A New MIMC Routing Protocol Compatible with IEEE 802.11s based WLAN Mesh Networks

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***Abstract*—Utilizing multi-interfaces and multi-channels (MIMC) is essential in increasing capacity and performance of emerging wireless mesh networks. However, the current IEEE 802.11s draft which is a standardization activity of the WLAN based mesh network does not sufficiently consider these capabilities. This may lead to poor performance of the network in terms of throughput and scalability. In this paper, first we analyze the misbehavior of the current standard especially in the path selection process. Then, we propose a new routing protocol that is suitable for the multi-interface and multi-channel environment. The proposed scheme selects high throughput paths based on channel diversity information and reduces the broadcast overhead of control messages. Moreover, it is fully compatible with Hybrid Wireless Mesh Protocol (HWMP) which is the default routing protocol proposed in the current standard. Interestingly, in the simulation study, we observe that the network performance increases even though only a partial number of nodes are equipped with the proposed scheme.**

Keywords-component; wireless mesh network; multi-interface and multi-channel; routing compatible with the HWMP

I. INTRODUCTION

In the last decade, wireless mesh networks (WMNs) have received great attention as a next-generation wireless multi-hop infrastructure, thanks to many of its advantages such as easy deployment, low management cost and good scalability [1]. As a wireless backbone, it is most challenging to enhance the network capacity for providing the required quality of network services to as many users as possible. A preferred solution is to integrate multiple radio interfaces into a mesh router. Multiple interfaces assigned to different channels can simultaneously transmit packets without interference [2]. Moreover, we can easily make a multi-interface based mesh router with cost effectiveness using inexpensive off-the-shelf WLAN cards.

A variety of mesh products are equipped with multiple interfaces in the market today [3-5]. However, they are not compatible with each other because each manufacturer employs its own routing protocol and solutions to its product. To solve this compatibility problem between mesh devices, the IEEE 802.11s task group has been organized and currently standardization activity is almost at its final stage [6]. The IEEE 802.11s draft standard defines *extensible path selection framework* which allows device vendors to implement their own path selection protocols and metrics. However, every mesh device must support at least the default protocol and the metric to ensure compatibility. *The Hybrid Wireless Mesh Protocol* is a default path selection protocol which combines an *on-demand mode* with a *proactive tree building mode*. As a default link metric, *the airtime link metric* reflects the amount of time consumed by transmitting the frame over a particular link based on the frame error rate and the bit rate. The HWMP accumulates all the link metric values included in the selected multi-hop path to obtain the overall cost of the path.

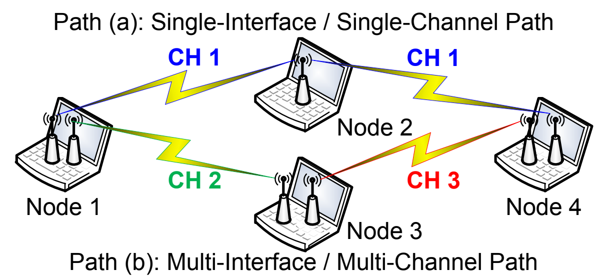

Figure 1. A comparison of the two possible paths: (a) SISC-based and (b) MIMC-based paths

Unfortunately, the metric and protocol defined as the default in the IEEE 802.11s do not consider the diversity of the channels assigned in each link, making them unsuitable for multi-interface and multi-channel mesh environments. For example, as shown in Fig. 1, it is obvious that the path (b) with MIMC outperforms path (a) which is based on SISC since the forwarder node can carry out a full-duplex communication by simultaneously receiving and transmitting the packet via using different interfaces and channels. However, with the HWMP, accumulated costs of two paths are identical if the other parameters (e.g., error rate and bit rate) are assumed to be the same. Moreover, since many control messages such as Path Request (PREQ) in the HWMP are disseminated by network-wide broadcasting, these messages should be retransmitted by every interface. As a result, the amount of transmitted control messages increases exponentially as the number of interfaces increases. This causes severe performance degradation due to the broadcast storm problem [7]. Therefore, reducing this overhead is one of the challenging issues to achieve better performance in the IEEE 802.11s based mesh network. We will show the detailed analysis of the misbehavior of the HWMP in Section III.

