An Improved Multi-Channel Multi-Interface Routing Protocol for Wireless Mesh Networks

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Abstract—In recent years, Wireless Mesh Networks (WMN) are emerging as a potential technology to enhance the ability and availability of wireless networks. WMN consists of wireless mesh routers and terminals connected by wireless multi-hop communication. Besides, in WMN, each wireless node owns many interfaces, and each interface operates on many channels. However, effectively using multiple orthogonal channels and multiple interfaces to increase the performance of WMN and decrease the radio link transmission interference is of significant challenge. In this paper, we consider routing issues in WMN. Then, we proposed an on-demand routing protocol, adaptive multi-channel multi-interface operation, improved from the AODV protocol. This protocol is capable of effectively managing communication in the WMN and limited effects of co-channel interference. The simulation results on NS2 show that our proposed protocol improves throughput, delay and packet delivery rate compared to existing traditional protocols.

Keywords—wireless mesh networks, multi-channel, multi-interface, AODV

1 Introduction

Mobile devices have been widely used and are essential communication tools for humans in modern society. The network connecting mobile devices is increasingly complex, diverse in types and technologies. The next-generation mobile networks are attractive research topics in both industry and academia [1].

According to Cisco forecast, by 2023, over two-thirds of the world population will be connected to Internet with over 13.1 billion devices will have mobile connectivity Each citizen will have more than 3.6 network devices equivalent to around 29.3 billion devices that will be connected to the Internet. Most devices will be equipped with M2M (Machine-To-Machine) communication modules, which are the formed principle of IoT networks. The total of M2M connection numbers will account for over 50% of global network connections. Furthermore, mobile networks must support many times higher data traffic compared to possible existing systems [2]. Existing network technical and technological standards will be unsuitable [3]–[4].

The advent of the 5th generation mobile network, so-called 5G in the early 2020s expected to meet data transmission requirements, connecting at least 100 billion devices and the communication ability at high speeds 10 Gbps with fast service response times, ultra-low latency, and ultra-high bandwidth [5]–[6]. 5G enables the realization of the Internet of Things era and toward to Internet of Everythings [7].

