공학박사 학위논문

A Distributed Message In Message Aware Concurrent Transmission Protocol in IEEE 802.11 WLANs

IEEE 802.11 무선랜에서의 분산적인 메시지-인-메시지 기반 동시 전송 프로토콜

2013 년 2 월

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강영명의 박사학위논문을 인준함

2013 년 2 월

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Abstract

A Distributed Message In Message Aware Concurrent Transmission Protocol in IEEE 802.11 WLANs

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The IEEE 802.11 Distributed Coordination Function (DCF) employs the carrier sense technology to avoid frame collisions. However, recent measurement studies demonstrate that the physical layer (PHY) *Capture Effect* frequently occurs; even when frames collide, one of them can be decoded successfully if its relative signal strength is high enough. Furthermore, a new wireless PHY technology, called *Message In Message* (MIM), adopts an advanced preamble detection function to enhance the PHY capture effect. To fully exploit MIM in multi collision environments, frame transmission orders have to be carefully scheduled. It also requires tight time synchronization at multiple Access Points (APs), thus induces large overheads.

In this thesis, we propose an opportunistic concurrent transmission protocol called DOMCT (*Distributed* Opportunistic MIM-aware Concurrent Transmission) which exploits the MIM functionality in a distributed manner obliterating the centralized control. In DOMCT, APs first prepare Interference MAPs (IMAP) to discover the possible simultaneous MIM transmission opportunities. Detecting the inadvertent frame transmission from a neighboring AP, an AP transmits another frame intentionally if both frames can be successfully decoded at destination nodes by the MIM capture effect. DOMCT achieves additional performance gains by employing enhanced mechanisms such as a per-station queue strategy and transmission ranking. By using the per-station queue strategy, DOMCT effectively fetches the MIM capable frames in real time. On the other hand, transmission ranking boosts the throughput performance by increasing the opportunities of concurrent transmissions.

Through both analysis and extensive ns-2 simulations, we show that DOMCT outperforms the legacy DCF by up to 61% and observe comparable performance to that of the centralized approach.

Keywords: IEEE 802.11 WLANs, scheduling, medium access control, Message-In-Message, MIM, Distributed WLAN, Physical Layer capture effect, MIM capture

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Chapter 1 Introduction

1.1 Background

To support the ever growing demands for mobile communications, IEEE 802.11 Wireless LANs (WLAN) have continuously evolved to higher speed variants [1][2][44][63]-[68][74]. Despite the improvements in PHY technologies, the goodput of WLANs does not increase in linear proportion to the PHY speed [3]. One limiting factor is large MAC overheads such as back-off time, long protocol header, ACK and various inter-frame shifts. Many clever schemes that reduce the MAC overheads have been proposed including frame aggregation [1] and binary back-off optimization [4][5]. These schemes are called as the temporal approach because they reduce the time required for MAC layer operations.

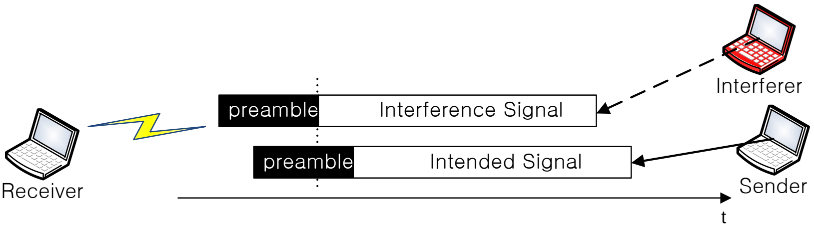
This thesis deals with the interference, another factor that degrades the WLANs performance. Interference is considered as one of the most important factors that decides wireless network throughput per unit area. Interference avoidance or reduction in multi-hop wireless networks has been the subject of active research during last several years and a plethora of mechanisms [6][7][8][43]-[48][57]-[62] that mitigate the effect of interference have been introduced. These mechanisms are referred to as a spatial approach because they essentially try to increase the number of simultaneous transmissions per unit area.

Advanced signal processing make it possible to decode one of simultaneously received frames – *i.e.,* collided frames – successfully if certain conditions are satisfied. The conventional wisdom is that if two or more frames arrive at a receiver at the same time then all of them fail and result in a collision. Recent observations confirm the PHY *capture effect*

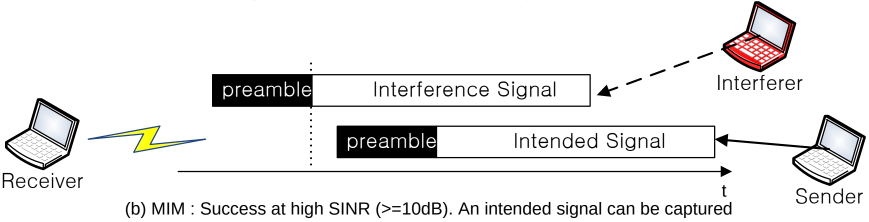
[9][10][11]; if two frames collide within a preamble period, a receiver can successfully lock on to a stronger signal if it is sufficiently more powerful than the other signal. The PHY capture effect improves the system goodput in a single collision domain. However, its performance gain in a multi-hop network is limited because collisions due to hidden terminals can occur randomly and the probability of preamble collisions is not great.

Contrary to the PHY capture effect which is rather an coincidental outcome, MIM (*Message in Message*) [10][11][12][13][49] is a result of ingenious engineering effort. Modern MIM-capable NICs, such as Atheros [14], can capture the intended signal with higher SINR (≥10dB) even when the intended signal arrives after the preamble of an interference signal [10][50]. The rationale behind the different capture behaviors is that MIM-*capable* NICs continuously search for a new preamble even if it has already locked on to a preceded frame while MIM-*incapable* NICs do not search for a new preamble once it synchronizes and locks on to the frame. Figure 1.1 explains the difference between the PHY and MIM captures.

MIM may not be very useful in a single collision domain because the carrier sense function prevents the frame transmission during busy periods. However, in multiple collision domains, MIM enables successful deliveries of otherwise interfering signals. N. Santhapuri et al. [12][15] proposed an MIM-aware centralized packet scheduling algorithm called *Shuffle* that supports concurrent transmissions from multiple APs. Suppose there are two signals interfering with each other. The basic rule of Shuffle is to transmit a relatively weaker signal before a relatively stronger signal so that both signals are successfully decoded via the MIM capture. Shuffle employs a centralized controller that coordinates frame transmission orders of all the APs in consideration. Shuffle, the first approach that deliberately exploits the MIM capability, suffers from the usual drawbacks inherent to the centralized approaches. In addition it can only be applied to a single autonomous system and also requires tight time synchronization among the APs.



(a) PHY Capture : Success at high SINR (>=10dB). An intended signal should arrive within the preamble time of an interference signal.