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In this paper, we propose a new routing protocol which is suitable for the multi-channel and multi-interface network environment. The proposed scheme selects high throughput paths based on channel diversity information and also reduces the broadcast overhead caused by control messages. The most important feature of the proposed scheme is that it is fully compatible with the existing HWMP in the IEEE 802.11s standard. In other words, mesh nodes equipped with the proposed routing protocol can coexist with other nodes equipped with the original HWMP in the same network. This is a very unique feature that distinguishes our scheme from others. Even though an enhanced routing protocol is implemented by a hardware vendor based on the extensible path selection framework in the IEEE 802.11s, it is not usable in the network consisting of mesh devices developed by other vendors. Generally, the HWMP is the only available protocol in such heterogeneous networks. However, even in these environments, our proposed scheme can still provide advanced functions while guaranteeing interoperability with the HWMP. Interestingly, in the simulation study using the *ns*-3 [8], we observe that the network performance increases even though only a partial number of nodes are equipped with the proposed scheme.

The rest of the paper is organized as follows. Background and related works are described in Section II. The preliminary analysis of the problem is presented in Section III. Section IV introduces the proposed scheme followed by performance evaluation in Section V. We conclude in Section VI.

II. BACKGROUND AND RELATED WORKS

A. Hybrid Wireless Mesh Protocol (HWMP)

As mentioned in the previous section, the HWMP, which is the default path selection protocol in the IEEE 802.11s draft standard, supports two modes; *on-demand mode* and *proactive tree building mode*.

On-demand mode allows mesh nodes to communicate with each other by creating peer-to-peer paths on the basis of the Ad Hoc On-Demand Distance Vector (AODV) [9]. First, a source node that does not have a valid path to the destination initiates Path Request (PREQ) broadcasting. Upon receiving a PREQ, the destination sends a unicast Path Reply (PREP) message back to the source. Intermediate nodes which have forwarded PREQ and PREP messages update their own path table to relay data packets between the source and the destination.

On the other hand, proactive tree building mode maintains a tree path from the root to all the other nodes. There are two sub-mechanisms for proactively maintaining path information; *Proactive PREQ mechanism* and *Proactive RANN mechanism*. The first method begins with periodically sending a proactive PREQ message by the root node. Unlike in on-demand mode, the target of the proactive PREQ is the broadcast MAC address. It means that every mesh node has to respond to the received PREQ by sending a PREP back to the root node. Meanwhile, in the Proactive RANN mechanism, a root node periodically broadcasts Root Announcement (RANN) messages to the entire network. Upon receiving a RANN, each mesh node can select whether or not it creates a path towards the root, which is different compared to the proactive PREQ method. A node that wants to create or refresh the path sends a unicast Path Request (PREQ) message to the root, which in succession responds by sending a unicast Path Reply (PREP) message. We summarize these features in Table I.

TABLE I. TWO SUB-MECHANISMS FOR PROACTIVE TREE BUILDING MODE IN HWMP

Mechanism	Handshaking	Message sequence
Proactive PREQ	2-way	Proactive PREQ → PREP
Proactive RANN	3-way	RANN → unicast PREQ → PREP

The on-demand and proactive tree building modes are not exclusive and can be used concurrently since the proactive modes are extensions of the on-demand mode and same messages are utilized. Generally, Internet access is one of the main services in WMNs, so it is expected that paths towards the gateway node are most frequently utilized. Therefore, it is a natural assumption that the gateway node connected to the Internet plays a role of the root node in the proactive tree path. On the other hand, peer-to-peer paths between non-root nodes are established by on-demand path selection.

B. Related Works

There have been several researches on routing metrics to effectively reflect the MIMC environment. Weighted Cumulative Expected Transmission Time (WCETT) metric is proposed for Multi-Radio Link-Quality Source Routing (MR-LQSR) protocol [10]. WCETT is based on Expected Transmission Time (ETT) which is a function of the loss rate and the bandwidth of the link. Then, WCETT assigns a weight to each possible path according to the number of the duplicated channel utilized in the path. However, WCETT may mislead on the actual interference since it assumes that duplicate channels always cause the interference regardless of the distance. Several enhancements have been made in MIC [11] and iAWARE [12] metrics. However, as these protocols consider more factors to calculate the routing metric, more information is required. This makes the algorithm more complicated and difficult to be implemented. Moreover, these schemes do not consider the compatibility with the new standards such as the IEEE 802.11s.

