstacles in industrial environments is critical for achieving ubiquitous network coverage [8]. Hence, we propose a hybrid mesh network (HMN) topology, which is a combination of wireless and wired mesh networking, and it allows the signals to cross-over the metallic walls through cables in harsh environments.

The proposed topology in this paper involves the usage of a hybrid mesh node, which encompasses both wired and wireless connections similar to [9]. The hybrid mesh node in simple term is a single node that can be potentially used at the walls or any other separation, but supporting both wireless and wired mesh networks. The hybrid mesh node has a wireless interface on one side and Ethernet cable interface on the other side. The use of two hybrid mesh nodes across the wall or any other harsh physical separation serve the purpose. This primarily happens by converting a wireless mesh network signal to an Ethernet signal at one hybrid node and reverse process at the other hybrid node.

Considering its easy and fast deployment with existing infrastructures [10] together with its high throughput and low latency advantages [11], WMN is a good candidate for harsh environmental conditions, such as post disaster communication [12], emergency crisis in smart cities [10], and industrial automation environment [13]. On the other hand, IoT is also one of the main technologies that comes into mind as a solution in harsh environmental conditions like high risky areas [14], energy optimization and data recording in this kind of environments [15], [16].

The rest of the paper is organized as follows: In Section II, previous works related to current topic is presented. Then, the proposed HMN topology is introduced in Section III. The performance of the proposed HMN topology is demonstrated

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Manuscript received November 3, 2021; accepted April 13, 2022.
DOI: 10.17694/bajece.1018583

in Section IV. Finally, the conclusions and future works are concluded in Section V.

II. Related Works

WMN is a wireless system with the decentralized topology, generally to serve a large geographical area. Every node in the network can independently interact with the other nodes around it without any centralized system and distribute data among each other. Each node having access to the surrounding nodes, makes sure that no interruption of data flow happens from one point to other if any of the intermediate node fails. The high level of reliability, along with the flexibility, self healing and self configurable properties [17] make WMN an ideal choice to integrate into emerging technologies and it is expected to play an important role in the IoT applications [18].

A routing protocol associated with every topology determines the specific choice of the route with which the components involved in the network communicates. A WMN can be employed with three types of protocols, which are proactive, reactive and hybrid protocols [19] . In proactive protocol [20], the route information is exchanged between the hosts periodically so that each node has the knowledge about the overall network. This protocol reduces the route discovery delay of the network but it is generally used for small networks. For instance, the protocols like Destination-Sequenced Distance-Vector Routing (DSDV) [21], Optimized Link State Routing Protocol (OLSR) [22] are the examples for proactive routing. On the other hand, the reactive protocols are the routing protocols that each node does not keep the knowledge of the full network topology but just only on demand. In this case, the route request will be flooded only when there is a requirement. As a result, the latency will be higher when a new route need to be discovered upon request. But, the reactive protocols reduce the traffic overhead as the request will be flooded only upon a requirement. The Dynamic Source Routing (DSR) [23] and Adhoc On-Demand Vector (AODV) [24] [25] are typically used reactive protocols. Given that the hybrid protocols are the combination of both proactive and reactive protocols, it exploits the advantages of both approaches. Additionally, Hybrid Wireless Mesh Protocol (HWMP) [26] and its secure version Secure Hybrid Wireless Mesh Protocol (SHWMP) are the common hybrid routing protocols that can be cited.

The conventional WMN find itself in a difficult position to fit in topologies with harsh environments. This is attributed to the fact that the path loss is high across these harsh environments and would finally end up being in no signal for such situation [27]. This along with the packet loss, which can happen with every hop in the WMNs, further exacerbates the performance of a network [28]. At the present, to the best of our knowledge, there is not any practical solution which can provide a reliable connection between the clients across signal opaque separation walls using WMN. A conventional WMN can provide a good connection in a non-harsh environments (e.g., open air) generally with a hop count of not more than four and also in a topology without any hard core separation walls. A normal wall cause permissible signal attenuation but with high opaque severity separation, large amount of signal attenuation can occur which lead the signal not to penetrate the obstacles. Using a wired connection across the wall in such scenario can minimize the signal attenuation and make the signal pass through the metallic walls. Hence, a combination of conventional wireless mesh networking along with a wired mesh networking (i.e., HMN) can serve the requirement of providing a reliable communication with high throughput and low latency in such harsh environments, which is the main contribution of this paper. Although there are protocols like Open Shortest Path First (OSPF) which is basically designed for wired links and has the possibility of extending to the wireless links [29], the major issue with these kind of protocols is that they are not currently deployed for the WMNs and the complexity can arise while trying to utilize its features over WMN.