(b) MIM : Success at high SINR (>=10dB). An intended signal can be captured even though it arrives after the preamble time of an Interference signal.

Figure 1.1 PHY capture vs. MIM capture

1.2 Main Idea and Contributions

In this thesis, we propose a *Distributed* Opportunistic MIM-aware Concurrent Transmission (DOMCT) protocol. In DOMCT, backlogged APs continuously overhear the transmission of neighboring AP, looking for the opportunities of concurrent transmission via MIM. Observing such opportunities, APs autonomously trigger impromptu concurrent transmissions. In a basic mode, APs initiate frame transmission in a random order. DOMCT achieves additional performance gains by employing enhanced mechanisms such as a per-station queue strategy and transmission ranking. By using the per-station queue strategy, DOMCT effectively fetches the MIM capable frames in real time. On the other hand, transmission ranking boosts the throughput performance by increasing the opportunities of concurrent transmissions.

- We propose a Distributed Opportunistic MIM-aware concurrent transmission protocol (DOMCT). Since DOMCT operates in a distributed manner, it eliminates the tight time synchronization requirement and high control overhead of the centralized scheme. Furthermore, the distributed nature of DOMCT supports backward compatibility with the legacy IEEE 802.11 DCF.
- We analyze the probability of the MIM capture in a two APs scenario to verify the potential gain from the MIM-aware concurrent transmissions. The result shows that MIM capture can significantly improve the channel utilization.
- We devise a per-station queue strategy and transmission ranking so that DOMCT achieves additional performance gains by employing those enhanced mechanisms.
- We compare the system throughput of DOMCT, DCF and Shuffle. Our ns-2 simulation shows that DOMCT improves the system throughput by 61% on average compared to the legacy DCF. Furthermore, DOMCT achieves the performance comparable to Shuffle, the state-of-the-art centralized approach.

1.3 Thesis Organization

The rest of the thesis is organized as follows. We present the related work in Chapter 2 and the detailed description of DOMCT protocol is given in Chapter 3. The two enhancements of DOMCT, per-station queue strategy and transmission ranking system are described in Chapter 4. We analyze the MIM capture probability in Chapter 5. Chapter 6 shows the simulation results. In Chapter 7, we demonstrate the feasibility of MIM in association control. Finally, we conclude the thesis and provide our future work in Chapter 8.

Chapter 2 Related Work

2.1 Capture Effect

Various previous studies on the PHY capture effect [9][16][17][18][19] mainly focused on increasing the PHY capture probability. Basically, the PHY capture effect is a coincidental outcome where only one of the collided frames may survive. In contrast, MIM has the capability to capture multiple frames from the collided frames. The authors of [10][11] thoroughly carried out empirical experiments and quantify the threshold that enables MIM captures. Shuffle [12][15] implements MAC layer frame scheduling in order to increase MIM concurrent transmissions. However, Shuffle aggressively disables carrier sensing and carries out consecutive concurrent transmissions causing legacy DCF devices to starve. In contrast, DOMCT increases the system throughput via opportunistic concurrent transmissions thus protecting ongoing transmissions of other APs.

2.2 Signal Processing Techniques for Interference Handling

A plethora of advanced signal processing mechanisms aim at reducing or eliminating potential interferences [20][21][22][51]-[56] have been proposed. SIC [20] decodes a relatively stronger signal from overlapped signals and then distracts a weaker signal by subtracting the stronger signal from the overlapped signals. This mechanism requires complex symbol level signal manipulation. Similarly, ZigZag [23] requires signal manipulation to recover the signal from the collided frames. It does not increase the wireless capacity but only reduces the number of retransmissions similar to PPR [24]. On the other hand, IAC [21], SAM [22], CSMA/CN [25] support concurrent transmissions by the interference alignment and interference cancellation using multiple signal streams obtainable in MIMO environments [63]-[84]. It is worthwhile noting that our proposal, DOMCT, targets single antenna systems.

2.3 Centralized Scheduling Architectures

Some of centralized architectures [15][26][27][28][29][30] provide the concurrent transmissions through MAC frame scheduling. However, these mechanisms do not take the MIM functionality into account except for Shuffle [15]. Therefore, they miss the potential concurrency gains from the MIM opportunities. CMAP [31] and OCP [32] support concurrent transmission in a distributed manner. CMAP [31] constructs a conflict map via empirical evaluations and permits concurrent transmissions from exposed terminals. This method is similar to our proposed scheme in the sense that it selectively activates carrier sensing and permits an additional concurrent transmission if it does not corrupt the ongoing frame. However, CMAP makes concurrent transmission decisions based on the historical concurrent transmission results (*i.e.*, success/failure) instead of the explicit SINR-based measurement. OCP [32] also constructs an interference map and conducts concurrent transmission opportunistically. However, as in CMAP, OCP decides the feasibility of concurrent transmissions based on empirical evaluations (*i.e.*, success/failure). In addition, OCP requires changes in the frame structure since it adds a post-amble at the end of the frame.

2.4 Assessing Interference

Assessing the exact interference between contending links is crucial to the system performance because the results of concurrent transmission is tightly coupled with the interference relationship. In [27][28], the authors introduced a SINR-based conflict map. These schemes are only applicable in a static environment due to large measurement overheads. In contrast, our solution can be operated both in static and mobile environments since we adopt a light-weight online estimation scheme that is similar to micro-probing [33] in constructing the interference map.

Chapter 3 A Distributed MIM-Aware Concurrent Transmission Protocol

DOMCT consists of two stages [34]. First, an IMAP is constructed by APs to find out the interference relations between the nodes. Then, based on the IMAP, frames are concurrently transmitted when the MIM capture threshold requirements are satisfied.

3.1 Interference MAP (IMAP)

Each AP constructs an IMAP [15] using a method similar to micro-probing [33]. Figure 3.1 describes the IMAP construction algorithm. Each AP builds its own IMAP shown in Fig. 3.2 (also, Fig. 3.3 shows the frame format of the IMAP) by employing the following operations. At the initial phase, each AP gathers the channel quality information from its clients. Each client piggybacks the SINR value from the AP to itself in ACK frames to APs. When an AP overhears an inadvertent frame transmission of neighboring AP (line 9), it decodes the MAC header and identifies the link ID (AP-station pair) of the overheard frame (line 10). Then, it initiates a concurrent transmission to its client immediately after the MAC header part of the ongoing frame (line 12). After this intentional concurrent transmission attempt, the AP looks up the SINR value piggybacked in the ACK frame and records it in the IMAP. Each AP shares its IMAP with its neighboring APs through beacon exchanges. Figure 3.4 shows the beacon format and Fig. 3.5 presents the IMAP transaction frame format which can be inserted into every beacon frame as an information element (refer to Fig. 3.6). This operation is repeated for all other links until the entire IMAP is finally established. Since the number of measurements required for verifying the possible concurrent links increases in the order of k^2 where k is the number of all clients in the network. We reduce these substantial measurement overheads by adopting micro-probing which requires only k measurements.