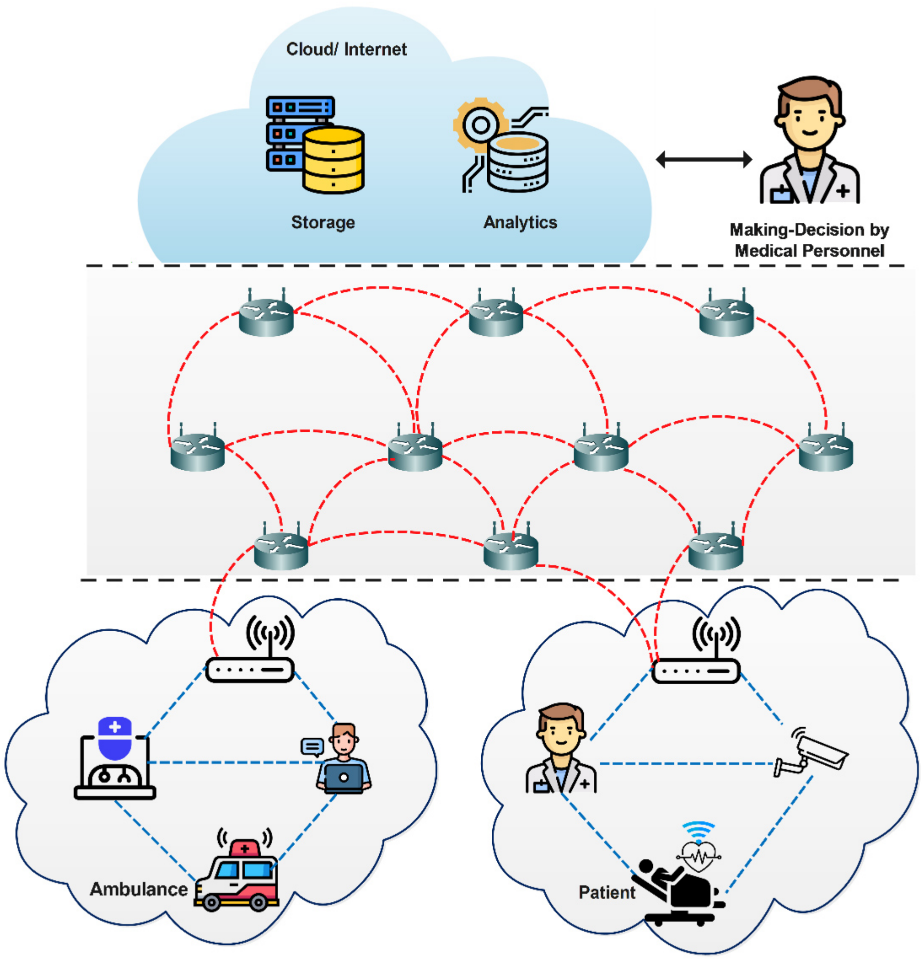

Fig. 1. The illustration of the WMN applications in e-Health domains

To achieve the requirements and quality of service of 5G networks, the researchers have proven that the evolution of the 4G networks must base on five core technologies, namely device-centric architectures, mm-Wave, massive MIMO, smarter devices, and M2M communications [8]. One of the typical networks for device-centric architecture and M2M communications are WMN [9]. In recent times, WMN has been focusing on research and application in various fields such as smart agriculture, manufacturing and IoT ecosystems [10–12]. Figure 1 presents a typical WMN application in smart healthcare domains. Specifically, mesh-connected client devices exchange data and communicate to wireless core routers, different mesh networks or the Internet. Through WMN, patients are supported by remote medical staff, doctors, and emergency services.

To improve the performance and quality of service of WMN, each network node usually has many interfaces. Each interface can operate at many channels [13]. WMN uses some key transmission technologies such as IEEE 802.11, IEEE 802.15 and IEEE 802.16 and has some main advantages as follows [14]:

– WMN can be deployed in a large area at a low cost;
– Mesh network technology can overcome connections with obscured range, large loss of transmission to expand service coverage;
– Using short-range communication technologies, WMN can improve transmission speed and energy efficiency, and channels of the same frequency can be reused between links over short distances;
– The mesh topology allows for multipath communication and increases the fault tolerance of the network;
– WMN technologies support and flexibly connect many different wireless access technologies.

Although WMN has many advantages, as described above. However, in wireless networks in general, performance and quality of service issues of WMN are challenging problems. Besides, due to the use of multi-channel multi-interface communication mechanisms, the problem of co-channel interference is also one of the significantly challenging problems [15].

In this study, we propose an on-demand routing protocol for WMN. This proposed protocol is capable of effectively managing channels in the network to reduce co-channel interference and improve the performance and quality of services. The rest of the article is organized as follows: In Section 2, we present the architecture of the WMN. The proposed routing protocol is described in Section 3. Section 4 presents the simulation and analysis results, and Section 5 is the Conclusion.

2 WMN architecture

In a WMN, network nodes consist of mesh routers and mesh clients. Depending on different application scenarios, the WMN architecture is organized like in [14] and [16].

– In the ***flat WMN architecture***, the wireless network nodes play both roles as terminals and routers. Consequently, each wireless node is a peer node and uses the peer-to-peer communication mechanism. This architecture has an outstanding advantage which is simple, but the disadvantage is low scalability and high resource constraints.
– In the ***hierarchical WMN architecture***, mesh-connected routers create the wireless core network infrastructure. The wireless routers have capable of self-configuration and self-maintenance communications. Mesh wireless routers also add bridge and gateway functions to connect to other networks or the Internet. This architecture enables resource management and mobility to be realized at mesh routers. When the client devices move, a client device group will create the ad-hoc

network organization. In the hierarchical architecture, some network state information is stored locally, and nodes play the role of group leaders performing the task of managing and coordinating routing information among the nodes in the network. When the network structure is changed, only the cluster leader is responsible for exchanging information with other nodes. This aims at improving system performance and optimizing the system.