III. The Design of Hybrid Mesh Network Topology

A. The Proposed Hybrid Mesh Node Structure

This section describes the structure of the proposed hybrid mesh node. The hybrid mesh node mainly consists of modules performing encapsulation and decapsulation, which is shown in Figure 1.

In this structure, any received wireless mesh signal is broadcasted to other wireless mesh nodes like in a conventional wireless mesh network. The same signal is also converted to an Ethernet frame by the encapsulation module in order to cross over the metallic obstacles. Then, the encapsulated signal is later put through the Ethernet cable, which is connected across the metallic obstacles to another hybrid mesh node on the other side of the metallic obstacles. The hybrid mesh node is best suited to be positioned in high density obstacle environment where wireless coverage is obstructed by the metallic surface and walls. This topology is specially developed to address harsh environments, such as factories. The Ethernet and mesh frames are converted into the network seamlessly by means of hybrid mesh node which combines wireless and wired interfaces.

B. The Implementation of Hybrid Mesh Node in OMNET++ Environments

We have implemented the proposed hybrid mesh node in OMNET++ environments [30]. Note that OMNET++ is an Eclipse-based simulation tool that generally utilizes some simulation frameworks. Thus, INETMANET framework that is based on INET, is used for the implementation of the proposed hybrid mesh node.

In this study, the proposed hybrid mesh node is realized as a mesh gateway in OMNET++ platform. It consists of an Ethernet mesh interface and wireless mesh interface for the point to point connection and wireless mesh connection, respectively. The implemented hybrid mesh node in OMNET++ is illustrated in Figure 2. In this implementation, the hybrid mesh node receives packets from its neighbour wireless mesh node, and then the received frame is encapsulated as Ethernet frame and forwarded over the wire in order to cross

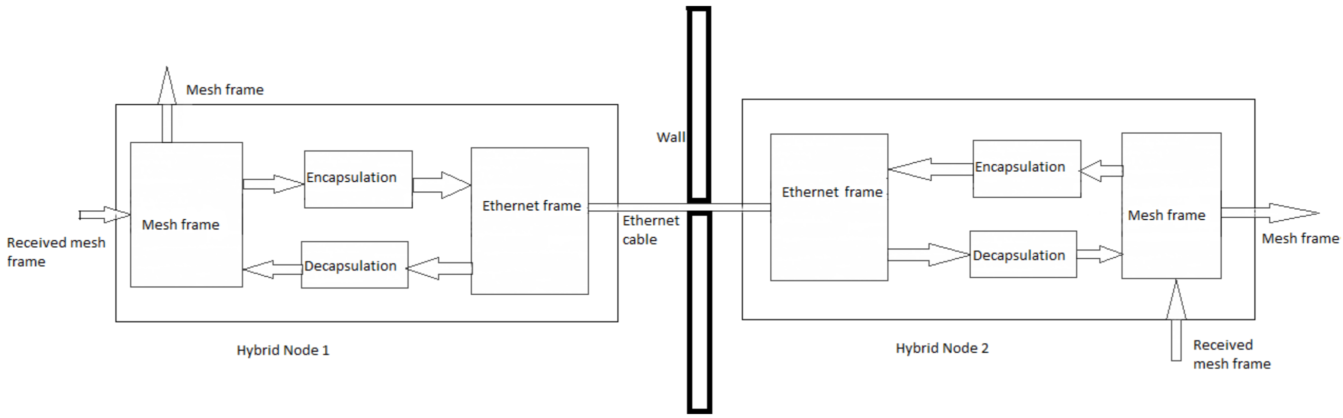

Fig. 1. The proposed hybrid mesh node structure

the metallic walls. On the opposite side of the wall, all the processes are applied reversely, which is the conversion of Ethernet frames into mesh frames through decapsulation module and then transmission of them over wireless interface. It is worth to note that the hybrid mesh node has an adaptive behavior in the sense that it can switch between wireless and wired interfaces if one of them fails. In other words, when the destination is accessible over wireless interface, the hybrid mesh node broadcasts mesh frames to other nodes acting as a mesh node without using wired interface. On the other hand, when the destination is not accessible over wireless interface, then the hybrid mesh node tries to expand the network coverage with the wired interface.