It is possible that more than one AP may try this operation resulting in collisions or ACK losses. To minimize the collisions among opportunistic APs, each AP estimates the number of neighbor APs [35] and takes a mini-slot back-off [36] at the end of MAC header part of the ongoing frame (line 11). The back-off value is set in proportion to the number of contending APs. We set the range of the mini-slot back-off window as same as the Binary Exponential Back-off (*BEB*) window counter. For example, if there are two APs (AP1 and AP2) contending for concurrent transmissions, each AP determines mini-slot back-off counter based on the number of contending APs (*e.g.*, AP1: 1, AP2: 3). AP1 conducts carrier sensing at the 1st mini-slot and finds it as idle. Thus, AP1 initiates concurrent transmission. AP2 tries to access the medium at the 3rd mini-slot, however it finds the preamble transmission of AP2, and gives up concurrent transmission. If an ACK frame is lost, we imply it as a concurrent transmission failure. Hence, the AP marks these links as a *failed link* in the IMAP. Thereafter, it avoids using them in order to protect the transmission of the neighboring APs (line 13-16).

When clients disassociated from the current APs, then IMAP should be updated accordingly. The appropriate IMAP update interval depends on several factors. Shorter update intervals waste the wireless bandwidth due to the control overhead in an unsaturated condition. On the other hand, longer update intervals fail to cope with dynamic channel fluctuation and user mobility. Therefore, instead of using a fixed update period, the IMAP is updated both periodically and opportunistically as follows,

$$\text{Periodic Update Interval} = \delta * \text{Periodic}$$

where δ is controlled in proportion to the arrival rate of the traffic volume. The periodic updates (*e.g.*, 1*sec*) refresh the entire contents in the IMAP. In our simulations, the average update period was measured as 0.64*msec*. In addition to the periodic updates, each time an AP conducts a concurrent transmission, the result, – *e.g.,* success or failure – is opportunistically updated in the IMAP. Therefore, the IMAP is kept up-to-date and it also copes with time-varying channel and user mobility.

Figure 3.1 IMAP construction algorithm

L1	L2	SINR (L1)	SINR (L2)	T/F
l_1	x_1	10	5	T
l_1	x_2	8	4	F
		⋮		
l_3	x_1	13	11	T
l_3	x_2	3	2	F

Figure 3.2. IMAP data structure

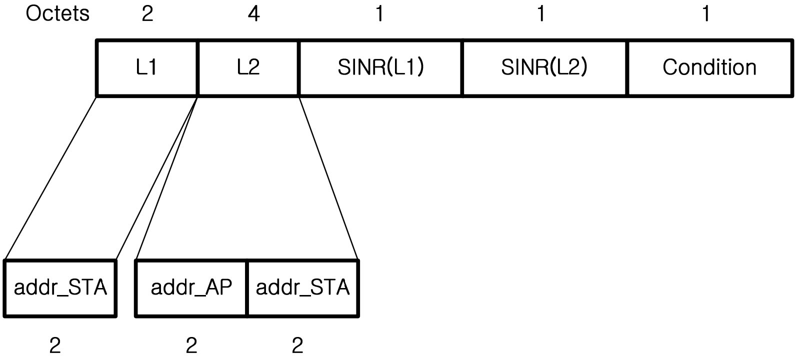


Figure 3.3 IMAP format

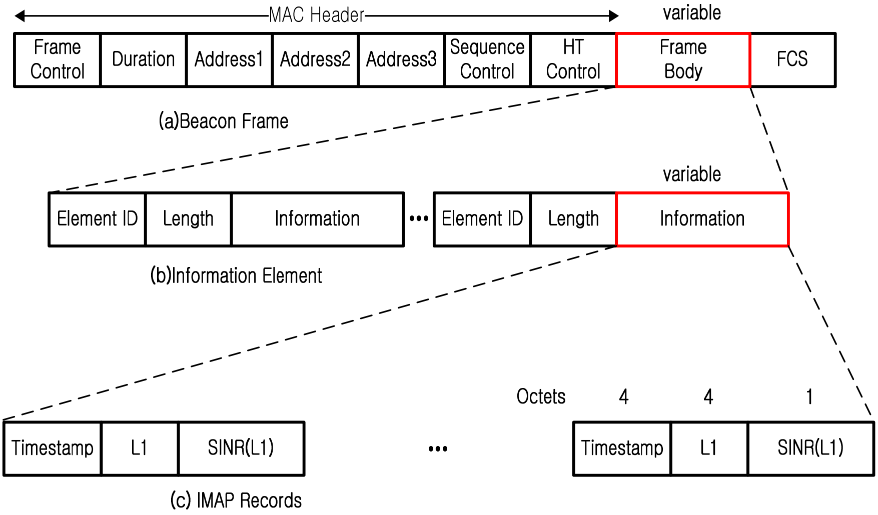


Figure 3.4. IMAP transactions in a Beacon frame

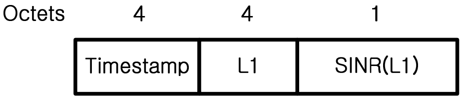


Figure 3.5 IMAP transaction frame format

Figure 3.6. IMAP transactions can be inserted in the reserved fields of beacon frames as an information element

3.2 Opportunistic Concurrent Transmission

The basic operation of the opportunistic concurrent transmission algorithm is described in Figure 3.7. When an AP overhears transmission from a neighbor AP, it looks up the IMAP to check whether a concurrent transmission is feasible or not (line 1-3). The concurrent transmission is admitted if the following conditions are met. 1) The SINR of the ongoing frame is no less than the first frame capture threshold ($\theta^F \geq$ 4dB in 802.11a radio) and the SINR of the concurrent frame is greater than or equal to the last frame capture threshold ($\theta^L \geq$10dB in 802.11a radio). 2) The SINRs of both frames satisfy the predetermined RX sensitivity (ex. -

88dBm for 6Mbps by the 802.11a standard) (line 4 and 11-16). To minimize collisions, it uses a mini-slot back-off at the end of each MAC header of the ongoing frame (line 5).

DOMCT requires a more sophisticated ACK processing mechanism in the unicast transmission. Even though two frames are delivered successfully, their ACKs can be collided at APs. We avoid ACK collisions by serialized scheduling ACK frames. For example, AP2 knows the ACK transmission time of AP1 by using the MAC header information of AP1's frame. AP2 avoids overlapping of its own ACK and AP1's ACK by delaying its ACK transmission until the end of ACK transmission to AP1. Note that our simulation results demonstrate that DOMCT operates well even without ACK serializing, since ACKs are typically transmitted at the basic data rate and the frame length is relatively short. Another possible solution is the piggybacking of SINR reports in the data frames to reduce the adverse effects of ACK collision. Besides ACK collisions, data and ACK frames can collide also. We can avoid this problem making the concurrent transmission completes at the same time the first data transmission finishes.

