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Design and Implementation of the IEEE 802.11n in Multi-hop over Wireless Mesh Networks with Multi-Channel Multi-Interface

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***Abstract*— In this paper, we present an implementation schemes of the IEEE 802.11n standard on wireless mesh network using multi-channel multi-interface technology and study for experimental results in an outdoor mesh testbed. We analyze the features of the IEEE 802.11n such as channel bonding, MIMO, and its behavior in multi-hop environment. In addition, we define the considerations for optimized design of mesh routers using IEEE 802.11n, and propose implementation schemes that can satisfy design requirements. As a result, we show the design techniques of high-performance wireless backbone network. Furthermore, we have implemented the real mesh router on an embedded board, and performed several experiments in an outdoor testbed. From experimental results, we evaluate the performance of the IEEE 802.11n over wireless mesh network with multi-channel multi-interface technique.**

Keywords: Wireless Mesh Networks; Multi-channel Multi-interface; IEEE 802.11n Testbeds

I. INTRODUCTION

Wireless mesh networks (WMNs) is regarded as a next-generation technology because it can provide high network extendibility and economic. WMNs researches based on IEEE 802.11s which is an IEEE 802.11 amendment for mesh networking are progressed actively [1]-[4]. WMNs have been selected as backbone network in many places due to provide the network stability and reliability of data transfer in wireless sensor networks, smart city applications, etc. The considerations of WMNs that ensure the value are stability, self-configuring, fast self-healing, minimizing interferences in the network, and securing link bandwidth.

In previous works, we researched multi-path routing technique to improve fast-recovery from network failures due to mesh router error [5], also researched multi-channel multi-interface (MIMC) technique to minimize interferences on the same channel in the WMNs. Due to these techniques, we achieved the improved fast-recovery by reducing overhead of establishing the new routing path. Moreover, we could mitigate the bandwidth degradation which caused by interferences and collisions on the same channel which used in adjacent links due to utilize multiple channels and directional antennas. In other words, we have implemented features of WMNs such as network reliability, fast recovery, multi-path routing scheme, and MIMC technique.

In order to accommodate more traffic in WMNs based on previous works, the research of applying IEEE 802.11n standard to each mesh link is needed. IEEE 802.11n which is the recently standard of wireless networking based on IEEE 802.11a/g, it has several features of enhancements for higher throughput such as 40MHz channel bonding, MIMO (Multiple-Input Multiple-Output), enhanced MAC mechanisms. Therefore, IEEE 802.11n supports 600Mbps data rate at PHY layer (using 4 data streams, 40MHz channel bandwidth, short guard interval). Channel bonding means that communication through 40MHz channel bandwidth instead of 20MHz which is used in legacy standards. MIMO is technology that can transmit two or more data streams through one channel by spatial partitioning. Enhanced MAC scheme achieves improving performance through miniaturization of radio preamble and radio header of CSMA/CA by the frame aggregation and the block ACK mechanism.

The IEEE 802.11n can accommodate more traffic in network by applying to each link of WMNs. However, according to mentions of IEEE 802.11n standard, it is designed for one-to-one connection such as AP-STA or IBSS (Independent Basic Service Set) [6]. Therefore, in this paper, we analyze the features of IEEE 802.11n which is designed optimally in single-hop connection, and then describe considerations when applying IEEE 802.11n to multi-hop connection as WMN with MIMC, it consists of the block ACK session setting, the management of MPDU sequence number, etc. In addition, we present the modifications of the AODV routing protocol due to use MIMC technique.

The remainder of this paper is organized as follows. Section II summarizes related work on measurement studies in IEEE 802.11n networks and performance optimization for WMNs. In Section III, we introduce our implementation features of applying IEEE 802.11n to each link of WMNs. In Section IV, we evaluate the performance of WMNs with MIMC based on IEEE 802.11n in the actual outdoor testbed from various angles. Finally, concluding remarks are given.

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II. RELATED WORK

Currently, a lot of researches of performance improvement of WMNs and analysis of IEEE 802.11n features are progressing. The main goal of performance improvement of WMNs is to increase utilizing bandwidth on end-to-end nodes and to decrease latency. So, many routing techniques and metrics are proposed. And researches on improvement of the IEEE 802.11n mainly discuss about enhanced MAC that is defined in standard, and it includes adaptive frame aggregation, MIMO optimization.

