Controlling Unfairness due to Physical Layer Capture and Channel Bonding in 802.11n+s Wireless Mesh Networks

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ABSTRACT
This paper analyzes the effect of physical layer capture (PLC) and channel bonding over high throughput wireless mesh backbone network built over IEEE 802.11n+s standard. With the help of PLC, a signal can be recovered from channel noise and interference if the difference between the received signal strengths is more than a predefined threshold. It is well known that PLC can affect fairness during channel access by biasing towards the link with better signal strength. In this paper, we show that in the presence of channel bonding, high throughput links always suffer due to PLC, that ensures severe unfairness in a mesh backbone network. As a consequence, the performance of the network drops significantly from its actual capacity. This paper presents an adaptive bonding opportunity and channel reservation scheme to mitigate from network unfairness in an IEEE 802.11n+s mesh network. The performance of the proposed scheme is analyzed and evaluated using a 13 node mesh networking testbed. It has been observed that the adaptive bonding opportunity and channel reservation performs significantly better in terms of fairness compared to the standard, and results in a notable performance improvement for end-to-end flow parameters.

Categories and Subject Descriptors
C.2.1 [Network Architecture and Design]: Wireless Communication

General Terms
Performance, Evaluation

Keywords
Wireless Mesh Network, Fairness, Channel Bonding, Physical Layer Capture

1. INTRODUCTION
High throughput wireless mesh network [8, 25] is gaining significant attention among the wireless researchers and system developers because of its capacity to replace the wired backbone infrastructure through a wireless one. The recent standardization of wireless mesh network, termed as IEEE 802.11s [3] amendment, and the commercial products for mesh networking supports, like Cisco 1500 series mesh access points [9], have advent the commercial and commodity uses of wireless mesh networks from small-scale ad-hoc networks [7] to enterprise backbone network [5]. IEEE 802.11n high throughput physical layer technology [26] has further exaggerated the development of wireless mesh network for commercial and enterprise use. The IEEE 802.11n high throughput physical layer supports channel bonding [11] to improve physical data rate in wireless medium, up to 600 Mbps with the combination of advanced modulation and coding schemes (MCS). Channel bonding [11, 13, 18] combines two consecutive 20 MHz bands to a 40 MHz band of wider channels, so that more data bits can be transmitted through spatial multiplexing. Though 40 MHz band theoretically doubles up the physical data rate compared to a 20 MHz band, it is more susceptible to channel noise. Therefore, minimum receiver sensitivity of a 40 MHz channel (−79 dBm) is comparatively more than that of a 20 MHz channel (−82 dBm) [13]. A few recent works [4, 22, 26] have designed MCS adaptation strategies to avoid data rate versus noise trade-off in IEEE 802.11n single hop networks. However, these schemes neither solve the problem completely, nor can avoid it for multi-hop communications.

In spite of its problems over multi-hop wireless networks [14, 15], IEEE 802.11n is attaining popularity for the design of high throughput wireless mesh backbone networks [17, 23, 24] due to its elevated capacity. IEEE 802.11s amendment [3] over wireless networking standard gives the protocol elements for medium access control (MAC) specifications for a mesh network with IEEE 802.11 supported physical layer compatibility. A wireless station (STA) that supports mesh functionality is termed as a mesh STA. A set of mesh STAs that share a common network profile is termed as a mesh basic service set (MBSS). In a MBSS, the mesh STAs form a multi-hop communication architecture, where one or more mesh STAs, called mesh gates, connect the network to the outside Internet. The intermediate mesh STAs work as a relay to forward the traffic towards or from the mesh gates. For a mesh backbone network, the mesh STAs also
act as the access point (AP) for the client STAs, and forwards the traffic from the client STAs to the mesh gates or vice versa. The IEEE 802.11s provides a set of protocol elements, namely mesh peer management protocol (MPM), mesh access function (MAF) and mesh path selection protocol for MAC layer service management. MPM is used for mesh discovery and peer establishment between two mesh STAs. MAF supports two types of channel access protocol, the mandatory IEEE 802.11 enhanced distributed channel access (EDCA) and the optional MAF controlled channel access (MCCA). EDCA is a contention based protocol, where a binary exponential back-off procedure is used for contention resolution. On the contrary, MCCA is a contention free reservation based channel access, where a mesh STA reserves transmission opportunities within a contention free access interval, called a delivery traffic indication message (DTIM) interval. The maximum amount of channel reservation in a DTIM interval is bounded by a parameter termed as MAF limit. The standard supports a hybrid path selection protocol for mesh networks, called hybrid wireless mesh protocol (HWMP). HWMP has a proactive as well as a reactive path selection protocol element to determine the best path between a pair of mesh STAs.