Figure 3.7 Opportunistic concurrent transmission algorithm

Figure 3.8. The operation of DOMCT protocol

Let us explain the DOMCT operation with an example shown in Figure 3.8. There are two APs (AP1, AP2) and three clients (R1, R2 and R3). Solid arrows represent a link between AP and client and dashed lines indicate potential interference relationships between concurrent transmissions. Both APs are located within the transmission range of each other as DOMCT requires the APs to overhear and examine the MAC header from the neighboring APs in order to identify the link ID. This implies that DOMCT is well suited for densely deployed WLANs which are common cases nowadays. The figure also shows the received SINR when frames are transmitted concurrently. We assume that both APs operate on the same frequency channel.

In this example, we can identify two cases of concurrent transmissions: (i) AP1→R1 and AP2→R3 transmissions, and (ii) AP1→R2 and AP2→R3. In the first case where AP1 and AP2 are transmitting frames to their corresponding clients R1 and R3 concurrently, both transmissions are successful. As long as AP1→R1 transmission precedes AP2→R3 transmission, a concurrent transmission of AP2 does not corrupt AP1's packet because both frames satisfy the MIM capture threshold requirements (*i.e.*, preceded packet ≥4dB, followed packet ≥10dB). On the other hand, in the second case, AP1's transmission may result in a collision while AP2's transmission is successful. That is because the SINR at R3 (13dB) satisfies the MIM capture threshold while the SINR at R2 (1dB) does not. In this case, AP2 should not transmit in order to protect the transmission from AP1.

Figure 3.9 explains the different transmission scenarios of DOMCT depending on the following three cases of MIM opportunity. First, if both AP1 and AP2 satisfy the MIM capture threshold requirements (A≥10dB, B≥10dB) then, concurrent transmissions are allowed regardless of transmission order. Second, if both the APs do not satisfy the MIM capture condition, they should obey the legacy DCF of single transmission at any time. Finally, if the results of concurrent transmissions depend on the transmission order, regulating the transmission order is important. In Fig. 3.9, concurrent transmission is possible when the transmission of AP2 follows the transmission of AP1 whereas the reversed transmission order makes the MIM capture unfeasible. In this case, AP2 may intentionally delay its transmissions in order to increase the opportunity of MIM capture.

Figure 3.9. Three concurrent transmission examples depending on the MIM opportunity

Chapter 4 Increasing MIM Opportunities

In DOMCT, it is important to provide the concurrent transmission opportunities as many as possible to increase the system throughput. We propose a per-station queue strategy and a transmission ranking mechanism to supplement the basic operation of DOMCT.

4.1 Per-station Queue Strategy

Even when an AP is given concurrent transmission opportunities, it may lose the chances due to the inappropriate frame sequence in its queue. We explain this situation using an example shown in Fig. 4.1(a). When AP2 overhears the transmission on the link 1 (AP1→R1), AP2 can concurrently transmit to link 3 (AP2→R3). However, the frame for the link 2 (AP2→R2) at the head of queue blocks the concurrent transmission opportunity.

Let each AP use the per-station queue. If an AP has at least one frame for each client and the MIM capture condition is satisfied then, the per-station queue strategy always enables the concurrent transmission by fetching the appropriate frame from the per-station queue on-the-fly. In Fig. 4.1(b), when AP2 overhears the transmission on the link 1(AP1→R1), AP2 can fetch a frame to R3. Now, two frames (AP1→R1, AP2→R3) can be transmitted concurrently via MIM. Thus, the per-station queue eliminates the blocking problem and increases the concurrent transmission opportunity.

The per-station queue strategy can be regulated depending on the performance criteria such as throughput, delay or fairness. To increase the throughput, the AP fetches the packet that belongs to the concurrent transmission links from the per-station queue. For a minimum delay, the AP fetches the packet in a FIFO manner. If fairness is the main objective then, the max-min fairness or proportional fairness may be employed. In this thesis, we choose throughput as an objective metric.

Figure 4.1. Per-station queue strategy

4.2 Transmission Ranking System

We devise transmission ranking (TR) to increase the number of MIM enabled concurrent links. In the TR, the AP gives priority to each AP-client link based on the potential number of concurrent transmission opportunities. We explain the basic idea of TR with an example shown in Fig. 4.2. Each AP has a ranking table whose entry represents the ranking of a link to each client. An entry consists of two fields, F and L. The F field is the number of neighboring links that can be activated concurrently with the current link. In other words, the neighboring links in the F field can transmit using MIM capture, by following the frame transmission of the current link. Meanwhile, the L filed shows the number of neighboring links that are compatible as preceding transmissions to the current link. For instance, if AP2 transmits a frame earlier than other APs, three links (*i.e.*, $AP_1 \rightarrow C_{11}$, $AP_4 \rightarrow C_{41}$ and $AP_3 \rightarrow C_{31}$) satisfy the MIM capture conditions, thus F=3. Meanwhile, delaying the transmission of AP_2 after the transmission of other APs enables only one concurrent link (*i.e.*, $AP_3 \rightarrow C_{32}$), thus L=1. Now, AP_i determines its transmission order by computing the F/L of each AP-client link. If F/L is greater than 1, AP_i transmits frames immediately. Otherwise it defers to increase the probability of concurrent transmissions.

It is necessary to acquire the inter frame transmission time of other APs in order to employ the TR. Thus, the TR can be activated with the persistent traffic such as VoIP and VoD (Video on-Demand) because the packet generation intervals of these applications are constant or predictable.

Figure 4.2. Enhancing the number of concurrent transmission links via transmission ranking

Chapter 5 MIM Opportunity Analysis

5.1 System Model

To demonstrate the potential improvement of MIM-aware opportunistic concurrent transmission over legacy DCF, we analyzed the MIM capture probability in a scenario where there are two contending links (AP1→ R1 and AP2→ R2), as shown in Fig. 5.1. Without the loss of generality, we assume that AP1 always precedes AP2 in transmission. We ignore background noise for simplicity. Let p_i be the transmission power of AP *i* (*i* ∈ set of *AP*) and G_{ij} be the channel gain between AP *i* and client *j* (*j* ∈ set of *client*). AP *i* is the transmitter, and the APs other than the transmitter AP *i* are all potential interferers. Then, the *SIR* (*Signal to Interference Ratio*) at client *j* is expressed as follow:

$$SIR_{ij} = \frac{p_i G_{ij}}{\sum_{k \neq i,j} p_k G_{kj}} \qquad (1)$$

where

$$G_{ij} = d_{ij}^{-\varphi} \quad .$$

In (1), $d_{ij}^{-\varphi}$denotes the distance between AP *i* and client *j* and φ is the path loss exponent. We set φ to 4 assuming an indoor environment. Suppose that the transmission powers of all APs are homogeneous and no fading occurs (*i.e.*, Free-space model), the *SIR* is determined only by the distance between the transmitter and the receiver. Therefore, the *SIR* (in dB) at R1 is given by:

$$SIR_{AP1R1} = 10\log\left(\frac{\mathrm{d}_{\mathrm{AP2\to R1}}}{\mathrm{d}_{\mathrm{AP1\to R1}}}\right)^{\varphi} \qquad (2)$$