From own previous work [7], [8], we have implemented WMNs using MIMC to improve the network performance. Kim et al. [7] proposed channel load routing scheme for WMNs with MIMC, this new routing protocol reflects current channel condition to routing in real-time, and was evaluated through comparing with ETX, ETT, WCETT, as well as Airtime which is defined in IEEE 802.11s. Kim et al. [8] presented the advantages of multi-path routing which supports lower overhead and high reliability during self-healing process. Opposed to [7], [8], in this paper, the IEEE 802.11n is applied to each link of WMNs to increase bandwidth and reliability.

Kim et al. [9] showed the limit of IEEE 802.11 MAC layer in multi-hop environment because it designed for single-hop. Also, they analyzed various MAC behaviors such as 802.11 DCF, 802.11e EDCA, and 802.11n A-MPDU and rate adaptation schemes that include ARF, RBAR, and 802.11n rate adaptation in few WMNs topologies through simulation. However, this paper proposes implementation features in order to overcome the limitations of IEEE 802.11 MAC policies.

Several researches [10]-[12] studied about frame aggregation scheme of IEEE 802.11n. Xiao et al. [10] conducted the efficient MAC enhancements to reduce the MAC layer overhead. Especially, they focused on adaptation frame aggregation method which can include multiple MAC/PHY frames/payloads in single transmission. Skordoulis et al. [11] presented the pros and cons of combination of frame aggregation units such as A-MSDU, A-MPDU through simulation. Lin et al. [12] analyzed the characteristics of frame aggregation units through comparison between A-MSDU and A-MPDU. While A-MSDU has lower overhead, but if it consists of over a certain number of MSDU in channel with high BER, then decrease performance because it doesn't have FCS in each sub-frame. So they proposed adaptive frame aggregation technique according to the bit error rate. Opposed to [10]-[12], in this paper, frame aggregation is considered in multi-hop network as WMNs with MIMC, and the results are verified by experiments in actual WMNs testbed.

A vast amount of research has been conducted experiments about features of IEEE 802.11n over actual implemented testbed [13]-[15]. Pefkianakis et al. [13] proposed the data rate adjust technique using MIMO which is one of features of IEEE 802.11n. The proposed technique allows select the best data rate when there are one or more data streams in 2x2/3x3 MIMO. Pelechrinis et al. [14] analyzed spatial division multiplexing of MIMO, and discussed experimental results of MIMO which operates with IEEE 802.11g or independently. Pelechrinis et al. [15] described the change of IEEE 802.11 features according to channel bandwidth, packet size and different data rate through experiments. Opposed to [13]-[15], in this paper, we implement with considerations of IEEE 802.11n features under single-hop as well as multi-hop and various topologies of WMNs.

Frohn et al. [16] studied that multi-hop performance was affected by BER, aggregation level and path length when using the IEEE 802.11n on the WMNs. And Friedrich et al. [17] built an actual testbed of WMNs using IEEE 802.11n, and conducted experiments of many parts such as the effect of channel bonding on the performance, the effect of channel bonding and path length on the mean size of frame aggregation, and the effect of limitation of frame aggregation level on the performance, etc. Opposed to [16], [17], we propose implementation features such as modification of block ACK session setting, management of MPDU sequence number, and change of the IEEE 802.11n mechanisms on the WMNs with MIMC technique. Furthermore, in implemented WMNs testbed, we analyze performance in multi-hop, packet loss rate, and latency.

III. IMPLEMENTATION FEATURES

In this section, we describe target H/W and open source platform that are the basis for the implementation. Also, we show the modified AODV by MIMC technique. Then we introduce how to establish block ACK session in each hop, method of management of MPDU sequence number in MIMC technique.

A. Hardware and Software Settings

In this paper, we implement the WMNs with MIMC using the IEEE 802.11n. For this implementation, we utilize Ubiquiti's Routerstation Pro as network board, Mikrotik's R52Hn as network card, and Atheros' ath9k as device driver and mac80211 as common L2 protocol.