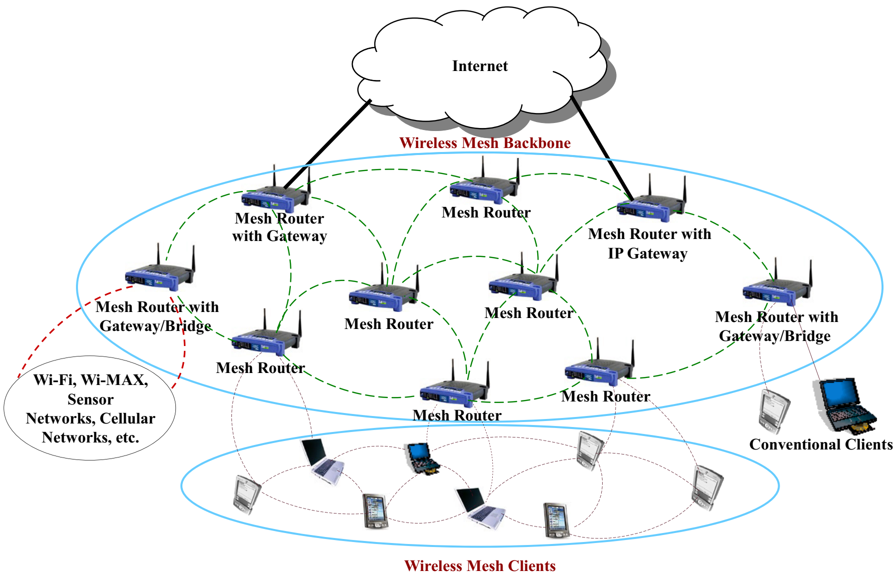

Fig. 2. An illustration of the Hybrid WMN architecture

– ***Hybrid WMN architecture*** is a combination of hierarchical WMN architecture and flat WMN architecture. Mesh-connected user devices can access the wireless core network through WMN routers or other user devices. The hybridization here is also shown in the aspect of using different wireless networks for communication. The hybrid WMN architecture can integrate many different network technologies for both the backbone network and the access network. Hopefully, this architecture will bring many benefits due to the ability to combine different network technologies. Figure 2 presents a typical Hybrid WMN architecture in which client devices can use communication technologies such as Wi-Fi, WiMAX, or sensor networks to connect to mesh routers.

We also propose a mobile node architecture to set up multi-interface multi-channel radio nodes in NS2, as shown in Figure 3. Each wireless node is equipped with multiple interfaces, and each interface can operate on many different channels.