As mentioned earlier, the set of protocols for IEEE 802.11n+s physical and MAC layer has the ability to exaggerate the design and development of a high throughput wireless mesh backbone network. This paper investigates the effect of IEEE 802.11n physical layer protocol elements over the performance of IEEE 802.11s MAC layer mesh functionality. The performance is analyzed and observed from practical indoor testbed scenarios, designed and developed at IIT Guwahati research laboratories. As mesh networking is known to be susceptible on channel interference [10, 20], the testbed environment employs PLC [19, 28] to restore data from interfered signals. In the case of PLC enabled devices, if the difference between the strengths of the interfered signals at the receiver exceeds a certain threshold, the receiver can correctly decode and capture the packet with higher signal strength. Lee et al [21] have shown that an one dB difference at the receive signal strength is sufficient for successful capture in Atheros adapters. However, it is well known that for a multi-hop networks, PLC can result in unfairness [16, 27]. However, the existing studies have not analyzed the effect of PLC over IEEE 802.11n+s channel bonding. This paper investigates inter-effect of PLC and channel bonding over a high throughput mesh network. The major contributions of this paper can be summarized as follows.

1. Using practical indoor mesh testbed setups, this paper analyzes the impact of PLC and channel bonding over the network performance metrics. Though PLC can improve overall network capacity, it affects network fairness. Network unfairness shows negative impact over the end-to-end performance parameters. Further, the analysis shows that PLC always biases the capture towards the 20 MHz channel in case of adjacent channel interference, while the signal transmitted using the 40 MHz channel gets dropped. As a consequence, the existing schemes [12, 13, 22, 27] fail to recover from unfairness in case of a high throughput mesh network in the presence of both 20 MHz and 40 MHz channels. It can be noted that the present research, like [13], as well as the commercial IEEE 802.11n products support intelligent and dynamic channel bonding, where the bonding opportunities are determined on the fly. Therefore in a MBSS, a mixture of 20 MHz and 40 MHz supported mesh STAs is common, and therefore this problem can not be avoided.

2. Based on the observations and analysis of the results from the testbed, this paper proposes an adaptive channel reservation algorithm with channel bonding synchronization, so that unfairness due to PLC can be mitigated in a best effort basis. It can be noted that several factors play interdependent role in the design of an optimum physical and MAC performance criteria, like channel bonding opportunities, selection of a particular MCS level that determines the physical data rate and the MAC layer channel reservation. An adaptive tuning mechanism is used to adjust these parameters for improved network performance in terms of fairness and throughput. This adaptive mechanism is termed as high throughput fair mesh (HT-fair Mesh).

3. The performance of HT-fair Mesh has been analyzed and evaluated using a general 13 node mesh networking testbed. The testbed result shows that HT-fair Mesh significantly improves fairness and average network throughput. At the same time, a significant improvement in the end-to-end flow performance has been observed for HT-fair Mesh architecture, compared to the standard IEEE 802.11n+s mesh, and other existing schemes.

The rest of the paper is organized as follows. Section 2 describes the general testbed setup and the results from the testbed to analyze the effect of interference over the performance of PLC enabled IEEE 802.11n+s networks. Section 3 gives the design and architecture of the protocol elements and rules for supporting fairness in an IEEE 802.11n+s high throughput wireless mesh network. The performance of the proposed protocol has been evaluated in Section 4, through the results from the testbed. Finally, Section 5 concludes the paper.

2. EFFECT OF INTERFERENCE OVER PLC ENABLED IEEE 802.11n+s

This section gives the detailed analysis of the effect of PLC and channel bonding in an IEEE 802.11n+s network. For this purpose, two simple topologies are used, similar to the conventional hidden terminal problem, as shown in Figure 1. Scenario-1 shows a direct interference scenario where STA-1 and STA-3 both simultaneously transmits to STA-2, and therefore, STA-2 is the common receiver. In Scenario-2, the communication from STA-3 to STA-4 creates interference at STA-2. This scenario is termed as the indirect interference scenario. It can be noted that these simple interference scenarios are used in this section for analyzing the behavior of the network under different control parameter settings. Later, we have shown the evaluation and analysis of the protocol elements from a more generalized scenario.