Routerstation Pro is high-performance embedded board with Atheros AR7161 680MHz chipset, it is suitable for the target platform of MIMC mesh router because it has 3 mini-PCI slots. R52Hn uses AR9220 chipset and supports up to 300Mbps data rates at PHY layer [18], [19].

We have selected OpenWrt KAMIKAZE r22190 (Linux 2.6.32.14) package for H/W platform. And we modify compat-wireless-2.6.38-rc7-2 that is driver package containing ath9k and mac80211 to implement mesh engine. To ensure the maximum performance of IEEE 802.11n, we have performed memory tuning of TCP/UDP in Linux kernel. In addition, other modules were removed caused by conflict with driver package modules [20], [21].

To support the IEEE 802.11n, Atheros distributed open source driver ath9k that supports IEEE 802.11n features on AP-STA connection, and mac80211 provides basic functions of mesh network. Figure 1 shows the implemented parts in ath9k in the transfer process of IEEE 802.11n standard. In particular, in frame aggregation scheme, ath9k supports only A-MPDU features.

Unfortunately, mesh mode of mac80211 does not provide MIMC technique and IEEE 802.11n features, IEEE 802.11n doesn't operate with MIMC of course. Therefore, we need to implement for operation of mesh mode with MIMC, and also we have to make IEEE 802.11n to operate in mesh mode with MIMC technique.

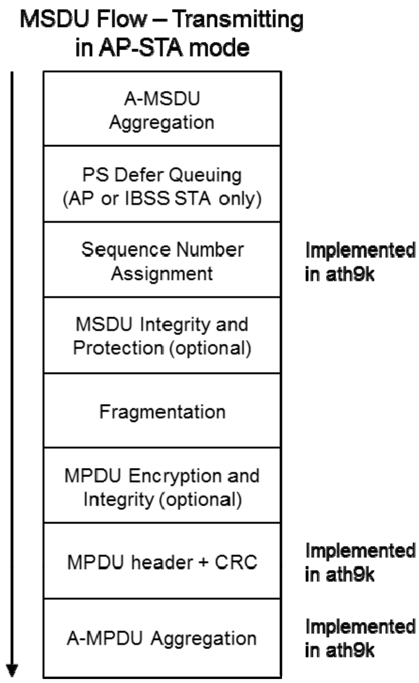

Figure 1. Implemented parts of IEEE 802.11n in ath9k

B. Modified AODV Routing Protocol for MIMC

To completely reduce interference in adjacent links, MIMC technique and directional antennas were used. In this way, one interface of mesh node takes charge of connection with only one neighbor node. For example, the mesh node that has 3 interfaces has 3 neighbors.

To implement MIMC technique, we use bonding module within Linux kernel. This module allows that one or more mesh interfaces in a mesh node can communicate using the delegate MAC address. The mesh engine that is implemented in this paper checks the packets from the IP layer. If the packet's destination address is broadcasting, then forward to all interfaces within the node, otherwise the packet is forwarded to appropriate interface after check mesh routing table. In addition to management each interface within a node using list, and this list is used to forwarding packets from IP layer to suitable interface.

In this paper, we have modified the AODV routing protocol that is on-demand method and is defined in HWMP (Hybrid Wireless Mesh Protocol) to operate in WMNs with MIMC. The WMNs which use AODV routing protocol generate route using PREQ (Path Request), PREP (Path Reply) frame for communication between nodes. In AODV behaviors, when node A tries to communicate to node B, node A broadcasts PREQ for generate route to node B. All nodes which received PREQ have re-broadcast this frame if PREQ's destination doesn't match own MAC address. In this way, if PREQ finally arrives at destination, then replies PREP to source through unicast. When PREP arrives at the source node, route information is formed in source and destination. All nodes that forwarded PREQ/PREP create a path to neighbor node which transmitted PREQ/PREP. However, if MIMC is used, the protocol has to manage routing tables which exist in each interface. Figure 2 and Figure 3 show route discovery process of modified AODV routing protocol.