The *SIR* of R2 is derived in a similar way. For more detailed analysis, refer to our previous work [37]. Next, we compute the probability of the MIM capture by applying the following two conditions;

$$SIR_{\mathrm{R1}} \geq 4\mathrm{dB} \qquad \text{(First MIM capture)} \qquad (3)$$

$$SIR_{\mathrm{R2}} \geq 10dB \qquad \text{(Second MIM capture)} \qquad (4)$$

5.2 Numerical Result

For ease of understanding, we explain the results with Fig. 5.1. The regions marked ⓐ and ⓑ in Fig. 5.1 represent the first and second MIM capture conditions (*i.e.*, Equations (3) and (4), respectively), respectively. We set the transmission range of an AP as 250m. By solving (5) below, we finally have the probabilities of the MIM capture as a function of distance between the APs as shown in Fig. 5.2.

$$\left(\frac{ⓐ}{\mathrm{TX}_{\mathrm{Range(AP1)}}} \times \frac{ⓑ}{\mathrm{TX}_{\mathrm{Range(AP2)}}}\right) \qquad (5)$$

We observe that the MIM capture occurs frequently as the distance between two APs increases. Moreover, if we consider the case of the reversed transmission order where AP2 initiates a transmission first, the total MIM capture probability will increase substantially. This results show that the MIM capture has a large potential to improve spatial reuse in the current wireless networks, where APs are densely deployed.

Figure 5.1 A two contending links topology used in the analysis

Figure 5.2. The probability of the MIM capture as a function of distance between the APs

Chapter 6 Performance Evaluations

6.1 Simulation Setup

We implemented the MIM functions of DOMCT in the ns-2 simulator [38] to compare with the legacy DCF and Shuffle. Note that most of the core functions of Shuffle (e.g., packet reordering) has been implemented. However, for fair comparison, we did not use the block ACK option, since it causes Shuffle enabled devices to dominate the wireless medium by using consecutive multiple transmissions.

We conduct simulations on the IEEE 802.11a WLANs environment and apply the two-ray ground propagation model. Each AP sends CBR traffic over UDP with 1500 byte frame length. The APs and clients are located in a 1000x1000 *meter* network and the simulation time is 50*sec*. Each AP always has packets on its queue (*i.e.*, saturated). The transmission rate is set to 6Mbps. All nodes are using the same channel since we assume the densely deployed WLANs. Figure 6.1 illustrates the basic topologies used in the simulation scenario. The aforementioned simulation settings are commonly applied in all scenarios unless otherwise stated.

Figure 6.1. Simple topologies used in the simulations

6.2 A Simple Two Flows Scenario

Figure 6.2 shows the MAC layer throughput improvement of DOMCT over DCF as a function of the distance between the two APs as shown in Fig. 6.1(a). Note that each AP-STA pair moves together in the same direction in parallel (*i.e.*, the x coordinates of both AP and STA are the same). The throughput improvement represents the ratio between the throughput of DOMCT and that of DCF ($\leftrightarrow \frac{\text{throughput of DOMCT}}{\text{throughput of DCF}} \text{x} 100\%$). The distance between the AP and the client is set to 5m. DOMCT increases the throughput by up to 61% if the distance between the APs is greater than 50*m*. The results show that the MIM opportunities are increased when the distance from an AP to a client is relatively short and that between the APs is large. The long distance between APs reduces interference and the short distance between an AP and a client increases the SINR. As the distance between the APs increases greater than 200*m*, the throughput decreases as the lower SINR is not enough to identify the opportunistic links. In theory, DOMCT may double the throughput of DCF if it has MIM opportunity on every link. Therefore, DOMCT shows better performance than DCF in most cases.

Figure 6.2. Throughput improvement of DOMCT over DCF

6.3 DOMCT with Per-station Queue

Figure 6.3 shows the throughput of DCF, DOMCT, DOMCT with per-station queue (DOMCT+Q), and Shuffle for the topology in Fig. 6.1(b). In this thesis, the throughput is normalized by the throughput gain over DCF unless otherwise stated. DOMCT exploits the opportunistic concurrent transmission technique, while DOMCT+Q adds the per-station queue functionality to DOMCT. In DOMCT+Q, if an AP has at least one frame for each client and concurrent transmissions are feasible, then the concurrent transmission can be enabled by fetching an appropriate frame from the per-station queue in real-time. We randomly varied the positions of APs and clients in Fig. 6.1(b) where the association of each AP-STA pair is sustained, and made 4 different topologies. In these topologies, when AP1 transmits a frame to R2, AP2 has an opportunity to concurrently transmit to R3 in most cases. DOMCT+Q increases the system throughput by up to 10% compared to DOMCT. The probability of occurring DOMCT+Q is expressed as the multiplication between the following two probabilities: i) the probability that the ongoing transmission of the other AP satisfies MIM constraints on more than one link of an opportunistic AP, and ii) the probability that the frame on the FIFO queue does not have any concurrent transmission opportunity. Hence, the performance of DOMCT+Q may vary significantly depending on the topology. Shuffle shows better throughput performance than that of DOMCT+Q thanks to the centralized scheduling that exploits the entire network information. Yet, the difference is not much since DOMCT+Q exploits almost all possible concurrent transmissions.

Figure 6.3 The effect of per-station queue strategy

6.4 DOMCT with Transmission Ranking

To see the effect of the TR, we conduct simulations with VoD applications. The inter packet generation time of each VoD session is set to 1200pkts/sec. We varied the number of VoD sessions from 2 to 5 and each AP-STA pair (*i.e.*, one VoD session) is randomly located in a 1*km* x 1*km* area. All other settings are the same as described in IV.A.

Figure 6.4 shows the aggregated throughput of the DCF, DOMCT, DOMCT with TR (DOMCT+TR) and Shuffle. DOMCT, DOMCT+TR and Shuffle outperform the DCF regardless of the number of VoD sessions due to the power of concurrent transmissions. We observe that the performance gain of DOMCT over DCF is irregular while

DOMCT+TR shows stable throughput improvement over DCF. DOMCT try to increase the concurrency of its own transmission, while DOMCT+TR enhances its own concurrency as well as the concurrency of the neighbors. As stated in Chapter 3, DOMCT+TR can be activated where the traffic with persistent sending rate such as VoIP and VoD since it needs to know the transmission interval of the other APs to regulate the transmission order. Shuffle finds out the optimal set of concurrent transmission links via packet reordering and this advanced operation is very similar to that of DOMCT+TR, thereby both schemes show close throughput performance in these traffic environments.