2.1 Hardware Setup

In these experiments, IEEE 802.11n supported Ralink RT-3352 router-on-chip [2] has been used as the core of the mesh STAs. The RT-3352 router-on-chip combines 802.11n draft compliant 2T2R MAC along with BBP/PA/RF MIMO, a
high performance 400MHz MIPS24KEc CPU core, a Gigabit Ethernet MAC, 5-ports integrated 10/100 Ethernet Switch/PHY, 64 MB of SDRAM and 32 MB of Flash. This chip can support up to 300 Mbps data rate with the maximum transmission power of 16dB.

2.2 Software Setup

Every mesh STA is equipped with Linux kernel version 3.12.24 with IEEE 802.11 protocol stack. The mac80211 submodule of the net module in the Linux kernel network protocol stack is patched with open source IEEE 802.11s implementation, open80211s [1]. We have used the intelligent channel bonding mechanism proposed by Deek et al [13] along with the IEEE 802.11n rate adaptation mechanism [22]. These schemes are implemented as a loadable kernel module (LKM), where the intelligent channel bonding mechanism first determines the bonding opportunity based on throughput measurement. Subsequently, the rate adaptation mechanism uses the rate upgrade or rate downgrade mechanism for the selected 20 MHz or 40 MHz channels. It can be noted that the capture threshold for the RT-3352 chipset is approximately 1.6 dB. The open80211s control parameter setup is given in Table 1. In the testbed, Seagull Multi-protocol Traffic Generator is used to generate traffic and measure performance. It can be noted that to keep the network saturated and to find out the maximum network throughput, we have used constant bit rate traffic with high traffic generation rate (200 Mbps).

IEEE 802.11s uses EDCA for control message communication at the contention phase, that are used to reserve MCCa transmission slots, also called transmission opportunities (TxDp). Within a DTIM interval, EDCA employs a binary exponential back-off mechanism, where a contention window is used to avoid interference during communication. For every unsuccessful communication attempt, contention window is doubled up, and that many slots are waited before attempting for another communication. Based on the standard, this contention based back-off mechanism is utilized in the experiments for MCCa control message communications. For details of EDCA and MCCa, the readers are referred to the IEEE 802.11 standard [3].

For all the experiments described in this section, a single experimental setup is executed five times, with the mean duration of execution being 2 hours, and the average is used to plot the graphs. The deviations in the results of different executions, known as confidence intervals, are also shown in the graphs as a vertical line at every point instance.

2.3 Experiment 1: Throughput performance with PLC, dynamic channel bonding and dynamic MCS selection

In the first experiment, we have evaluated the throughput performance for the direct and the indirect interference scenarios as shown in Figure 1, in the presence of PLC, dynamic channel bonding [13] and dynamic MCS selection [22]. Figure 2 shows the throughput performance for the links in the direct and the indirect interference scenarios. It can be seen from the figure that for the direct interference scenario, the throughput for link-11 (STA-1 \rightarrow STA-2) and link-12 (STA-3 \rightarrow STA-2) drops several times, resulting in significant throughput unfairness. Further, this throughput unfairness is not specific to a particular link. For the indirect interference scenario, the throughput for link-22 (STA-3 \rightarrow STA-4) remains almost stable, whereas the throughput for link-21 (STA-1 \rightarrow STA-2) drops several times, resulting in throughput unfairness. It can be noted that in the indirect interference scenario, only the link-21 gets affected due to the interference from link-22.

In the next experiments, we have analyzed this phenomenon in a case-by-case basis to find out the probable reasons behind this unfairness. These cases are described in the following subsections.

2.4 Experiment 2: Effect of PLC over channel bonding

In this experiment, the effect of PLC over throughput performance is evaluated in the presence and absence of channel bonding. For this purpose, we have used the direct and indirect interference scenarios as shown in Figure 1 with static bonding opportunities and static MCS. Two MCS are used...
from the available MCS set, MCS 7 and MCS 14. MCS 7 uses one spatial multiple input multiple output (MIMO) stream with 64-quadratic amplitude modulation (64-QAM) at a coding rate of 5/6 that provides 72.20 Mbps at 20 MHz channel and 150 Mbps at 40 MHz channel. On the other hand, MCS 15 uses two MIMO spatial streams with 64-QAM at the same coding rate, that provides 144.40 Mbps at 20 MHz and 300 Mbps at 40 MHz. It can be noted that all the links operate at overlapping channels, and therefore co-channel interference is common during communication.