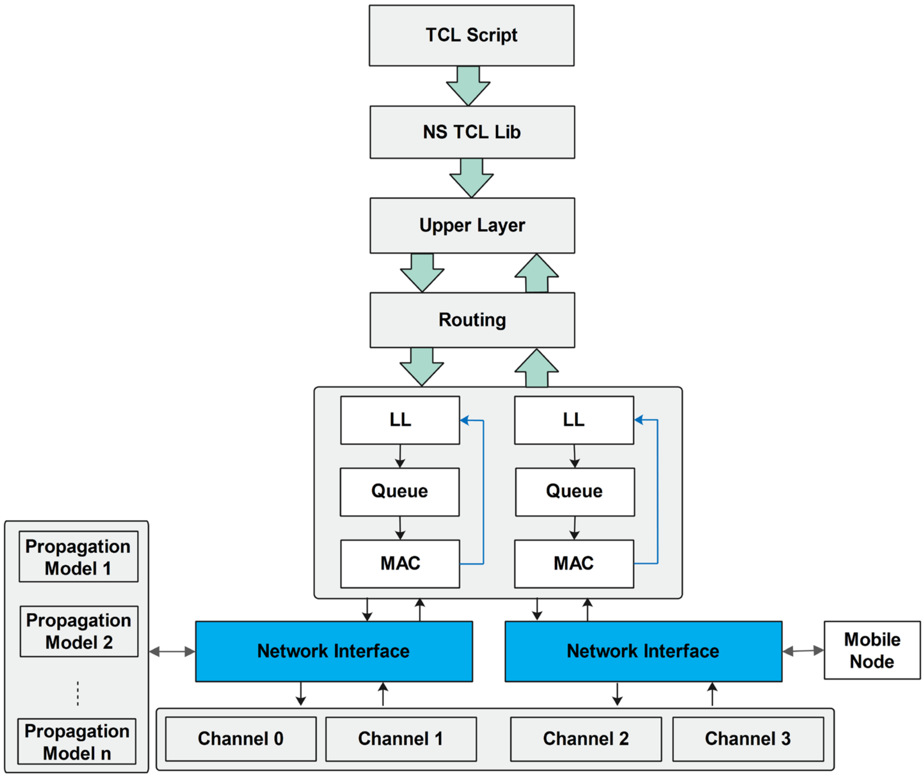

Fig. 3. Multi-channel multi-interface wireless node architecture in NS2

3 The proposed protocol

3.1 System model

We consider a radio communication system with N channels for data traffic and an additional channel for signal traffic. In this model, we set up each radio node with two interfaces.

- A fixed interface is assigned with a specific channel to receive data.
- A switchable interface capable of being assigned automatically among available channels for data transmission. These channels are also known as switchable channels. The switchable interface allows a node X transmits data to a Y neighbouring node by switching to the fixed channel of the Y node.

We also establish in the way that each wireless node stores two tables: MNT Table (MyNeighborsTable) stores fixed channels of neighbour nodes, and CUT Table (ChannelUsageTable) stores two-hop channel usage information.

3.2 Interface and channel assignment

(1) Fixed Interface: the fixed interface has main function: (1) to select a fixed channel for receiving data packets and (2) to notify neighbouring nodes about it. For example, a node is assigned the fixed channel with the value of 1. Then, node A uses this channel to receive data packets from other nodes. *Neighbouring* nodes should use different fixed channels to avoid co-channel interference that can lead to reducing system performance.