Figure 6.4. The effect of transmission ranking

6.5 Performances under a mobility scenario

In this subsection, we study the impact of mobility on DCF, DOMCT and Shuffle. We further categorize DOMCT into unicast (DOMCT-UC) and broadcast transmissions (DOMCT-BC) in order to study the effect of the ACK packets. We disabled the block ACK option and applied a unicast operation to Shuffle as described in Chapter 4. In these experiments, we used the topology shown in Fig. 6.1(a). In the mobile scenario, the APs are fixed while the clients move randomly following the random waypoint mobility model with a random speed, random pause time and to a random destination.

Figure 6.5 shows the normalized throughput of DCF, DOMCT-UC, DOMCT-BC and Shuffle. We run the experiment 10 times and averaged the results. From the results, we observe that the mobility does not seriously affect the DCF. The performance of DOMCT-BC is degraded by mobility, showing 3% throughput reduction. This is mainly due to the invalidity in the IMAP table. In the meantime, mobility decreases the throughput of DOMCT-UC by 7%. Note that DOMCT-UC may cause ACK collisions intermittently while DOMCT-BC is free from ACK collisions. Shuffle in the unicast mode shows very similar performance results to that of DOMCT-UC, as expected. In summary, considering the benefits from concurrent transmissions, we observe that DOMCT maintains its performance in the mobile environment regardless of the usage of ACKs. We give the following three reasons: i) ACK packets are ordered in sequence to reduce ACK collisions. ii) DOMCT uses data packets as well as ACK packets to determine the concurrent transmission success, so that the effect of ACK collisions is minimized. iii) Each time the AP carries out a concurrent transmission, the result such as success or failure is updated in the IMAP in an opportunistic manner. This keeps the IMAP entries up-to-date so that it can cope with the time-varying channel and user mobility.

Figure 6.5 Unicast Vs. Broadcast in a mobile scenario

6.6 Performances in a random topology

Until now, we have performed the simulations in small-scale environments. Next, we conduct throughput comparison in a larger random topology.

We varied the number of AP-station pairs from 2 to 25 and each AP-STA pair is randomly located in a 1*km* x 1*km* square. Only the downlink traffic is generated at each AP. We conducted 10 runs and the results were averaged.

Figure 6.6 shows the normalized throughput of DCF, DOMCT and Shuffle as a function of the number of AP-STA pairs. As the number of AP-STA pair increases, the throughput gain of Shuffle and DOMCT over DCF also increases. The reason is that, while DCF experiences more contentions between APs, DOMCT and Shuffle get more concurrent transmission opportunities. On the other hand, Shuffle consistently outperforms the other two methods since it exploits more information such as scheduling information of all APs in the entire network. Nevertheless, DOMCT offers close throughput compared to Shuffle, as it takes advantage of almost every possible concurrent transmission opportunities. As a matter of fact, the throughput performance of the centralized approaches can be viewed as the upper-bound for other distributed methods. However, the centralized approach can be deployed only in a single administrative WLANs environment. Furthermore, it needs to disable the carrier sense mechanism to increase the concurrency, so that other co-existing legacy devices that use DCF will starve due to the unfairness. In contrast, DOMCT is a distributed solution and thereby has the flexibility to be either employed as a stand-alone solution or adopted partially into the legacy DCF based systems.

Figure 6.6. Concurrency gains in a random topology

Next, we perform another simulation in a more typical topology. As shown in Fig 6.7, there are three APs and each AP has 3, 5, and 10 clients, respectively. APs are randomly located in a 1*km* x 1*km* square and sustain the initial position until the end of simulation while each STA is randomly located and also moves to other positions in a random manner. However, they do not change the AP it currently associated.

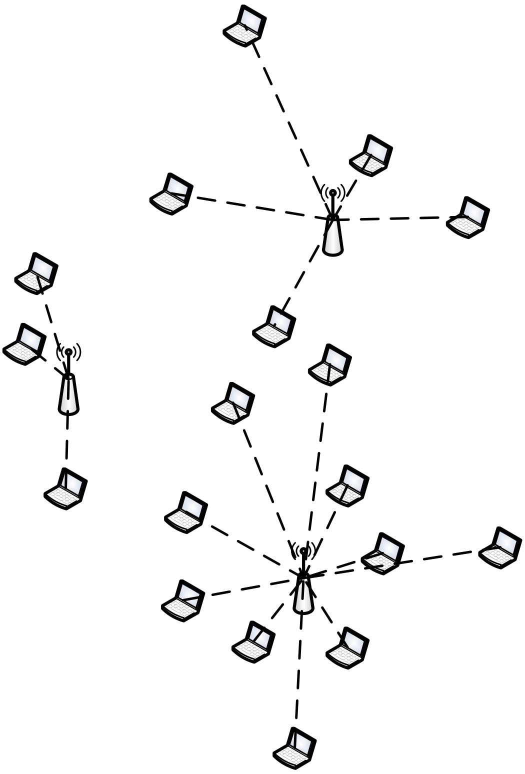


Figure 6.7 A general topology in a typical WLAN: 3 APs have 3, 5, and 10 clients, respectively

Figure 6.8 shows the throughput improvements of DOMCT and DOMCT+Q, and Shuffle over DCF. The results are very similar to that in Fig. 6.6. Shuffle shows the best performance thanks to the power of centralized scheduling while DOMCT and DOMCT+Q offer close throughput compared to Shuffle.

Figure 6.8 A throughput performance in a typical WLAN environment

6.7 Other performance results

We have carried out following simulations to highlight the other performance factors such as collision ratio, average delay gain, and goodput. In this simulation, 10 AP-STA pairs are randomly generated and located in a 1km x 1km square. Each saturated AP contends for a channel. Table 6.1 summarizes the simulation results. We can observe that about 10 percent more collisions than the DCF are happened due to opportunistic concurrent transmissions, however DOMCT achieves up to the 31% average delay gain over DCF, which result in 61% higher goodput than that of DCF.

Table 6.1 Other Performance Evaluation Results: collision due to DOMCT, average delay gain of DOMCT over DCF, and goodput

Performance Metric	Values
Collision Due to DOMCT	10.1%
Average Delay gain (over DCF)	31%
Goodput (over DCF)	61%

Chapter 7 MIM-Aware Association Control

MIM-aware concurrent transmissions are possible only when the relative SINR satisfies the MIM capture threshold requirements which are severely affected by the network topology. Thus, it is a challenging task to construct a MIM-available network topology to enhance the concurrent transmission opportunities. A dynamic association control can be a simple yet powerful solution to this problem because it is a built-in function in a current wireless access network system, and requires no additional protocol development.