For direct interference scenario as shown in Figure 1, we have changed the channel bonding configurations for the two links, STA-1 → STA-2 (termed as link-11) and STA-3 → STA-2 (termed as link-12), from the configuration set \{(20 MHz, 20 MHz),(20 MHz, 40 MHz),(40 MHz, 20 MHz),(40 MHz, 40 MHz)\}. At every instance, the link throughput\(^2\) is calculated which is plotted in the graphs shown in Figure 3. In the figure, these four instances are shown along the x-axis as 20/20, 20/40, 40/20 and 40/40 respectively. It can be noted that IEEE 802.11s supports peer link specific configurations, and therefore such link specific parameter configurations is directly available with IEEE 802.11s MPM protocol for peer establishment. Figure 3 shows the results for four instances, with all the links operating at MCS 7 and MCS 15, and with enabling and disabling PLC. It can be seen from the figure that when PLC is disabled, the throughput for the links is at per the physical data rate, that is the 40 MHz link attains higher throughput compared to the 20 MHz link. However, when PLC is enabled, the throughput for 20 MHz increases significantly, but the throughput for 40 MHz increases only when both the links use the same channel. In a mixed scenario of 20 MHz and 40 MHz channels, the link throughput for 40 MHz is almost stalled. As discussed earlier, IEEE 802.11s uses EDCA along with binary exponential back-off for communicating MCCA control packets that are used for TxOpps reservations within a DTIM interval. In the presence of PLC, the control packets transmitted using 20 MHz channel gets decoded correctly at the receiver as they require lower receiver sensitivity (−82 dBm, compared to −79 dBm for 40 MHz), and TXOpps are reserved within the DTIM interval. In every such cases, the mesh STA that communicates using the 40 MHz channel suffers from consecutive back-off due to continuous packet loss, and gradually attains a large contention window. As a result, the mesh STA with 40 MHz channel seldom gets a chance to reserve TxOpps within the DTIM interval. Therefore, we observe severe unfairness in a mixed environment of 40 MHz and 20 MHz channels.

Figure 3: Effect of PLC over Channel Bonding: Direct Interference Scenario

Figure 4 shows the results from the indirect interference scenario. The main difference of this scenario from the direct interference scenario is that the link STA-3 → STA-4 (termed as link-22) can transmit data without any interference, although the communication through the link STA-1 → STA-2 (termed as link-21) suffers from interference. The experimental results from this scenario give some important and interesting observations which are summarized next.

1. When PLC is disabled, link-22 attains better throughput compared to link-21. This is natural as link-21 experiences interference whereas link-22 can transmit data with maximum capacity. Consequently, in the scenarios when both links use different channels, the 20 MHz throughput for 40/20 scenario is more compared to the 20 MHz throughput for 20/40 scenario, and vice-versa for the 40 MHz throughput.

2. For the 20/40 scenario, enabling PLC improves the throughput for both 20 MHz and 40 MHz links. However in case of the 40/20 scenario, enabling PLC significantly improves the throughput only for the 20 MHz

\(\text{Throughput (Mbps)}\)

\(\text{Capture Disabled, MCS 7}\)

\(\text{Catch Enabled, MCS 7}\)

\(\text{Capture Disabled, MCS 15}\)

\(\text{Capture Enabled, MCS 15}\)

\(\text{Throughput (Mbps)}\)

\(\text{Link-11: STA-1 → STA-2}\)

\(\text{Link-12: STA-3 → STA-2}\)

\(\text{Link-21: STA-1 → STA-2}\)

\(\text{Link-22: STA-3 → STA-4}\)
link (link-22), whereas the throughput for the 40 MHz link (link-21) drops drastically. From the traces of the mesh STAs, it has been observed that, in case of interference between 20 MHz and 40 MHz channels (we call this as asymmetric channel interference) at STA-2, the packets transmitted through the 40 MHz channel gets suffered. Consequently, STA-2 can decode the overheard control packets from STA-3, however fails to decode the packets from STA-1 in case of an asymmetric channel interference.

3. For symmetric channel interference (both the interfering links use either 20 MHz or 40 MHz channels), the decode probability solely depends on the signal strength. In the testbed setup, the effect of external interference noise is almost equal for both the links, and therefore they achieve long term throughput fairness according to the IEEE 802.11 EDCA air-time fairness principle [6].