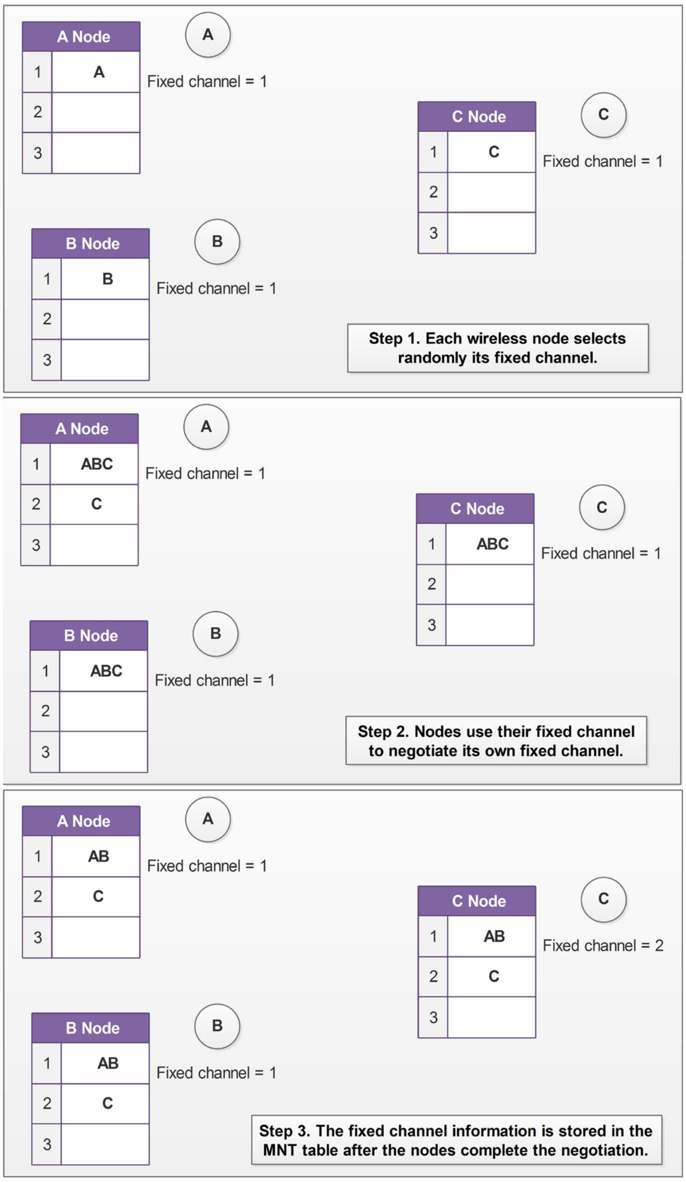

Fig. 4. The three-step negotiation process determines the fixed channel of the wireless nodes in the WMN

Initially, each wireless node randomly selects its fixed channel. Then, each node sends broadcast Hello packets containing information about its fixed channel and the MNT table in 2-hops. When a node receives a Hello packet, it updates the MNT table with information about the fixed channel of its neighbour and the CUT table with information about the number of nodes using the same fixed channel. Updating the CUT table based on the neighbours' MNT tables ensures that the CUT table will always contain the channel usage information in 2-hops. When an index is not updated for a period of time, it is removed from the table. Figure 4 illustrates the channel assignment algorithm in a simple example of *three* nodes and *three* channels in a WMN.

Besides, when receiving a Hello packet, the network node will check the information in its CUT table. If there are a lot of nodes using the same fixed channel, it will actively look for other channels with fewer nodes. If found, the network node performs a fixed channel change and sends Hello packets to the neighbouring nodes to announce its new fixed channel.

(2) Switchable Interface: After the fixed channel has been assigned to each node, the system needs to manage the switchable channels. In reality, to transmit data in the network, nodes must establish the channel of the switchable interface, which is the same as the fixed channel of the destination node. Therefore, we need a routing scheme to decide the channel switching, as follows:

Each channel (fixed and switchable channels) is associated with a packet queue at the source node, as shown in Figure 5. When multiple channels are used, a packet broadcast on a channel will be received only by nodes listening on that channel. Therefore, to send a broadcast packet, a copy of this packet will be added to all queues and will be broadcast when the channel is scheduled to broadcast. In this way, we are sure that all nodes will receive a broadcast packet.

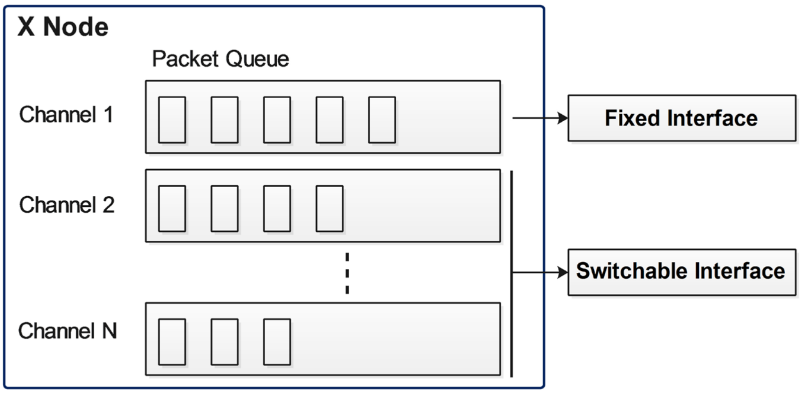

Fig. 5. Queuing model of channels in a wireless node

To ensure fairness of the system, the channel that has the earliest queued packets is always selected as the next switchable channel. The switchable interface only changes the channel when one of the conditions is satisfied, as follows:

- The queue of the switchable channel is empty; or
- The switchable channel has been operated over a period (*Max Time*).