In this chapter, we propose a novel association control scheme named MIM-aware Association Control scheme (MIMAC). MIMAC enhances spatial reuse of the channel (i.e., the concurrent transmission opportunity) through MIM-aware dynamic AP association control. While the conventional association control schemes such as RSSI-based mechanism and its variants [39][40] have not taken the MIM function into account, our proposed scheme MIMAC produces much more concurrent transmission opportunities by dynamically changing the association of clients from MIM-unavailable APs to MIM-available APs. We formulate this dynamic association control problem as a Mixed Integer Program (MIP) to find out the optimal associations among APs and clients in a centralized enterprise network. Note that previously stated DOMCT is devised to operate in a distributed manner whereas MIMAC is adopted in a centralized manner.

MIMAC is suitable in NOX [41] and OpenFlow-based architecture [42] due mainly to the following reasons; (i) Topology information of the entire network is readily available at the NOX controller, and (ii) The NOX controller has the right to regulate the association of OpenFlow APs.

The NOX controller can construct an Interference MAP (IMAP) easily and MIMAC can identify underlying concurrency completely based on the IMAP. Accordingly, MIMAC controls the association among APs to increase the concurrent transmission opportunities with minimal efforts.

To demonstrate the effectiveness of MIMAC, we compared the system throughputs among the legacy DCF, Shuffle and MIMAC through simulation-based evaluations with various parameters. The evaluation results show that MIMAC outperforms the other competitive schemes significantly thanks to the MIM-aware scheduling and association control.

Our main contributions are summarized as follows. First, we show that a dynamic association control scheme, the built-in function in 802.11 based WLANs, can overcome the topology limitation of MIM-aware concurrent transmission systems and produce new concurrent transmission opportunities. Second, we formulate the dynamic association control problem as a Mixed Integer Program and assess the throughput performance of our proposed scheme compared to legacy association scheme. Third, we show that MIMAC fits well in emerging centralized network control architecture, namely, NOX/OpenFlow wireless systems, and detail how it can be adopted on these architectures. Finally, we demonstrate that MIMAC achieves significant throughput enhancement compared to the various legacy systems through our simulation-based evaluation.

7.1 Overview

Although the MIM-aware concurrent transmission protocols, such as Shuffle, can increase the system throughput, the benefits are restricted by the underlying network topologies. The reason is that the MIM-aware concurrent transmissions are possible only when the relative SINR satisfies the MIM capture threshold requirements, which are inherently determined by the underlying network topologies.

Consider an example as shown in Fig. 7. In Fig. 7.1(a), R1 and R2 are associated to AP1, and R3 is associated to AP2, respectively. In this scenario, AP1 cannot take the advantage of MIM-aware concurrent transmission over the transmission of AP2 since the SINR of AP2→R3 link (1dB) does not satisfy the MIM capture threshold requirement (4dB). Therefore, all transmissions should be serialized. However, if we change the association of R2 from AP1 to AP2, we can produce a new concurrent transmission opportunity. Fig. 7.1(b) shows a changed situation. Now, AP1 can transmit a packet to R1 concurrently over the transmission of AP2 to R2 because SINRs of both links (AP2→R2: 5dB, AP1→R1: 15dB) satisfy the MIM capture threshold requirements.

Therefore, it is important to construct MIM-capable network topology in order to fully utilize MIM-aware concurrent transmissions in a system. Based on this observation, we propose a dynamic MIM-aware association control scheme, namely MIMAC. As we can see in Fig. 7.1, simple association control can make fair throughput improvement and it is a fundamental function in a general enterprise WLANs system. MIMAC produces new concurrent transmission opportunities by changing the association of clients from MIM-unavailable APs to MIM-available APs. MIMAC obtains the optimal association among APs and clients by formulating the global topology information as a Mixed Integer Program (MIP). We will explain the detailed description on our proposed solution in the following subsection.

MIMAC is fundamentally designed for a centralized managed WLAN system, where global topology information is readily available and the association among APs is controllable in a centralized way. In subsection 7.3, we will explain our target centralized system of NOX/OpenFlow architecture in detail.

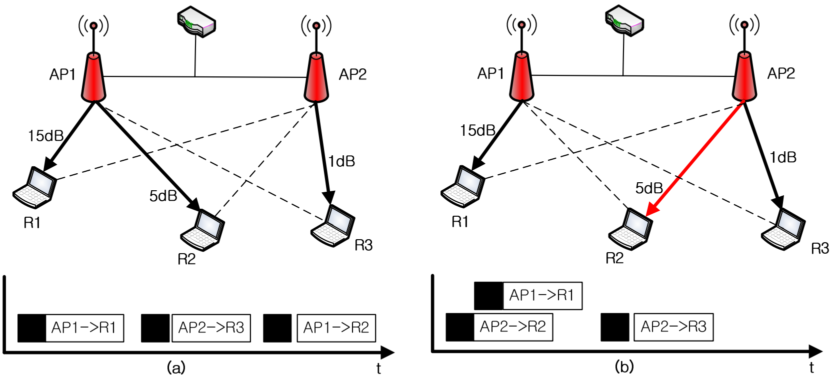


Fig. 7.1 MIM-aware Association Control; (a) No MIM opportunity. (b) New MIM-aware concurrent transmission opportunity with dynamic association control.

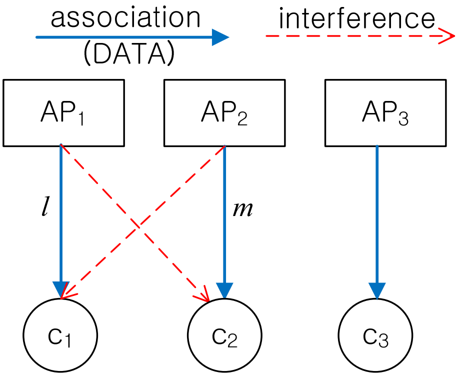


Fig. 7.2 Considered WLAN system : Association and Interference relationship

7.2 MIP Formulation

The objective of MIMAC is to find out the optimal associations among APs and clients that maximize the system throughput. The key idea to realize this objective is to formulate the global network topology information as a Mixed Integer Programming (MIP) mainly because this problem is equivalent to activating the maximum number of concurrent links in the network. Note that we assume unit data rate in this thesis.