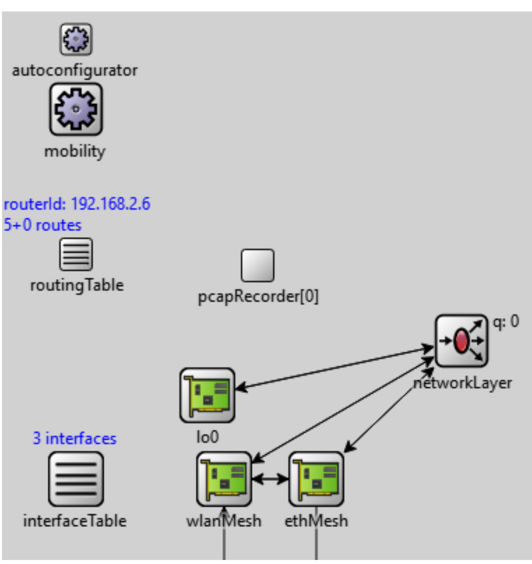

Fig. 2. The implementation of hybrid mesh node structure in OMNET++ environment

IV. Simulation Setup and Results

A. Simulation Setup

In order to demonstrate the performance of the proposed HMN for multi-hop networks in harsh environments, we consider an industrial area consisting of metallic walls and obstacles as shown in Fig 3. The industrial harsh environment is considered as $250m \times 100m$ with all metallic walls. This area has total 6 rooms and the metallic walls are configured in order to pass the data traffic over the hybrid mesh nodes. In the simulation setup, we consider 6 mesh hosts (e.g., mesh IIoT users), 6 Wi-Fi access points (APs) that is called fixhosts in OMNET++ and 10 mesh nodes (called MPP in OMNET++). It is worth to emphasize that the connection of the proposed hybrid mesh nodes is illustrated in OMNET++ as two hybrid mesh nodes connected back-to-back through a wall. Note that the Wi-Fi APs are equipped with dual radios, i.e. 5GHz and 2.4GHz in our study. Based on this dual-radio feature, all the Wi-Fi APs utilize 5GHz radio for the AP-to-AP communications links and 2.4GHz radio for the AP-to-Mesh hosts communications links. Without loss of generality, the mesh hosts, APs and hybrid mesh nodes are positioned sequentially in this setup for tracking multi-hop network easily. Thus, the proposed HMN is designed as a grid topology in OMNET++ environment. In conclusions, the simulation parameters in Table I is used to obtain the results unless otherwise stated.

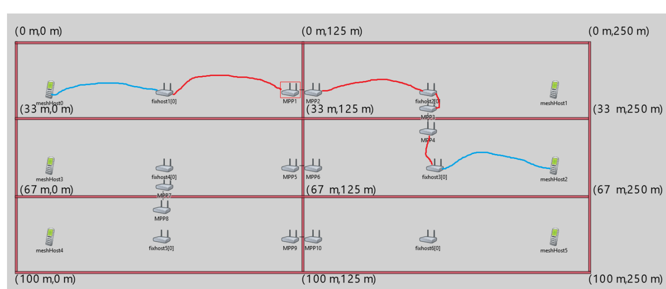

Fig. 3. Simulation environment for the proposed HMN

The simulation is performed for high density obstacle separations in order to show the performance of the proposed HMN in terms of throughput, delay, and jitter. We assume that meshHost0 sends video-stream packets to other Mesh hosts, which are meshHost1, meshHost2, meshHost3, meshHost4, and meshHost5. Note that each mesh host is associated with its mesh node, for example meshHost0 and fixhost1[0], and this is due to the design methodology of OMNET++ plat-

TABLE I
SIMULATION PARAMETERS

Parameters	Parameter values
Simulation Time	10s
Network Toplogy	Mesh
Number of Mesh IIoT Users	6
Area	250m x150m
Material Type	Aluminium
Radio Standard	IEEE 802.11g
Radio Bands	2.4GHz and 5GHz
Channel Propagation Model I	Rician ($K = 8$dB)
Channel Propagation Model II	Rayleigh Fadings
Path-loss exponent	$\alpha = 2.5$
Radio Maximum Tx Power	11 mW
Data Rate	54Mbps
Application Data	UDP and TCP
Packet Size	1400B, 512B and 256B
Routing Protocol	HWMP
Routing Metric	Hop Count