There have been some researches to analyze the performance of the existing HWMP. The authors in [13] compare the performance of the HWMP with the AODV using the OPNET simulator. In the simulation results, the HWMP shows somewhat better performance than the AODV with aid of the proactively managed tree path. On the other hand, the authors in [14] present the scalability problem of the HWMP using the *ns*-2 simulator. They argue the performance of the HWMP is very sensitive to the network traffic and size. Recently, [15] analyzes performance characteristics of the various HWMP modes using the *ns*-2. A detailed evaluation of these modes provides their suitability for specific environments. However, these works have limitations that did not include evaluation results in the MIMC environment.

Recently, several open source communities have made an effort to implement the IEEE 802.11s protocol in the Linux or

Unix environment [16, 17]. Open80211s is a representative project and currently has merged into development of the mainline Linux kernel. Several additions which are not implemented yet in open80211s such as 6 MAC addresses and proxy update are made by [18] to support interworking with external networks. However, previous researches do not pay enough attention to the MIMC environment, so the performance of the HWMP is still doubtful in such network environments.

III. Preliminary Analysis: Path Instability Problem of the HWMP

In this section, we provide the detailed analysis of the misbehavior of the HWMP in the MIMC environment. We have conducted a simulation study using the *ns*-3 based on the simple scenario as shown in Fig. 1. Two 802.11a radios are installed in each mesh node and the data rate is fixed to 54 Mbps. A TCP connection is created from node 1 to node 4, and transmission of data packets is initiated at 5 seconds for duration of 10 seconds.

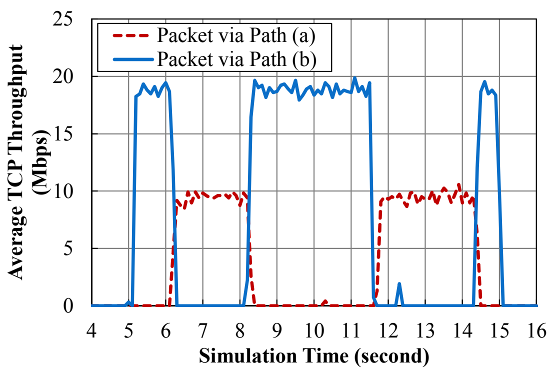


Figure 2. Path instability of the HWMP

We measure the average throughput at the destination node. Based on the forwarding node, we can distinguish the path utilized by each packet. For example, if a packet is forwarded by node 2, path (a) is utilized and vice versa. As shown in Fig. 2, the HWMP frequently changes the path, and it leads to the degradation of the throughput. There are two reasons for this path instability in the HWMP. First, excessive packet transmission increases the error rate of links involved in the path and thus the path cost also increases. Therefore, the other path will be preferred and likely to be selected in the next path update. The second reason is that the HWMP does not recognize advantages of MIMC paths as we mentioned before. In HWMP, MIMC paths do not gain higher priority than the SISC paths. If we can allow more priority to the MIMC paths, the path instability may not occur even though the link cost increases due to packet transmissions.

Table II shows the possible performance gain when the path is fixed. When only path (b) is utilized, the average TCP throughput increases up to 18.48Mbps which is 34% more than the original HWMP. On the contrary, the throughput decreases when only path (a) is utilized. Therefore, it is very important to select better paths as well as to prevent frequent path changes. Based on this observation, we propose an advanced routing protocol to cope with the misbehavior of the HWMP and achieve possible enhancement in performance.