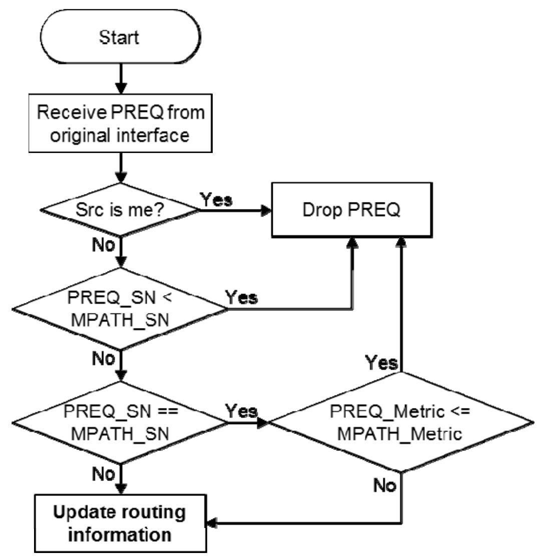

Figure 2. PREQ Process (frame received on original interface of path)

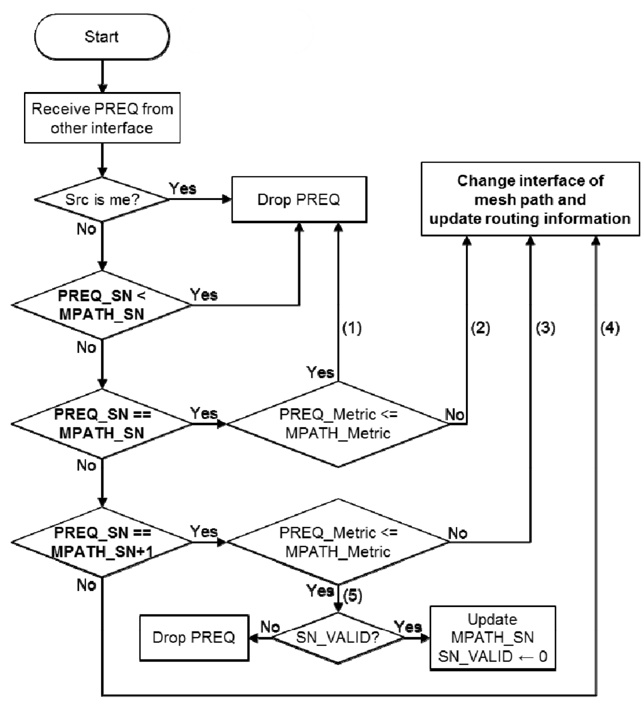

Figure 3. PREQ Process (frame received on other interface of mesh path)

Figure 2 shows process of PREQ when this management frame was received on original interface. The routing protocol checks SN (Sequence Number) of PREQ, and if PREQ_SN (SN of PREQ) is less than MPATH_SN (SN of current path in routing table), determines that PREQ has old routing information and discards it. And if PREQ_SN is equal to MPATH_SN, then checks routing metric. If PREQ_Metric is worse than MPATH_Metric, discards it, and otherwise updates routing information to PREQ's. Finally if PREQ_SN is greater than MPATH_SN, determines that PREQ has recently routing information and update routing information.

Figure 3 shows process of PREQ when this management frame was received on other interface of original path's one. There are 5 considering points, except on the case that PREQ_SN is less than MPATH_SN. First, PREQ_SN is equal to MPATH_SN, PREQ_Metric is less than or equal to MPATH_Metric, then this PREQ frame is discarded because it has old information or was passed by path with routing metric. Second, PREQ_SN is equal to MPATH_SN, PREQ_Metric is greater than MPATH_Metric then current routing information is modified to PREQ's due to find the better path. Third, PREQ_SN is 1 greater than MPATH_SN, PREQ_Metric is greater than MPATH_Metric then modify routing information by same reason of second case. Fourth, if PREQ_SN is 2 or more greater than MPATH_SN, then PREQ's information is reflected to routing table regardless of the metric.

Finally, PREQ_SN is 1 greater than MPATH_SN but PREQ_Metric is not better than MPATH_Metric, we should to consider many situations. Basically, PREQ is propagated through broadcast, it is not always received through the path that has good metric caused by interference, processing time in each node, wireless communication errors, etc. Therefore, in order to prevent frequent changes of the path, the case that PREQ is received on the path which has bad metric with low probability should be considered. If SN_VALID flag is valid by checking, then MPATH_SN increase one and set the flag to invalid. Otherwise, discard the PREQ frame. In this way, when PREQ was received first through the path that has bad metric, routing protocol can handle that situation. In addition, the routing protocol can control the problem occurrence on mesh node or links as quickly as possible. In other words, through interoperability between multiple interfaces, modified AODV can ensure reliability and stability of network.