The experiments discussed in this subsection reveal that in an environment where MCS is kept fixed, PLC significantly hampers the performance of a 40 MHz link in the presence of asymmetric channel interference. In the next set of experiments, we evaluate the effect of MCS setup over throughput performance along with channel bonding and PLC.

### 2.5 Experiment 3: Effect of MCS selection over PLC and channel bonding

![Figure 5: Effect of MCS Selection over PLC and Channel Bonding: Direct Interference Scenario with Good Signal Quality (≥−50 dBm), Maximum Aggregate Network Throughput is 195 Mbps (MCS 15 and 40 MHz at both the links)](image)

Figure 5: Effect of MCS Selection over PLC and Channel Bonding: Direct Interference Scenario with Good Signal Quality (≥−50 dBm), Maximum Aggregate Network Throughput is 195 Mbps (MCS 15 and 40 MHz at both the links)

In this set of experiments, we have evaluated the effect of MCS selection along with PLC and channel bonding over the throughput performance in the network scenario shown in Figure 1. In these figures, the x-axis represents the MCS for link-11 (STA-1 → STA-2); and the y-axis represents the MCS for link-12 (STA-3 → STA-2). Every pie in the graphs represents the aggregate throughput, where the black arc denotes the throughput share for link-11 and the gray arc shows the throughput share for link-12. The total size of the pie indicates the percentage of aggregate throughput with respect to the maximum throughput (195 Mbps for good signal quality and 113 Mbps for poor signal quality). The major observations from these figures are summarized next.

1. The maximum throughput is achieved with good signal quality, when both the links use 40 MHz channel and MCS 15. However, in the case of poor signal quality, maximum throughput is obtained when both the links use 20 MHz channel and MCS 13. As discussed earlier, 40 MHz channel is more sensitive to interfer-
ence noise. Further, higher MCS levels require higher receiver sensitivity. As a consequence, MCS 13 at 20 MHz channel performs best with poor signal quality.

2. When both the links use same channel, fairness is affected by MCS selection. However, higher MCS does not indicate higher data rate always. For instance, in Figure 6 when both the links use 20 MHz channel, whereas link-11 and link-12 are configured with MCS 13 and MCS 15 respectively, link-11 attains more throughput compared to link-12. Similar observations can be made for Figure 5 also, even with good signal quality. As higher MCS levels require higher receiver sensitivity, PLC is more biased towards lower MCS levels in case of an interference from the higher MCS levels. The existing works [13, 22] are built on the fact that the throughput increases or decreases unilaterally with MCS levels for single hop 802.11n without PLC. However, this fact does not hold true as PLC biases towards lower MCS levels and 20 MHz channel. Therefore, the existing schemes fail to provide fairness in case of PLC enabled system.

3. Irrespective of signal quality and MCS selection, the 40 MHz link always suffers in case of asymmetric channel interference, as evident from Figure 5 and Figure 6. Similar observations are made for the indirect interference scenario, except that only the link STA-1 \rightarrow STA-2 gets affected due to the interference from the link STA-3 \rightarrow STA-4. However, the results are not shown in the paper due to space constraints.

2.6 Should PLC be avoided in high throughput mesh networks?

From the testbed results, we can conclude that PLC significantly affects network fairness in a network with mixed mode 20/40 MHz channel bonding in the presence of asymmetric channel interference. Network unfairness significantly affects end-to-end performance, where some of the flows may get stalled due to unfairness problem in one of the links at the end-to-end flow path. Automatically a question may arise: should PLC be avoided in high throughput mesh networks to mitigate network unfairness? The answer of this question is based on two observations:

- It is evident from Figure 5 and Figure 6 that a channel contention among the 20 MHz and the 40 MHz channels always causes the wider channel to suffer, when PLC is enabled. Even during the contention between packets transmitted through different MCS levels, packets with higher MCS level may dropped during collision, if the required signal strength is not met for PLC.
- However, from Figure 3 and Figure 4, we can see that if the interfering links use same bonding configurations, then PLC significantly improves link throughput. In some cases, we can even witness more than 100% improvement in the network throughput with PLC.

Although PLC may reduce average network performance in a high throughput mesh network, there is an option to intelligently use channel bonding configurations at the presence of PLC, such that the advantages both these technologies can be utilized simultaneously. However, unfairness can not be avoided completely only through intelligent channel bonding configurations and MCS selections. From Figure 5 and Figure 6, it can be seen that high throughput links are generally able to transmit more packets compared to low throughput links, in case of symmetric channel interference. Therefore we also need to tune the channel reservation protocol, so that network fairness can be ensured without affecting network throughput.