TABLE II. Performance Results of The HWMP

HWMP	Throughput (Mbps)	Average Latency (*ms*)
Using both paths	13.8	65.22
Only using path (a)	8.52	93.41
Only using path (b)	18.48	52.51

IV. Proposed Scheme

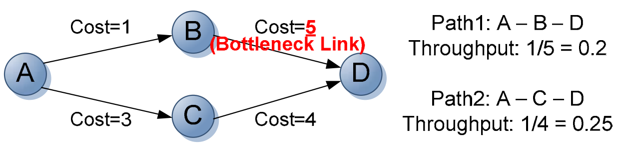
The proposed scheme consists of two phases; *channel-aware path selection phase* and *control message reduction phase*, which are detailed in the following subsections. The IEEE 802.11s standard does not define any channel assignment algorithm and the HWMP does not consider channel information as we mentioned before. Therefore, we decouple the routing problem from the channel assignment problem and mainly focus on designing an efficient routing algorithm to reduce complexity and to maintain the compatibility with the HWMP. We assume that channels are assigned for each interface in advance by existing channel assignment algorithms [2]. For example, we utilize the BFS based channel assignment algorithm [19] for the simulation study in Section V.

Even though some joint channel assignment and routing schemes have been proposed [20], they are mostly impractical for implementation in real environments due to their high complexity. For example, "Common Channel Framework (CCF)", a dynamic channel switching scheme discussed in the early stage of the IEEE 802.11s, has been removed from the draft due to the difficulty of implementation with the problems of irregular channel switching delay and additional control message overhead.

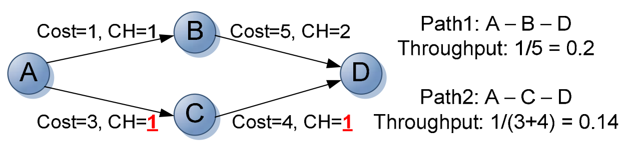
A. Channel-aware Path Selection Phase

The proposed path selection algorithm basically utilizes the same path discovery mechanism of the HWMP and the airtime link metric to maintain compatibility. A source node initiates PREQ broadcasting while the destination node responds by sending a unicast PREP. However, the intermediate nodes receiving control messages also consider channel diversity and path throughput to calculate the path cost.

First, we introduce the concept of *path throughput* to select the high performance path in the MIMC environment. As shown in Fig. 3(a), two paths are available between node A and D. Let us assume each link uses independent channels, so no interference is expected. In the HWMP, the path cost is the sum of individual link costs, and thus path 1 would be preferred. This is the correct selection when only one packet is delivered. For example, since the path cost represents the time required to deliver a packet in the airtime metric, path 1 takes 6 time units while path 2 takes 7 time units to send a packet through the given path. Therefore, path 1 is thought to be better than path 2. However, this may not be true when multiple packets are continuously transmitted as in many applications such as FTP or video streaming. In such cases, the link having the largest cost in the path becomes a bottleneck, so it limits the end-to-end throughput. For example, when the size of each packet is assumed to be same, the bottleneck link B-D in Fig. 3(a) can transmit a packet only at every 5 time units. Therefore, destination node D also receives a packet at every 5 time units even though link A-B can transmit a packet at every 1 time unit. However, path 2 can deliver a packet to the destination at every 4 time units, so this path provides the better end-to-end throughput. We define this end-to-end throughput with multiple packets as path throughput.



(a) Bottleneck link *vs.* Path throughput



(b) Channel diversity *vs.* Path throughput

Figure 3. Two elements that affect path throughput

Now we consider the effect of channel diversity. Fig. 3(b) shows the same situation as Fig. 3(a) with different channel values. Path 1 consists of two links with different channels, but path 2 consists of two links with the same channel. In path 2, link A-C and link C-D cannot transmit simultaneously due to radio interference. Therefore, node D receives a packet at every 7 time units through path 2. As a result, path 1 is thought to be better than path 2, unlike the observation we have made in Fig. 3(a).

As shown in the previous example, an intermediate node has to know the channel value and the link cost of the previous hop in order to estimate the exact path throughput. However, the HWMP accumulates the cost of each link included in the path when PREQ and PREP messages are forwarded, so the intermediate node cannot distinguish the cost of the only previous hop link. To solve this problem, we extend two additional fields such as the link cost and the channel number at the end of the PREQ and the PREP message formats. For example, node B in Fig. 3 (b) will include cost 1 and channel 1 in the control messages as the information of link A-B. Moreover, we assign 1-bit among unused bits in the flag field to indicate the existence of the extended fields.[1] The nodes equipped with the original HWMP will simply ignore these extended fields because they regard them as meaningless dummy data.