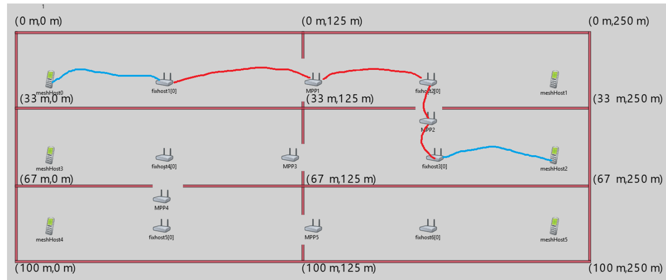

Fig. 4. Simulation environment for the conventional WMN

TABLE II
THE PAIRS OF MESH HOSTS

Server	Client
meshHost0	meshHost2
meshHost4	meshHost1

form. Furthermore, the video-stream packets are sent through User Datagram Protocol (UDP). For the path selection in the proposed HMN shown in Figure 3, the hybrid mesh node broadcasts path request message (PREQ) which includes Medium Access Control (MAC) address of the destination to all other hybrid mesh nodes until it reaches to the destination node. Each PREQ message contains sequence number in order to specify the minimum cost of path selection. Once the PREQ message arrives at the destination, it sends unicast path reply message (PREP) to the source for updating their paths.

In order to compare the performance of the proposed HMN with the performance of the conventional WMN, simulation environment shown in Figure 4 is considered for the conventional WMN. This setup takes into account of the case where the walls are half open allowing the signal to propagate between rooms in order to form direct mesh connectivity. This represents the situations where the topology has walls with some soft separation areas like doors, windows and even some open areas. It is obvious that the conventional wireless mesh nodes are used in this scenario. For instance, all the wireless mesh nodes broadcast PREQ to neighboring wireless mesh nodes and find the path from fixhost1[0] to fixhost3[0]. In this case, it can be observed that the total number of hops required to reach fixhost3[0] is 4. The lack of wire link property of WMN, wireless mesh node needs to broadcast mesh frames all around its neighbourhood to find the path to the destination. In this case, extra wireless mesh nodes might be used with additional hops to support the signal path as shown in Figure 4. As a result, the increase in the traffic load can hamper the throughput and exacerbate the latency of the network and hence deteriorates the performance of the mesh network.

Another scenario is simulated by sending video-stream packet between two pairs simultaneously using both UDP and Transmission Control Protocol (TCP) in order to show the effects of multi-user TCP and UDP traffics on the performance of the proposed HMN. The pairs of mesh hosts for this scenario is given in Table II.

We also investigate the effects of propagation channel on the performance of the proposed HMN by considering the path loss and small-scale fading effects. For the small-scale fadings, we consider Rayleigh fading channels for Non-line-of-sight (NLOS) and Rician fading channels for Line-of-sight (LOS) environments [31].

B. Simulation Results

The simulation results are obtained using the simulations parameters and setup in the previous section. Initially, we study the performance of the proposed HMN in Rayleigh channel considering the effects of different packet size (1400B and 256B) and the performance results in terms of throughput, delay, and jitter are shown in Figures 5, 6 and 7, respectively. According to the results in Figure 5, the throughput decreases as the number of hops increases for both packet sizes. Furthermore, the throughput increases with the packet size proportionally since the low packet size require more packets need to be transmitted than the higher packet size for the same amount of data. For instance, the proposed HMN achieves 1.62 Mpbs and 6.58 Mbps throughput when it utilizes packet sizes of 256B and 1400B, respectively, for 6 hops. Unless otherwise stated, we consider to use 1400B for the subsequent simulations.

The results in Figures 6 and 7 reveal that increasing the number of packet size for a given fixed time increases the delay and jitter. It is obvious that utilizing large packet size in order to send data will increase the delay and jitter. Additionally, it can be seen from the results that delay and jitter is proportional to the number of hops.

Following the performance study of the proposed HMN in harsh environments, now we compare its performance with that of conventional WMN in terms of throughput, delay and jitter considering the simulation environments in Figures 8, 9 and 10.