C. *Establishing Block ACK Session in Multi-hop*

According to the IEEE 802.11n standard, block ACK session should be established between two HT STA (High Throughput Station) in order to use block ACK policy in MAC layer [6]. The establishment of session is achieved through the exchange of ADDBA (Add Block ACK) frame. In situation that two stations are operated in HT, one station send ADDBA request frame to other station, this frame includes block ACK policy, TID (Traffic Identification – QoS class) window number, and buffer size. The station which receive ADDBA request frame should check information of received frame, and if possible to establish a session, then reply with ADDBA response containing same information. After exchange ADDBA frames between two stations which can operate on HT, block ACK session is established.

In ath9k driver, the establishing block ACK session is essential requirements for IEEE 802.11n operation. Thus, to activate IEEE 802.11n link, mesh engine has to set block ACK session on target link. In this paper, we have implemented process of block ACK establishment on multi-hop environment in order to apply IEEE 802.11n to each mesh link on WMNs with MIMC.

Figure 4 shows operation process of mesh engine when station attempts to transmit data on multi-hop path. When node 1 tries to transmit data to node 3, mesh engine performs route discovery, block ACK session establishment, transmit data, and close the block ACK session. First, multi-hop path is created between node 1 and node 3 by PREQ/PREP. After that, a node that want to send data (node 1, node 2) transmit ADDBA request frame to each neighbor node (node 2, node 3). A node which receives ADDBA request frame checks information as block ACK policy, TID window number, buffer size, and respond with ADDBA response after set start sequence number for TID window. We implement this mechanism with considering MIMC, thus block ACK session establishment is processed in all links on path at the same time.

When block ACK session is established, QoS data such as A-MPDU is transmitted through TID window which is set in establish process, and receiving node receives QoS data through TID window that has same number with transmitting node's window. When the transfer of data blocks is complete, the sender requests block ACK with BAR (Block ACK Request), and the recipient sends BAR to sender to verify the data block. After complete transfer data on 1-hop, transmission of data blocks is started in next-hop that is already establish block ACK session.