3. HT-Fair Mesh: A HIGH THROUGHPUT FAIR MESH PROTOCOL

In this section, the design and implementation details of HT-Fair Mesh, a fair high throughput mesh protocol, has been discussed, that intelligently selects bonding opportunities and channel reservations within a DTIM interval, to avoid network level unfairness. Figure 7 gives a high level block diagram description of the proposed protocol elements for the HT-Fair Mesh, according to the IEEE 802.11n+ protocol stack. In the proposed architecture, IEEE 802.11n is used for the physical layer as well as logical link control (LLC) sublayer of the data link layer, whereas IEEE 802.11s is used for MAC layer mesh functionality supports. As discussed in previous section, the mesh STAs are PLC enabled. Both the transmitter and the receiver modules maintain a database called information engine (InEn) which is used to store neighbor information. We exploit the IEEE 802.11n and IEEE 802.11s control messages, like MCS feedback and MCCA setup broadcast, to collect neighbor information.

In the proposed architecture, the IEEE 802.11n module contains a 'Rate/Bonding Opportunities Selection Engine' (RBOSen) that determines the bonding opportunities, data stream and MCS levels for communication. The RBOSen works in a close loop, where both the transmitter and the receiver determine the data rate parameters and the bonding opportunities collectively. For this purpose, we have used the standard IEEE 802.11n MCS Request and MCS Feedback messages, without incorporating any extra message overhead to the system. It can be noted that, a number of works [12, 22] have mentioned that close loop rate adaptation is more effective for IEEE 802.11n, compared to open loop rate adaptation \(^3\). At the receiver side, the RBOSen coordinates with two more submodules, called the frame monitor and channel quality estimator. The frame monitor intercepts the incoming data and control frames to collect neighbor information, and to store it at the InEn. The channel quality estimator determines the channel quality from the signal strength measurements of the incoming packets. In the implementation, we have used diffSNR as the channel quality estimation metric, as proposed by [12], which is the difference between the best and the worst signal strength measured at the receiver interface. As shown in [12], diffSNR gives a good prediction of the best MCS level along with MIMO data streaming, though it can not capture fairness requirements when PLC is enabled. The experimental results from the previous section indicate that, to achieve fairness along with PLC, all the neighboring mesh STAs should use either 20 MHz or 40 MHz, but not the both. For this purpose, we use a different method to determine the

\(^3\)In case of an open loop rate adaptation, the transmitter alone decides the data rate, whereas for a close loop rate adaptation, the data rate is determined cooperatively by the transmitter and the receiver.
bonding opportunities, as discussed next.

In IEEE 802.11s mesh mode with MCCA as the channel access protocol, a mesh STA reserves slot within a DTIM interval. The time is divided into periodic intervals of contention interval and DTIM interval. In the contention interval, mesh STAs exchange control frames to set up communication and reserve channel with the DTIM interval. These control frames are used to exchange and negotiate control parameters between peer STAs, before they start actual communication. In *HT-Fair Mesh* architecture, similar periodic intervals, like contention interval followed by DTIM interval, are used for setting up mesh communications.

### 3.1 Selection of 802.11n parameters: Channel Bonding opportunities, MCS levels and MIMO streaming mode

In this subsection, we describe the protocol rules for the MCS, data stream and bonding opportunities selection. As mentioned earlier, this is a cooperative decision between the transmitter and the receiver. The 802.11n parameters are chosen based on following rules:

1. In IEEE 802.11n MCS Request frame, a bit is reserved to indicate bonding opportunities, where ‘zero’ (‘0’) denotes no bonding (20 MHz), and ‘one’ (‘1’) denotes channel bonding (40 MHz). At the beginning of a contention interval, mesh STAs first exchange IEEE 802.11n control frames, followed by IEEE 802.11s control frames.

2. If a mesh STA has data packets to transmit, it first waits for a random amount of time to overhear any MCS Feedback frame from its neighbors. After that, it sends a MCS Request frame to the peer mesh STA which acts as the receiver. A transmitter mesh STA includes a ‘zero’ in the bonding opportunity field of the MCS request frame (such that, it is configured to use the 20 MHz channel), if and only if all of its active neighbors\(^4\) are configured with 20 MHz channel. Otherwise it includes an ‘one’ in the bonding opportunity field of the MCS Request frame.