When a node receives PREQ or PREP messages, it first looks for whether the extended fields exist or not by checking the flag field. When the control messages are sent from the nodes equipped with the original HWMP, the extended fields do not exist. In this case, the path cost is simply accumulated as same way as the HWMP. Otherwise, the path cost is updated using equation (1).

[1] There are two unused bits in the flag field of the PREQ element in the IEEE 802.11s draft version 7.0.

$$Cost_{2hop} = \begin{cases} Cost(A,B) + Cost(B,C), & if\ CH(A,B) = CH(B,C) \\ Max(Cost(A,B), Cost(B,C)), & if\ CH(A,B) \neq CH(B,C) \end{cases} \quad (1)$$

This equation calculates the cost of the two hop path consisting of three nodes *A*, *B* and *C*. *CH(A, B)* is defined as the channel value assigned for the link A-B. When the same channel is assigned to both links consisting of the two-hop path, the path cost is the sum of each link cost, which is same in the HWMP. However, when two links use different channels, we select the maximum cost among them as a path cost. For example, in Fig. 3(b), the cost of path 1 is 6 while the cost of path 2 is 7. As a result, the proposed scheme selects path 1 which can provide more throughput than path 2. On the contrary, the HWMP will select path 2 without consideration of channel information resulting in poor performance.

Updating of the path cost is operated in each intermediate node as control messages are propagated. Therefore, radio interference within two-hop range is always considered throughout the entire path. Since we choose the maximum cost for the multi-channel path, it is possible that the destination node receives several PREQ messages with the same path cost. To give priority to the shortest-hop path in this case, we add the weight of 10 percent when updating the cost of the multi-channel path and this weighted cost is accumulated as the number of hops increases.

B. *Control Message Reduction Phase*

Another important issue is how to reduce control message overhead. The HWMP periodically initiates proactive PREQ or RANN broadcasting to maintain the proactive tree path. The number of transmissions of control messages proportionally increases as the number of interfaces increase. The basic idea behind this phase is that we control the broadcasting so that minimum number of interfaces rebroadcast the received control messages. Here, we assume the proactive PREQ mechanism is utilized for the proactive tree building mode in the HWMP. However, we believe the proposed scheme can also be easily operated in coherence to the proactive RANN mechanism.

First, we divide proactive PREQ messages into two types; $PREQ_F$ and $PREQ_R$. Upon receiving a $PREQ_F$ message, a node rebroadcasts it using every interface, which is same as the normal HWMP procedure. On the other hand, when a node receives a $PREQ_R$ message, the node rebroadcasts it by using only the necessary interfaces. We assign another bit in the flag field of the PREQ message for the root node to indicate the type of the proactive PREQ messages. Fig. 4 shows two intervals; I_F and I_R. I_R is same as the proactive PREQ interval defined in the IEEE 802.11s draft, and I_F is the multiple of I_R. In Fig. 4, I_F is 3 times longer than I_R. The root node sends a $PREQ_F$ message in every I_F interval, but $PREQ_R$ messages are transmitted in the other intervals.

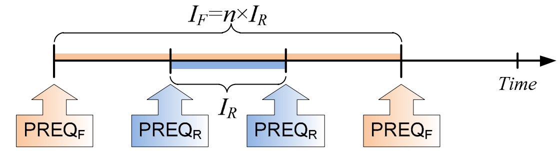
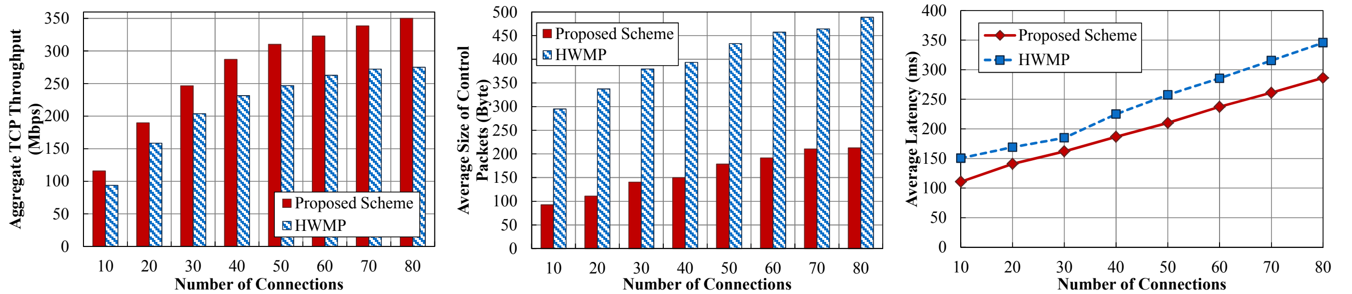