(3) Route Discovery Process: We propose an on-demand routing protocol, improved from AODV protocol (Ad hoc On-Demand Distance Vector) [17], using the WCETT metric [18] to calculate and making-decision. The routing process begins when a route needs to be established between two nodes. The source node broadcasts a route discovery packet, the so-called RREQ (Route Request). The RREQ packet transmitted to node *X* on channel *i* contains the WCETT metric value and used channels along the path. This process will broadcast the RREQ packet in the same way as the AODV protocol.

When the destination node receives the RREQ packet, it resends a route through a reply packet called RREP (Route Reply) with a list of nodes, corresponding channels, and the WCETT metric. The source node will use the lowest-cost path for data transmission and save this path to the local routing table for a period.

(4) Route Maintenance: When a node detects a failed route, it broadcasts an error message called RERR (Route Error) to report a broken link. The RERR packet contains a list of all the fixed channels of the neighbours directly connected to it. RRER messages are sent from switchable interfaces and received by fixed interfaces.

3.3 Routing function

In this work, we use the WCETT metric to select a route with high achieved end-to-end throughput in multi-hop radio networks. This metric sets a weight based on the quality of each connection. Then these weights are combined to select the most suitable route. Specific calculations are presented as follows:

SwitchingDelay: The interface switching is necessitated if a wireless node sends data packets on more than one switchable channel. This will cause an interface switching delay called *Switching_Delay*. If a packet is sent out on a fixed interface, its *Switching_Delay* equals 0. Else, if a packet needs to be sent out on the j channel, but the switchable interface is using the other channel, it has the switching delay cost *Switching_Delay*.

ETT Metric: This metric is proposed to improve the limitations of the ETX metric. The ETT is defined by multiplying the ETX value and the link bandwidth to determine the required time to transmit a packet over the link, as follows:

$$ETT_j = ETX_j \times \frac{S}{B} + SwitchingDelay(j) \quad (1)$$

where,

- ETX_j is metric measures the link quality between two wireless nodes directly.
- *SwitchingDelay(j)* is the interface switching cost of a channel. It determines the delay of a packet caused by the interface switching.
- *S* is the packet size, and *B* is the bandwidth of the link.

When using the ETT metric, the cost of a route is equal to the total cost of the links. This may be incorrect because co-channel interference is not considered when the network nodes use the same transmission channel.

WCETT Metric: Aim to improve the ETT metric, the authors [12] proposed the WCETT metric to reduce co-channel interference. This mechanism minimizes the number of nodes which use the same channel on the entire path. Considering a route consisting of *N* hops, the total transmission time of the hops on the same channel *j*, is determined as follows:

$$X_j = \sum_{\text{Hop } i \text{ uses } j \text{ channel}} ETT(i), \quad 1 \le j \le \text{N} \tag{2}$$

Since the entire route throughput would be dominated by the bottleneck channel. Set *j* channel that has the largest X_j value. For the purpose to balance the effect between channel *j* and the other channels on the entire route throughput, they proposed a weighted average (*β*). This leads to the cost function as follows:

$$\text{MIMC} = (1-\beta) \times \sum_{i=1}^{\text{N}} ETT_i + \beta \times \max_{1 \le j \le \text{k}} X_j \tag{3}$$

The detailed information of ETX, ETT and WCETT metrics are described in the reference [18]. In this research, the authors have thoroughly studied the effects of β on the performance of multi-hop, multi-channel, multi-interface wireless networks. The effect of *β* in our system model is similar. Therefore, we choose a fixed value of *β* = 0.5 to balance the diversity of channels and route latency.