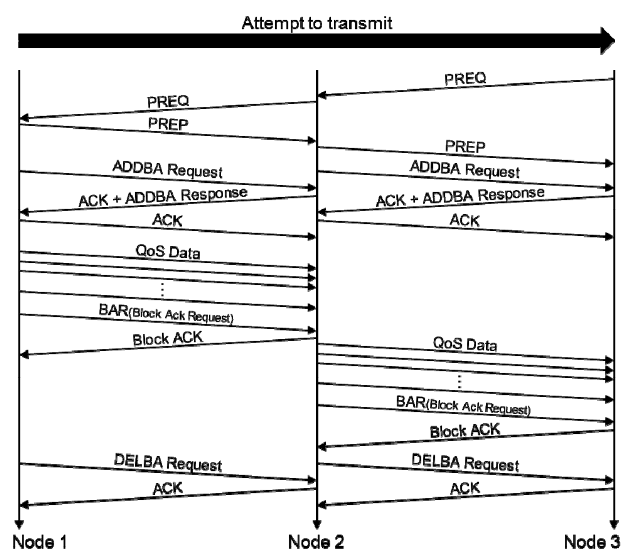

Figure 4. Block ACK session establish process

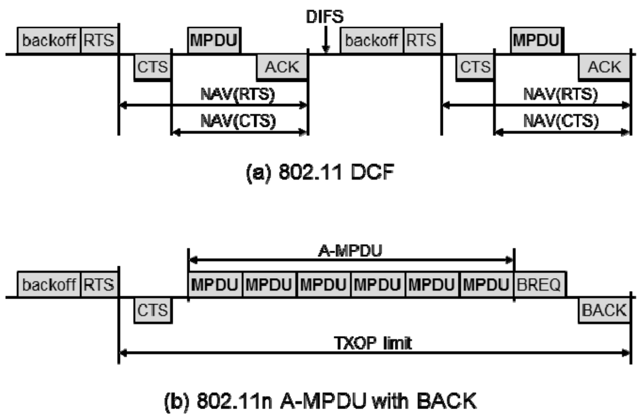

Figure 5. IEEE 802.11 MAC mechanisms

D. *Management Sequence Number of MPDU*

The one or more MPDU is transmitted during one TXOP (Transmission Opportunity) limit in between two nodes with block ACK session established. Figure 5 shows differences of IEEE 802.11 MAC mechanisms such as DCF (Distributed Coordination Function) of IEEE 802.11 and BACK (Block ACK) of IEEE 802.11n. DCF operates as 4 way handshake as RTS (Ready To Send) – CTS (Clear To Send) – data – ACK, and to ensure reliable transmission by setting NAV (Network Allocation Vector). BACK operates as RTS – CTS – A-MPDU – BREQ (Block ACK Request) – BACK. MPDU is transmitted after aggregated by TXOP limit at once.

MPDUs which are transmitted within the TXOP limit need not be in sequence because using block ACK policy. However, in most cases, MPDUs are aggregated sequential when A-MPDU is formed. Therefore, minimum reorder algorithm is required in recipient for retransmitted MPDUs.

In our WMNs with MIMC, all mesh interfaces have each MAC level TID buffer. Therefore, in this paper, we have implemented that MPDU management such as removing duplicate MPDUs, reorder MPDUs are operated on each link in same time. The mesh node that uses IEEE 802.11n links generates A-MPDU with all data frames and then transmits A-MPDU on the block ACK mechanism. A-MPDU is divided into MPDU in recipient, and is handled by mesh routing, i.e., forwarding, receiving.

IV. EXPERIMENTS RESULTS

In this section, we describe the actual implemented outdoor testbed of WMNs with MIMC. Also, we perform several experiments and analyze the results.

A. *Outdoor Testbed*

All of experiments are performed on outdoor testbed which located in Pusan National University. The outdoor testbed was constructed with implemented mesh routers in this paper which are installed on the roof of each building, and playground.

Figure 6. WMNs with MIMC outdoor testbed topology

Figure 6 shows our outdoor testbed of WMNs with MIMC. The testbed is composed of 9 mesh routers, and each mesh router has interfaces the same number of links. Each interface runs in 5GHz channel, and the links using IEEE 802.11n have been deployed in where bottleneck may occur. Other links use the IEEE 802.11a standard. Each mesh router uses directional antennas, especially, the links using IEEE 802.11n communicate over 2x2 MIMO directional antennas. The maximum distance between mesh routers using directional antennas is about 200m.

B. *Experiments Scenarios*

In this paper, we perform various experiments to measure the performance of WMNs and features of IEEE 802.11n. Before performing the experiments, we have tuned the TCP/UDP memory in kernel and removed conflicted modules. First, we observe the impact on performance such as the number of data streams, channel bonding in single-hop. Next, after establishment of block ACK session in multi-hop, we analysis the performance and various parameters change by the number of data stream and channel bonding in 3 hops.

In addition, we measure the IEEE 802.11n parameters such as average aggregation level in each node and distribution of MCS class and analyze relation with the performance in multi-hop. We performed 10 independent replicates of each measurement experiment and derived the considered performance measures with 95% confidence level. We used *iperf* that is the bandwidth measurement tool.

C. *Experimental Results and Analysis*

We first perform experiments to investigate the impact of IEEE 802.11n features on the performance at user-space. Table 1 shows the single-hop performance at user-space according to channel bonding and the number of data streams. The distance between nodes is set to 150m.