The results in Figure 8 show that the performance of the proposed HMN is better in Rician channel than Rayleigh channel. This is due to the fact that Rician is a channel modeling the LOS environments which is less harsh than the Rayleigh channel. More importantly, the proposed HMN outperforms the conventional WMN for both Rician and Rayleigh channels.

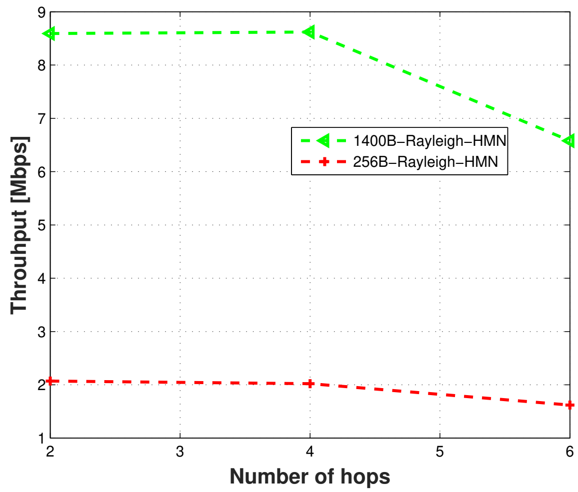

Fig. 5. Throughput vs. Number of Hops performance of HMN for different packet size in Rayleigh channels.

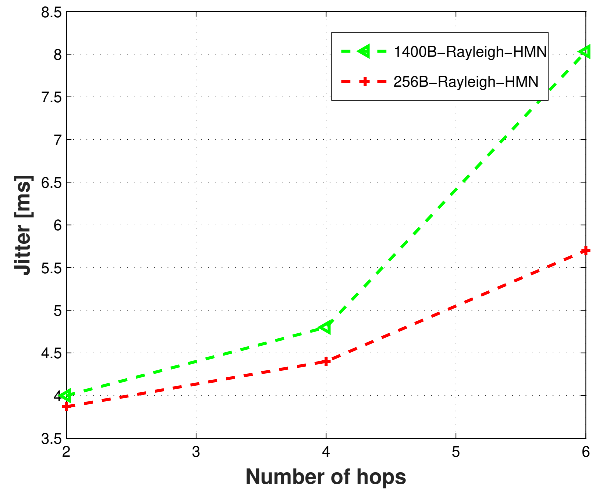

Fig. 7. Jitter vs. Number of Hops performance of HMN for different packet size

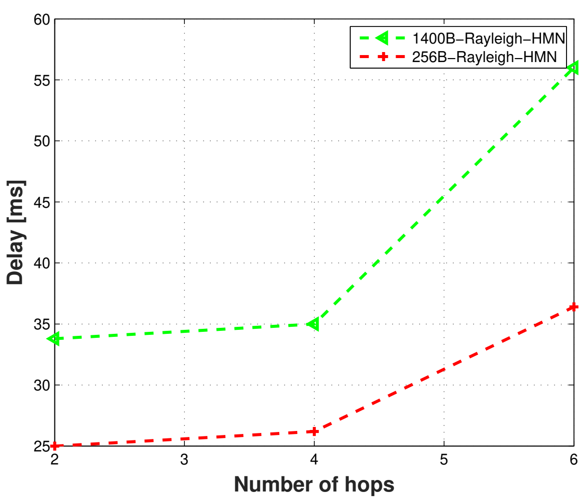

Fig. 6. Delay vs. Number of Hops performance of HMN for different packet size

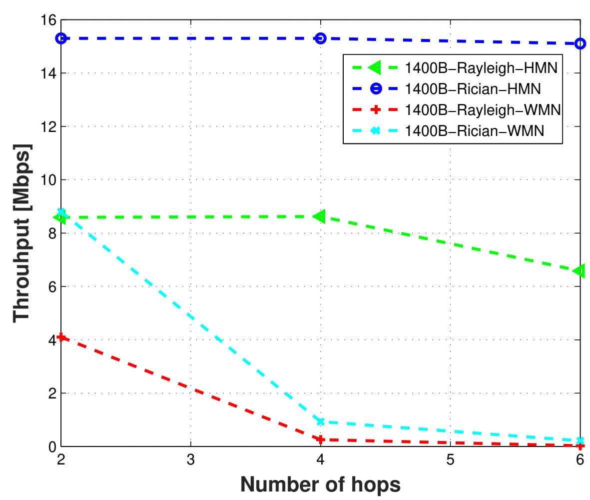

Fig. 8. Throughput performance of HMN and WMN under different channels.