4 Simulation results and analysis

In this section, we use NS2 simulation software for the performance evaluation of the proposed protocol, so-called MIMC-AODV, in the scenarios that use 2, 5, and 8 channels, respectively, denoted as "*MIMC-AODV*-x". Then we use obtained figures to compare with the traditional AODV routing protocol, which only uses one channel. We set up a WMN structure with 100 nodes randomly distributed in an area of 1000 × 1000 (m).

Table 1. Simulation parameters

Parameter	Value
Simulation Area	1000 × 1000 m
Number Nodes	100
Interface Number of Nodes	2
Channel Numbers	2, 5, 8
Traffic Type	CBR
Packet Size	512 byte
Time Simulation	150 (s)
MAC Layer	802.11a
Data Rate	54 Mbps
Transport Protocol	UDP
Transmission Distance	250 (m)
Mobility Speeds	[1–5] (m/s)
Interface Switching Delay	1 (ms)
Protocols	MIMC-AODV, AODV

In our simulation scenarios, each wireless node is equipped with two IEEE 802.11a interfaces, the first is the fixed interface, and the second is the switchable interface. The network nodes use the random way-point model with a random speed in the range [1–5] (m/s). The data rate is set at 54 Mbps. The transmission range of each wireless node is 250 (m). The interface switching delay is installed equally to 1 ms. We use UDP traffic with end-to-end connection numbers: 2,4,6,…,16, respectively. Simulations are done in 150 seconds. The simulation parameters are summarized in Table 1.

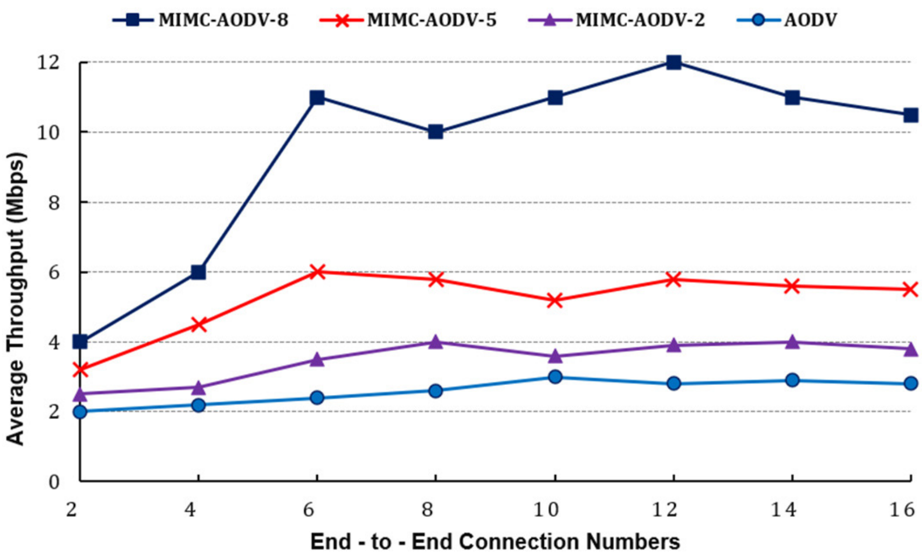

Fig. 6. Average throughput and network traffic

In the first experiment, we compare the average throughput of the proposed protocol when operating with switchable channel numbers of 2, 5, and 8, respectively and the traditional AODV protocol under different traffic scenarios. The results are presented in Figure 6. Simulation results showed that the average throughput increases proportionally with the switchable channel numbers of the system. Specifically, the throughput of MIMC-AODV-8 that uses eight switchable channels has superior throughput compared to other routing schemas. The throughput of the traditional AODV protocol is the lowest because it only uses one channel to communicate. Besides, when the traffic network is low, the connection numbers are less than 4, all routing schemes have a rather low throughput. This can be explained as follows: when the network traffic is low, switchable channels to limit channel interference in WMN is not really necessary. This result indicates that multi-interface multi-channel WMN structures are suitable for high traffic WMN scenarios.