3. Whenever a peer STA receives a MCS Request frame, it executes one of the following steps based on the bit value received with the bonding opportunity field:

   (a) If the bonding opportunity field carries an ‘one’, it uses the transmitter reported setting, that is 40 MHz, as the bonding opportunity.

   (b) If the bonding opportunity field carries a ‘zero’, it computes the optimal bonding opportunity based on [13].

After that, the receiver finds out the optimal MCS level and MIMO streaming mode for the corresponding bonding opportunity, according to the *diffSNR* reported by the channel quality estimator. The computation of the optimal setting for MCS level and MIMO streaming mode is based on the scheme proposed in [12]. Finally, the receiver broadcasts a MCS Feedback frame with the selected bonding opportunity along with the MCS level and MIMO streaming mode.

In the design of *HT-Fair Mesh*, the receiver has to agree with a 40 MHz communication, whenever the transmitter includes an ‘one’ in the bonding opportunity field of the MCS Request frame. The reason behind this is that, a transmitter includes an ‘one’ in the bonding opportunity field of the MCS Request frame, only when at least on of its peer mesh STA is configured with 40 MHz channel. Therefore, the transmitter should not transmit using 20 MHz, as it may affect the 40 MHz communication. However, the transmitter is free to transmit either by 40 MHz or by 20 MHz, when all of its active peer STAs are configured with 20 MHz. In that case, the receiver decides the best bonding opportunity, along with MCS level and MIMO streaming mode.

\(^4\)A neighbor mesh STA is called an active neighbor if it has already transmitted a MCS Feedback frame.
and broadcast the information through the MCS Feedback frame.

3.2 Tuning 802.11s parameters to support fine grained fairness

Controlling channel bonding opportunities alone is not sufficient to avoid unfairness in the network. As discussed in the previous section, unfairness is still possible because of the data rate differences (that again depends on the MCS level, MIMO streaming mode and bonding opportunity) among the peer STAs. To avoid such unfairness, we further tune the IEEE 802.11s channel access protocol elements. According to the MCCA protocol features, a mesh STA is allowed to reserve a maximum numbers of TxOpps within a DTIM interval, which is bounded by a parameter called ‘MAF Limit’. However, the standard does not provide any mechanism to determine the value of the MAF limit. In this architecture, we have dynamically tuned MAF Limit to provide fair channel share to all the competing mesh STAs. After the MCS selection is complete, every mesh STA is aware of the selected data rate (this can be directly computed from the bonding opportunity, MIMO streaming mode and MCS levels received through the MCS Feedback frame). Consequently, every mesh STA computes MAF limits dynamically based on the physical data rate (according to selected MCS levels) and traffic load, as discussed next.

Let $D_S$ denotes the differentiated physical data rate for mesh STA $S$, which is calculated as follows:

$$D_S = \text{Maximum supported physical data rate} - \text{Physical data rate determined by RBOSen} + 1$$

Every mesh STA also maintains a parameter called Traffic Load Estimator (TLE), which is defined as the amount of backlogged traffic at every mesh STA. This information can be obtained directly from the backlogged interface queue size and propagated through the traffic indication map (TIM) to one-hop neighbors. It can be noted that every mesh STA periodically broadcast beacon which contains the TIM for that mesh STA. Let, $T_S$ denotes the TLE for mesh STA $S$. Then,

$$\text{MAF Limit for STA } S = \frac{D_S \times T_S}{\sum_{S \in N_S} (D_S \times T_S)}$$

where $N_S$ is the set of two-hop peer mesh STAs for STA $S$. The dynamic MAF limit proposed in this paper allowed every mesh STA to reserve channel according to its data rate and traffic load. Therefore, a mesh STA configured with higher data rate is allowed to reserve inversely proportionate number of TxOpps in a DTIM interval, if it contend with a mesh STA configured with lower data rate.

4. HT-Fair Mesh: PERFORMANCE ANALYSIS AND COMPARISON

In this section, we have analyzed the performance of HT-Fair Mesh using the results from the testbed. First, we have evaluated the performance using the direct and the indirect interference scenario, as shown in Figure 1. After that, the performance is evaluated over a general 13-node mesh testbed, with similar software and hardware configurations as discussed earlier.