The reason is the wired link reduces the traffic load just near its mesh nodes and also hybrid node capable of obtaining the Ethernet frames and sending mesh frames at the same time in the HMN case. On the other hand, in the WMN case, all the nodes are connected and communicates just only via wireless link that creates heavy traffic loads on each of them. As a result, the throughput of each node drastically decreases when the hop counts increase. Furthermore, it has to be noted that WMN's performance deteriorates for every hop count it undergoes whereas the changes are not that drastic in the HWM case. It is attributed to the usage of wide of nodes, such as MPP, fixhost, and host, rather than multiple simple mesh nodes as the only node utilized. The graph would depict a steeper plunge for WMN in performance and it is owing to the scale of representation in the plot as lower values comes as fractions and would be hard to represent when compared with other higher values.

According to the results in Figure 9, the proposed HMN experiences more delay in Rayleigh channel compared to Rician channel since the former one is more harsh environment than the latter one. Additionally, the proposed HMN performs better than the conventional WMN for both channels in terms of delay, especially for large number of hops. Similarly, the proposed HMN performs better than the conventional WMN for both channels in terms of jitter according to the results in Figure 10.

The performance of the proposed HMN topology is also evaluated under UDP and TCP traffic by sending video-stream packets and the role of nodes are given in Table II. The simulation results are obtained and tabulated in Table III in terms of throughput and number of hops. The results indicate that throughput is higher under UDP traffic than that of TCP for both two cases and it is attributed to the fact that TCP has more overhead inherently than that of UDP.

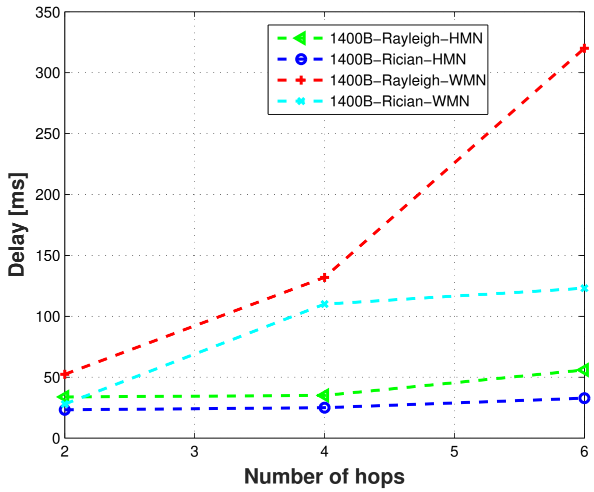

Fig. 9. Delay performance of HMN and WMN under different channels.

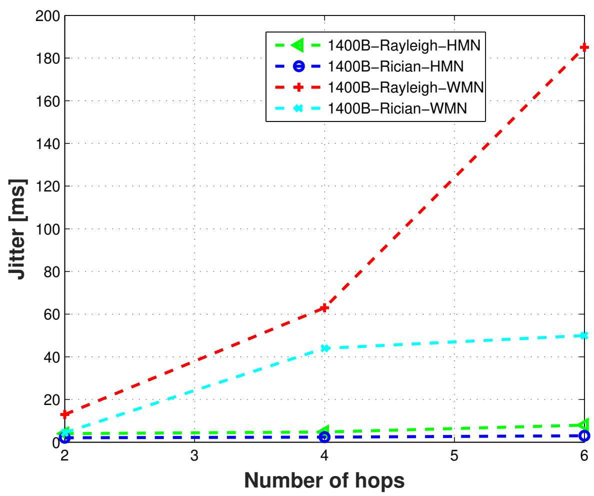

Fig. 10. Jitter performance of HMN and WMN under different channels.