Figure 4. Two types of proactive PREQ messages and their intervals



(a) Aggregate TCP throughput (b) Control packet overhead (c) Average end-to-end latency

Figure 5. TCP performance results varying the traffic load

The node needs to determine which interfaces have to rebroadcast the received $PREQ_R$ messages. The basic rule is that $PREQ_R$ messages are forwarded only to the child nodes in the proactive tree path. With the HWMP, every node responds to the received proactive PREQ message by sending a PREP message back to the root node. Therefore, each node can recognize its child nodes when it forwards the PREP messages destined to the root node. In this case, the previous hop node of the PREP is the child node in the tree path. Consequently, $PREQ_R$ messages tend to refresh the existing tree path while $PREQ_F$ messages can fully reorganize the tree path.

Simply increasing the proactive PREQ interval is also possible in reducing the control message overhead. However, an increase of the update interval makes a path failure difficult to be recognized. However, the proposed scheme does not change the update interval. Therefore, we can conclude that the proposed scheme for control message reduction is more advantageous.

In the heterogeneous network where both the proposed scheme and the HWMP exist, the node equipped with the original HWMP just rebroadcast the received PREQ messages by all interfaces regardless of the types of proactive PREQ.

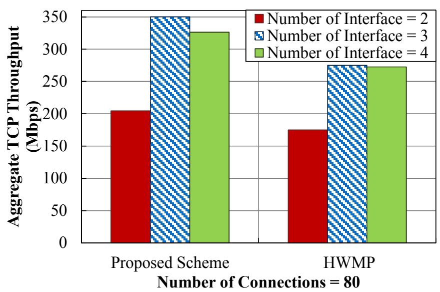
V. PERFORMANCE EVALUATION

The performance of the proposed scheme is evaluated using the *ns*-3 simulator [8]. In our simulation model, 36 nodes including one gateway are randomly deployed in 150*m* ×150*m* square area. Basically, three 802.11a radios are installed in each mesh node except the second scenario and the data rate is fixed to 54 Mbps. With this configuration, transmission range without frame error is approximately 34*m* and the average number of neighboring nodes is 5, which shows a moderate density. The gateway node is configured as the root of the proactive tree path and the farthest node from the root is maximum 5 hops. Since 7 orthogonal channels are available in the reference WLAN card [21], we assign these channels in the 5GHz band to interfaces based on the BFS algorithm [19]. We measure the TCP performance of the proposed scheme and the HWMP in three different scenarios. During 100 seconds simulation time, 10 to 80 TCP sessions are created at random time with randomly selected destinations. A TCP session is alive for duration of 10 seconds. The data source is the gateway node because it is expected that download traffic from the Internet is the majority of the normal user traffic in the WMN. Five different topologies are utilized and we repeat each scenario five times with different random seed numbers.