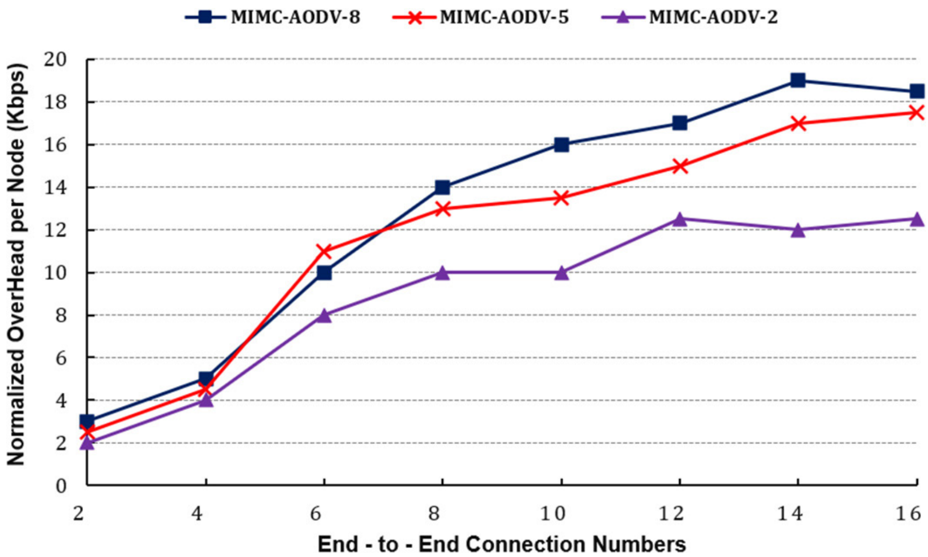

Fig. 7. The normalized overhead of MIMC-AODV and network traffic

In the second experiment, we evaluate the normalized overhead metric of the proposed protocol when operating with switchable channel numbers of 2, 5, and 8, respectively, under different traffic scenarios. The results are presented in Figure 7. Simulation results show that the normalized overhead value tends to increase when the network traffic increases. The normalized overhead of the MIMC-AODV-2 schema is always the lowest of all simulation scenarios. The normalized overhead of the MIMC-AODV-5 and MIMC-AODV-8 scenarios are quite similar when the network traffic is small (terminal connections are less than 8). However, when the connection numbers are greater than 8, the normalized overhead of the MIMC-AODV-8 scheme increases rapidly and is highest compared to other routing schemes. These simulation results indicated that when the high network traffic uses an MIMC-AODV scheme with a too high switchable channel number can increase congestion and collisions. Therefore, selecting suitable channel numbers based on traffic scenarios in multi-interface multi-channel WMN will be an important research problem in the future.

5 Conclusion

In this work, we have proposed a multi-interface multi-channel on-demand routing protocol for WMN, improved from the AODV protocol. Our protocol uses a fixed interface and switchable interfaces to communicate in-network, the so-called MIMC-AODV. The primary meaning of this protocol is to manage and exploit multi-channel, multi-interface operations effectively. This protocol uses a new metric, improved from the ETT metric for more efficient route selection. Furthermore, an efficient route maintenance mechanism is also proposed. The simulation results and performance evaluation on the NS2 show that the proposed protocol operating with switchable channel numbers 2, 5, and 8, respectively, under different traffic scenarios, provide the average throughput many times higher than the traditional protocols, which use only one channel for communication. Moreover, the simulation results also show that the normalized overhead metric increases proportionally with the number of switchable channels. This result proves that it is necessary to set the switchable channel numbers suitable for the network traffic. In the next studies, we will show the relationship between network traffic, mobility speed and switchable channel numbers for multi-interface multi-channel WMN scenarios to maximize performance and QoS of the network.

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