TABLE III
PERFORMANCE OF HMN UNDER UDP AND TCP TRAFFIC

Client nodes	Throughput (Mbps)		Number of hops
	TCP	UDP	
meshHost1	1.3	6	6
meshHost2	0.97	7.19	4

In summary, the results show that the proposed HMN topology enables high performance wireless mesh networking even in harsh environments. This is achieved by the proposed HMN node, which converts the mesh frames into the Ethernet frames. This simply increases the coverage of network and it decreases the network latency and traffic load on the mesh nodes. As a result, the proposed HMN topology improves throughput, delay and jitter of conventional wireless mesh network. On the other hand, the conventional WMN suffers from the number of hops since the higher number of hops degrades the network performance and the complexity of WMN increases with number of mesh nodes and number of connection.

V. CONCLUSIONS

In this study, we proposed a multi-hop dual-radio hybrid wireless-wired mesh network topology (HMN) in order to address the signal propagation issue in harsh environments by emphasizing on IIoT applications. The proposed HMN topology allows the signal to cross over obstacles, such as metallic walls in harsh environments. In addition, the proposed HMN topology is implemented in OMNET++ environments and its performance is evaluated for different packet sizes under different fading channels. Furthermore, the performance of the proposed HMN is compared with that of conventional WMN. The results reveal that the proposed HMN outperforms the conventional WMN under different fading channels. In addition, the performance of the proposed HMN is investigated under TCP and UDP traffic. The results suggest that the proposed HMN topology is a promising solution for the realization of multi-hop IIoT networks in harsh environments. Inclusion of MIMO and multi-channel to the proposed HMN is expected to improve the performance of the multi-hop IIoT networks in harsh environments further, which can be considered as future directions.

REFERENCES

[1] M. Raza, N. Aslam, H. Le-Minh, S. Hussain, Y. Cao, and N. M. Khan, “A critical analysis of research potential, challenges, and future directives in industrial wireless sensor networks,” *IEEE Communications Surveys Tutorials*, vol. 20, no. 1, pp. 39–95, 2018.

[2] J.-S. Lee, Y.-W. Su, and C.-C. Shen, “A comparative study of wireless protocols: Bluetooth, uwb, zigbee, and wi-fi,” in *IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society*, 2007, pp. 46–51.

[3] P. Rawat, K. D. Singh, H. Chaouchi, and J. M. Bonnin, “Wireless sensor networks: a survey on recent developments and potential synergies,” *The Journal of supercomputing*, vol. 68, no. 1, pp. 1–48, 2014.

[4] G. Zhao *et al.*, “Wireless sensor networks for industrial process monitoring and control: A survey.” *Netw. Protoc. Algorithms*, vol. 3, no. 1, pp. 46–63, 2011.

[5] C. Hennebert and J. D. Santos, “Security protocols and privacy issues into 6lowpan stack: A synthesis,” *IEEE Internet of Things Journal*, vol. 1, no. 5, pp. 384–398, 2014.

[6] G. R. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, and B. Walke, “Ieee 802.11s: The wlan mesh standard,” *IEEE Wireless Communications*, vol. 17, no. 1, pp. 104–111, 2010.

[7] K. K.C, “Wireless mesh network: A survey,” in *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, 2016, pp. 1966–1970.

[8] J. Karedal, S. Wyne, P. Almers, F. Tufvesson, and A. F. Molisch, “A measurement-based statistical model for industrial ultra-wideband channels,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 8, pp. 3028–3037, 2007.

[9] W. S. Kish, A. Miu, and R. Mok, “Establishing a mesh network with wired and wireless links,” May 22 2018, uS Patent 9,979,626.

[10] A. Cilfone, L. Davoli, L. Belli, and G. Ferrari, “Wireless mesh networking: An iot-oriented perspective survey on relevant technologies,” *Future Internet*, vol. 11, no. 4, p. 99, 2019.

[11] T. Qiu, N. Chen, K. Li, M. Atiquzzaman, and W. Zhao, “How can heterogeneous internet of things build our future: A survey,” *IEEE Communications Surveys Tutorials*, vol. 20, no. 3, pp. 2011–2027, 2018.

[12] M. A. Ertürk, M. A. Aydin, L. Vollero, and R. Setola, “Ieee 802.11 s mesh network analysis for post disaster communication,” in *International Telecommunications Conference*. Springer, 2019, pp. 53–59.

[13] M. R. Ericsson, A. Anand, J. Harkulich, and K. A. Helfrich, “Data collection for assistance in an industrial automation environment,” Jul. 24 2018, uS Patent 10,031,495.