TABLE 1. PERFORMANCE IN SINGLE HOP

IEEE 802.11n Features	1 data stream	2 data streams	1 data stream + channel bonding	2 data streams + channel bonding
Performance[Mbps]	35.91	84.11	83.58	140.75

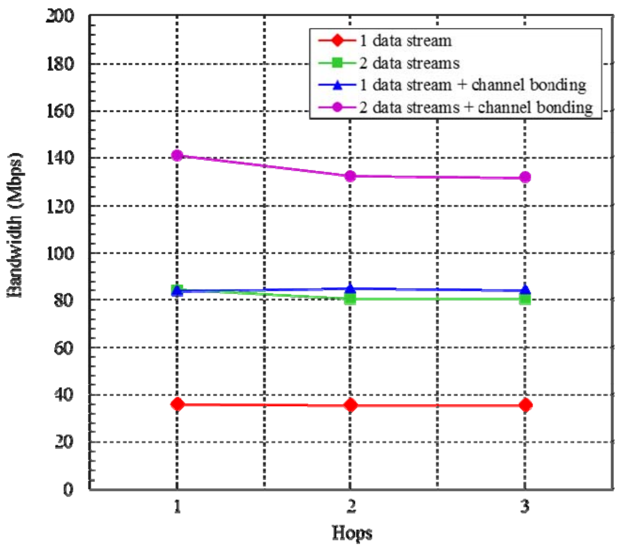

Figure 7. WMNs with MIMC outdoor testbed topology

If mesh link uses all features of IEEE 802.11n such as spatial multiplexing and channel bonding, then data rate is set to 300Mbps at PHY layer. Otherwise, only channel bonding is used in mesh link, then 135Mbps data rate is set, and only spatial multiplexing (2 data streams) is used in mesh link, then data rate is set to 130Mbps. Lastly, although IEEE 802.11n is applied to mesh link but not use the main features, then data rate is set to 65Mbps.

Figure 7 shows the performance at user-space in multi-hop over changing the IEEE 802.11n features, this experiment is performed to analysis the effect of IEEE 802.11n features on multi-hop performance. When mesh link uses only 1 data streams, the performance is 35.45Mbps on 3-hop. If 2 data streams are used without channel bonding, then the performance is 80.15Mbps on 3-hop, and only channel bonding is used, we get 83.97Mbps bandwidth on 3-hop. Finally, when full features are used in mesh links, there are 131.68Mbps bandwidth on 3-hop. In last case, the performance is 140.75Mbps on 1-hop, 132.25Mbps on 2-hop, and 131.68Mbps on 3-hop, respectively. We can see that performance is maintained in 130~140Mbps even if the number of hop is increased. A little decline of performance between 1-hop and 2-hop is caused by overhead of forwarding process and limit of processors throughput.

Figure 8 shows the average aggregate size at each node in a multi-hop communication. We observe that impact of spatial multiplexing is greater than channel bonding on mean aggregate size. When 2 data streams and channel bonding are used in multi-hop link, the number of average aggregate size in third node is 26.38 frames. However if only spatial multiplexing or channel bonding is used, then 21.81 frames or 8.67 frames are aggregated in third node respectively. The actual performance using full features is about 63% increased than using only 1 feature, but average aggregate size is not 63% greater than using only 1 feature. This result means that frame aggregate level is not affecting the actual performance absolutely.