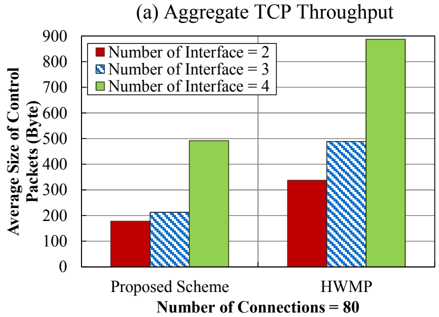
First, we measure TCP performance results as the number of TCP connections increases. The aggregate TCP throughput represents the sum of throughputs of all destination nodes, which gives an insight to estimate the total capacity of the network. As shown in Fig. 5(a), the proposed scheme always provides more throughput than the HWMP regardless of the traffic load. Moreover, as the number of connections increase, the performance gap between the proposed scheme and the HWMP also increases at the most up to 75Mbps. This result comes from the fact that the HWMP does not consider channel diversity in the MIMC environment. On the contrary, the proposed scheme well reflects channel diversity, so better performance is achieved. Fig. 5(b) shows the average control packet overhead that is defined as the sum of all control packets generated by the path selection protocol from each node per second. The control packet overhead of both schemes linearly increases as the traffic increases. This is because the increasing number of path errors due to congestion initiates frequent on-demand path recovery. However, the proposed scheme produces only 40% of control packets against the HWMP in all the scenarios. This result proves the proposed control message reduction algorithm successfully works. Fig. 5(c) illustrates the average end-to-end latency. The proposed scheme also shows 42*ms* less latency on average than the HWMP. Consequently, we can conclude that the proposed scheme outperforms the HWMP in terms of the throughput, the control packet overhead and the latency.

The second scenario shows the impact of increasing the number of interfaces on the performance. Fig. 6(a) shows the aggregate TCP throughput with the various numbers of radio interfaces. When the number of interfaces increase from 2 to 3, the aggregate TCP throughput of the propose scheme and the HWMP increase 71% and 57% respectively. However, the aggregate TCP throughput slightly decreases when the number of interfaces is 4. Since the number of available channels is limited, the use of excessively many radio interfaces increases the probability to use the same channel in the neighborhood. It aggravates radio interference and channel contention. Moreover, the control packet overhead exponentially increases as the number of interfaces increases, as shown in Fig. 6(b). This is another reason for the performance degradation. However, the propose scheme produces much less control packets than the HWMP regardless of the number of interfaces.

In the last scenario, we evaluate the performance of the proposed scheme in the heterogeneous network consisting of two types of nodes, where one is equipped with the proposed scheme and the other is equipped with the HWMP. Fig. 7(a) shows that the average TCP throughput linearly increases from when more than half of the nodes are equipped with the proposed scheme. Fig. 7(b) also shows a similar tendency in terms of the control packet overhead. These results verify that the proposed scheme successfully maintains the compatibility with the HWMP.

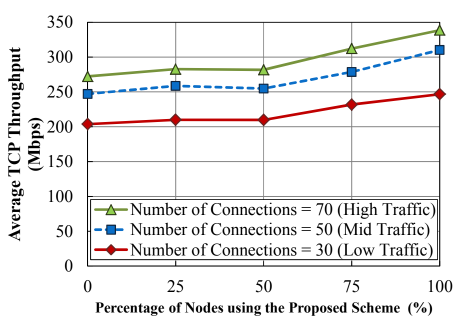


(a) Aggregate TCP Throughput

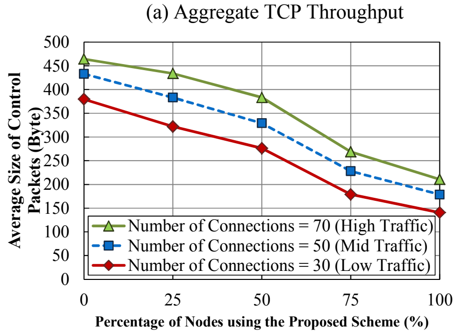


(b) Control packet overhead

Figure 6. TCP performance results varying the number of interfaces



(a) Aggregate TCP Throughput



(b) Control packet overhead

Figure 7. TCP performance results in the heterogeneous network

VI. Conclusion

The IEEE 802.11s is the key standard for realizing the WMN based future wireless infrastructure. However, the current standard has performance limitations due to the lack of consideration of the MIMC characteristics. In this paper, we analyze in detail the misbehavior of the default routing protocol defined in the IEEE 802.11s standard, and propose a new MIMC routing protocol that is suitable in this environment. The important feature of the proposed scheme is that it provides full compatibility with the current standard, allowing performance enhancement even though a partial number of nodes exploits the proposed scheme. Future works would include evaluation results in the real testbed.

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