[14] M. Thibaud, H. Chi, W. Zhou, and S. Piramuthu, "Internet of things (iot) in high-risk environment, health and safety (ehs) industries: A comprehensive review," *Decision Support Systems*, vol. 108, pp. 79–95, 2018.

[15] G. d. Campo, S. Calatrava, G. Cañada, J. Olloqui, R. Martinez, and A. Santamaria, "Iot solution for energy optimization in industry 4.0: Issues of a real-life implementation," in *2018 Global Internet of Things Summit (GIoTS)*, 2018, pp. 1–6.

[16] F. Touati, A. S. P. Gonzales, Y. Qiblawey, and K. Benhmed, "A customized pv performance monitoring system in qatar's harsh environment," in *2018 6th International Renewable and Sustainable Energy Conference (IRSEC)*, 2018, pp. 1–6.

[17] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless mesh networks: a survey," *Computer networks*, vol. 47, no. 4, pp. 445–487, 2005.

[18] Y. Liu, K.-F. Tong, X. Qiu, Y. Liu, and X. Ding, "Wireless mesh networks in iot networks," in *2017 International Workshop on Electromagnetics: Applications and Student Innovation Competition*, 2017, pp. 183–185.

[19] V. M. S. and D. K. N., "Routing protocols for wireless mesh networks," *International Journal of Scientific & Engineering Research*, vol. 2, pp. 1–5, 2011. [Online]. Available: http://www.ijser.org

[20] S. Kumar, "Reactive and proactive routing protocols for wireless mesh network using multimedia streaming," in *Proceedings of the International Conference on Recent Advances and Future Trends in Information Technology (iRAFIT 2012)*, 2012.

[21] M. Manjunath and D. Manjaiah, "Spatial dsdv (s-dsdv) routing algorithm for mobile ad hoc network," in *2014 International Conference on Contemporary Computing and Informatics (IC3I)*, 2014, pp. 625–629.

[22] ——, "Spatial dsdv (s-dsdv) routing algorithm for mobile ad hoc network," in *2014 International Conference on Contemporary Computing and Informatics (IC3I)*, 2014, pp. 625–629.

[23] M. Ramadhan and M. Davis, "Performance study of a cross-layer optimization to the dsr routing protocol in wireless mesh networks," in *2009 International Conference on Network and Service Security*, 2009, pp. 1–5.

[24] S. Kolipaka, B. N. Bhandari, and A. Rajani, "Performance analysis of aodv with multi-radio in hybrid wireless mesh network," in *2014 Eleventh International Conference on Wireless and Optical Communications Networks (WOCN)*, 2014, pp. 1–5.

[25] L. Bello, P. Bakalis, S. J. Manam, T. I. Eneh, and K. A. Anang, "Power control and performance comparison of aodv and dsr ad hoc routing protocols," in *2011 UkSim 13th International Conference on Computer Modelling and Simulation*, 2011, pp. 457–460.

[26] I. Ibrahim, N. M. A. Latiff, S. K. S. Yusof, N. N. N. A. Malik, and S. H. S. Ariffin, "Performance comparison of aodv and hwmp routing protocols in wireless mesh networks," in *2013 IEEE International RF and Microwave Conference (RFM)*, 2013, pp. 116–120.

[27] S. Aksu and G. K. Kurt, "Effects of propagation path loss on the quality of voip over wireless mesh networks," in *2011 IEEE 19th Signal Processing and Communications Applications Conference (SIU)*, 2011, pp. 912–915.

[28] A. A. Pirzada, M. Portmann, and J. Indulska, "Performance comparison of multi-path aodv and dsr protocols in hybrid mesh networks," in *2006 14th IEEE International Conference on Networks*, vol. 2, 2006, pp. 1–6.

[29] P. Garnepudi, T. Damarla, J. Gaddipati, and D. Veeraiah, "Proactive, reactive and hybrid multicast routing protocols for wireless mesh networks," in *2013 IEEE International Conference on Computational Intelligence and Computing Research*, 2013, pp. 1–7.

[30] "Omnetpp Home Page," https://omnetpp.org/.

[31] T. Sarkar, Z. Ji, K. Kim, A. Medouri, and M. Salazar-Palma, "A survey of various propagation models for mobile communication," *IEEE Antennas and Propagation Magazine*, vol. 45, no. 3, pp. 51–82, 2003.

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