4.1 Performance for the direct and indirect interference scenario

Figure 8 shows the throughput performance for HT-Fair Mesh architecture, in the direct and the indirect interference scenario, respectively. In case of direct interference, both the links attain almost similar throughput over time, and results in a long-term throughput fairness. Though the throughputs for the two links are different in case of the indirect interference scenario, it is because of the interference effect. In indirect interference scenario, communication through link-22 (STA-3 $\rightarrow$ STA-4) causes interference to the communication through link-21 (STA-1 $\rightarrow$ STA-3), however, link-22 experiences an interference-free communication. For this reason, link-22 attains higher throughput compared to link-21. Although, the throughput for link-21 remains steady with respect to time, and does not fade out like the earlier scenario, as shown in Figure 2. The proposed scheme avoids asymmetric channel interference, which is the main reason behind throughput fading in the 40 MHz channel. Further, the proposed scheme improves fairness through a proportional allocation of channel share based on their physical data rate.

Figure 9: 802.11n+s Indoor Mesh Testbed used for Evaluation

Next, we evaluate the performance of the proposed scheme from a 13 node 802.11n+s indoor mesh networking testbed as shown in Figure 9. The hardware and software configurations for every node is similar to that described earlier in Section 2. The traffic configuration is also similar except that in this scenario, we gradually increase the application layer data generation rate to evaluate the performance both at the saturation as well as the unsaturated traffic scenar-
Every mesh STA generates a traffic flow destined for the mesh gate (upload traffic), and the vice versa (download traffic from the mesh gate to the mesh STAs).

Figure 10: Network Performance Metrics from the Mesh Testbed

Figure 10 shows the average network throughput and fairness index calculated from the testbed traces. We have compared the performance of HT-Fair Mesh with the standard IEEE 802.11n+s along with Minstrel rate adaptation (the default rate adaptation for Linux kernel protocol stack) and the dynamic channel bonding and MCS selection [13, 22] (denoted as Dynamic MCS Selection in the graphs). Fairness is measured in terms of Jain Fairness Index which is defined as:

\[
Jain\ Fairness\ Index = \frac{\left( \sum F_i \right)^2}{n \sum F_i^2}
\]

where \( F_i \) is the performance parameter for \( i^{th} \) elements (in case of throughput fairness among the mesh STAs, \( F_i \) is the throughput for \( i^{th} \) mesh STA), and \( n \) is the total number of such elements. Figure 10 shows that HT-Fair Mesh supports significantly higher fairness compared to the standard as well as the dynamic MCS selection plus channel bonding schemes, without any loss in the average network throughput. Furthermore, the average saturation network throughput improves around 20 percent compared to the dynamic MCS selection plus channel bonding schemes.

Figure 11: End-to-end Performance Metrics from the Mesh Testbed

Figure 11 compares the performance of three protocols for end-to-end performance parameters: HT-Fair Mesh, the dynamic channel bonding and MCS selection scheme [13, 22] and the standard IEEE 802.11n+s along with Minstrel rate adaptation. Network unfairness affect the end-to-end performance parameters significantly by stalling some of the intermediate links in an end-to-end flow path. As a consequence, after the network gets saturated, the end-to-end throughput drops, and the delay increases, as seen from Figure 11. HT-Fair Mesh improves network fairness, which in turn improves the end-to-end throughput even more than 120 percent in some cases, and reduces the end-to-end delay. The proposed scheme overcomes the unfairness caused by PLC in case of a high throughput mesh network, and results in a noteworthy performance improvement, as evident from the testbed results.

5. CONCLUSION

PLC can improve network capacity by reducing the effect of inter-channel and co-channel interference, and is widely used in modern commodity and commercial wireless devices. In this paper, we have analyzed the impact of PLC over high throughput wireless mesh networks. This paper shows that PLC may result in a negative impact over high throughput mesh networks in case of asymmetric channel interference. Whenever two communication with different channel bonding opportunities interfere, the data transmitted through the 40 MHz channel gets lost. This in turn ramify severe unfairness in the network. We have analyzed the effect of PLC over channel bonding using testbed analysis, and reported the probable causes for such unfairness behaviors. Following the findings from the testbed analysis, we have designed and developed a high throughput fair mesh protocol, by augmenting the standard IEEE 802.11n+s protocol stack, that employs an adaptive selection of channel bonding opportunities, along with dynamic MCS and MIMO streaming mode selections. The performance of the proposed protocol has been analyzed through the testbed results, and compared with other existing protocols from the literature.

References