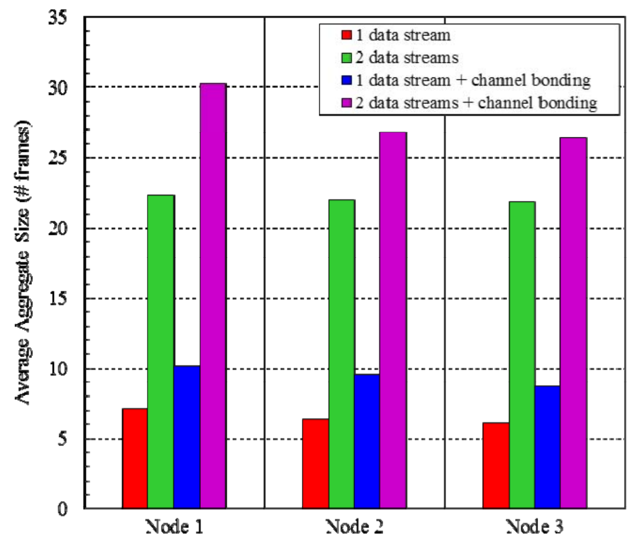

Figure 8. Average aggregate size at each node

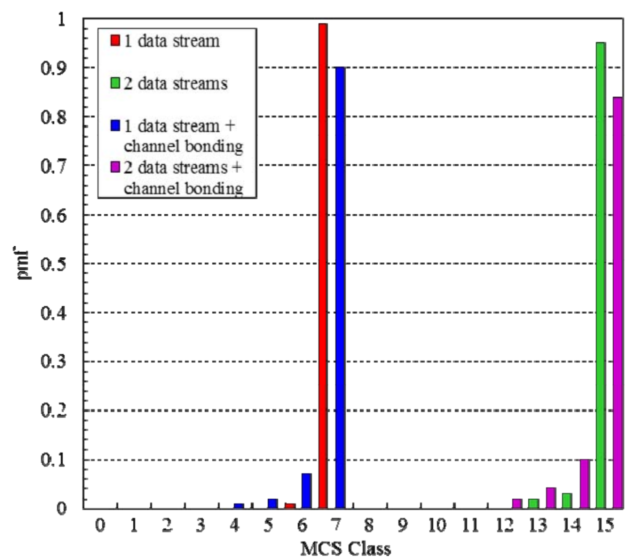

Figure 9. MCS class distribution in a multi-hop communication

Figure 9 shows the MCS (Modulation and Coding Scheme) class distribution in multi-hop communication. The index 0~7 means communicate on 1 spatial stream, other means using 2 spatial streams. For example, MCS index 15 uses 2 spatial streams and 64-QAM as modulation type, 5/6 as coding rate. When MCS index is 15 using 40MHz channel and 400ns GI (SGI), the data rates is 300Mbps at PHY layer. Due to use 2x2 MIMO directional antennas, transmission error rate is not high. So when we use 2 data streams, MCS index is distributed in 12~15, otherwise in 4~7. In this graph, we can observe that MCS index has better value with deactivated channel bonding. We suppose that channel bonding is vulnerable to interference, so MCS index using 40MHz channel bandwidth changes more frequently.

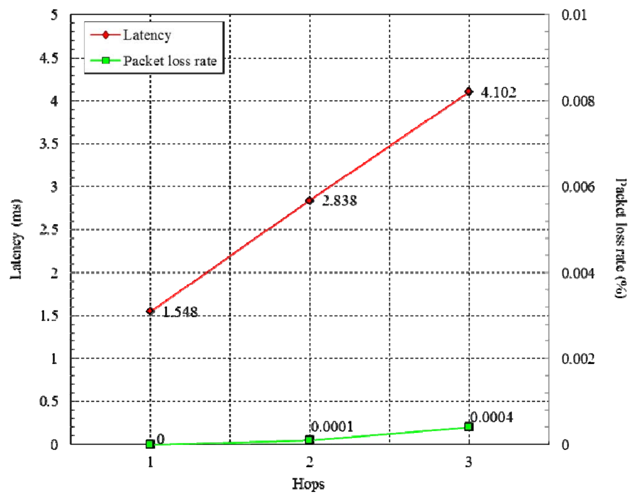

Figure 10. Link latency and packet loss rate in a multi-hop communication

Figure 10 shows the delay time and packet loss rate in a multi-hop communication. We can observe when the number of hop increases, latency also increases linearly. We suppose that large delay is due to overhead of frame aggregation / de-aggregation and reordering process in intermediate nodes. We also have measured packet loss rate, 0.0004% of packet is loss of UDP flows.

V. CONCLUSION AND FUTURE WORK

We presented the design of applying IEEE 802.11n to multi-hop link in WMNs with MIMC for increasing performance. We implemented the modified AODV routing protocol for MIMC, the technique of establishing of block ACK session in multi-hop, and the method of MPDU management in multi-hop.

We constructed the outdoor testbed of WMNs with MIMC, and we perform various experiments in this testbed to measure and analyze the IEEE 802.11n features in multi-hop environment. The performance in multi-hop of MIMC was increased about 63% by channel bonding and spatial multiplexing. The packet loss rate was not significantly changed even if the number of hops increases, but delay time was increased linearly.

In the following research, we will study the adaptive deployment of 802.11a and 802.11n link in MIMC WMNs to solve the bottlenecks and lack of available channel at the same time. Also the optimization of frame aggregation and reordering MPDU in multi-hop will be studied to reduce end-to-end delay in WMNs with MIMC.

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