Table 7.1 Notations used in the MIP

Parameter	Meaning
x_l	1, if link l is activated. 0, otherwise
$SRC_{m,l}$	1, if link m has same src node with link l 0, otherwise
$DST_{m,l}$	1, if link m has same dst node with link l 0, otherwise
y_{lm}	1, if link l transmits data earlier than link m 0, otherwise
P_{max}	Maximum TX Power
G_{ml}	Path gain (from the transmitter of link m to the receiver of link l)
M	Upper bound of interference $(e.g., M_l = \sum_{m \neq l} x_m P_{max} G_{ml} + \eta_l)$
l, m, n	Link instances
τ^{SL}	SINR threshold for last transmitted (i.e., activated) link
τ^{SF}	SINR threshold for first transmitted (i.e., activated) link

Fig. 7.2 illustrates the considered WLAN system. Each client is associated to one of APs in the network. If an AP and a client are associated, a link is made between them (e.g., l and m in Fig. 7.2). When an AP transmits a frame to its client, other clients that are not the intended receivers treat the received signal as interference. Note that we only focus on the downlink traffics (i.e., AP→client) in this thesis since the downlink traffics are dominant in most WLAN systems [15]. Uplink traffics (i.e., client→AP) can be scheduled in a reserved time slots, i.e., uplink time window [15]. Next we explain the MIP formulation of MIMAC. We summarized the notations used in this MIP in Table 7.1.

Although the MIM-aware concurrent transmission protocols, such as Shuffle, can increase the system throughput, the benefits are restricted by the underlying network topologies. The reason is that the MIM-aware concurrent transmissions are possible only when the relative SINR satisfies the MIM capture threshold requirements, which are inherently determined by the underlying network topologies.

We introduce a binary variable x_l to represent the activation of the link l (i.e., x_l is 1 if l is active and 0 otherwise). Then, the following MIP represents the maximum number of concurrent links under the control of MIMAC.

$$\text{Max} \sum_{l} x_l \tag{1}$$

Next, we explain the constraints of (1) to enable the MIM-aware concurrent transmissions.

■ **Node activity constraints**

We use the following two binary parameters, $SRC_{m,l}$ and $DST_{m,l}$ to represent the activity constraints of APs and clients, respectively. $SRC_{m,l}$ = 1 if both the links l and m have the same source AP and 0 otherwise. Eq. (2) denotes that each AP can transmit a frame to only one client (*i.e.*, one link) at a time. $DST_{m,l}$ = 1 if both the links l and m have the same destination (*i.e.*, the same client) and 0 otherwise. Eq. (3) represents that a client cannot receive the frames from multiple APs at the same time. That is, a client should associate with only one AP and receive a frame from that AP at a moment.

(2) $\forall l \mid l \neq m$

$$x_l + \sum_m SRC_{m,l} x_m \leq 1$$

(3) $\forall l \mid l \neq m$

$$x_l + \sum_m DST_{m,l} x_m \leq 1$$

■ **Ordering constraints**

In (4), $y_{lm}$is a binary variable representing the transmission order. $y_{lm} = 1$ if m follows l in the ordering, and 0 otherwise. Eq. (5) states a loop-free ordering on the active links. This constraint means that it cannot happen that l follows m, m follows n, and n follows l. Refer to [15] for more detailed explanation.

(4) $\forall l, m \mid l \neq m$

$$x_l + x_m - 1 \leq y_{lm} + y_{ml} \leq \min(x_l, x_m)$$

(5) $\forall l, m, n \mid l \neq m \neq n$

$$x_l + x_m + x_n - 2 \leq y_{lm} + y_{mn} + y_{nl} \leq 2$$

- **MIM-SINR constraints**

Now we describe the MIM capture threshold constraints according to the transmission order. Assuming additive multiple interference, the total interference of the last activated (*i.e.*, transmission is made) link is represented as follows

$$I_l = \sum_{m \neq l} y_{ml} P_{max} G_{ml} \quad (6).$$

In (6), P_{max} is the maximum transmission power of the APs and G_{ml} is the path gain of signal when the source (*i.e.*, an AP) of the link m transmits a frame to the destination of the link l. We assume that the transmission power of the APs are identical and G_{ml} is determined by the distance between a transmitter and a receiver.

Similarly, the total interference of the first activated link is represented as follows

$$\sum_{m \neq l} (y_{ml} + y_{lm}) P_{max} G_{ml} \quad (7).$$

If a link is not activated, then the interference term above has no constraint. For this reason, a large constant M (*e.g.*, set $M_l = \sum_{m \neq l} x_m P_{max} G_{ml} + \eta_l)$ is adopted and set to the upper bound of interference. Finally, we have the following MIM capture constraints.

(8) $\forall l$

$$\left(\sum_{m\neq l} y_{ml}\, P_{max}G_{ml} + \eta_l\right)\tau^{SL} \leq x_l P_{max} G_{ll} + (1 - x_l)M_l$$

(9) $\forall l$

$$\left(\sum_{m\neq l} (y_{ml} + y_{lm})P_{max}G_{ml} + \eta_l\right)\tau^{SF} \leq x_l P_{max} G_{ll} + (1 - x_l)M_l$$

In (8)-(9), τ^{SL} and τ^{SF}denote the MIM capture threshold values and $\eta_l$is a background noise factor.

7.3 MIMAC in NOX/OpenFlow Architecture

MIMAC is fundamentally designed for a centralized managed WLAN system, where global topology information is readily available and the association among APs is controllable in a centralized way. However, changing associations increase not only concurrent transmission opportunities but also association control overheads. In addition, some flows might be re-routed due to the changed association. To compromise these overheads, we target a centralized network system such as NOX/OpenFlow architecture. Basically, in a centralized network system, the association control overhead and re-routing problem can be minimized.

Fig. 7.3 shows how MIMAC can be employed in a NOX and OpenFlow architecture, an emerging centralized control architecture [41][42]. The system consists of NOX controllers, FlowVisors, OpenFlow Switches, and OpenFlow wireless APs. The NOX, a centralized controller, gathers information such as network topology, interference relationships among APs and clients, and so on. It updates the routing table periodically. Each flow is routed separately by a FlowVisor under the control of the NOX. The proposed MIM-aware Association Control scheme, MIMAC, is placed at the NOX controller and examines the concurrent transmission opportunities based on the IMAP (i.e., interference relationship).

MIMAC harnesses the following four key features of the NOX/OpenFlow architecture, which enables our solution to be deployed readily in the NOX/OpenFlow-based wireless systems. First, the NOX named by a centralized controller maintains topology information of the entire network. This makes the NOX construct an IMAP (i.e., interference relationship) easily. As a result, NOX can completely verify the possibility of MIM-aware concurrent transmissions in a centralized manner. Second, the NOX has rights to control the associations among OpenFlow APs. This privileged feature of the NOX enables MIMAC to produce the concurrent transmission opportunities with the minimal overhead. Third, the NOX can handle the re-routing of the flows that was arisen from association control. Association changes may cause not only association overheads but also a path change (i.e., re-routing). Since the NOX maintains topology information and the routing table, it updates the routing paths on-the-fly according to the result of the association changes. Lastly, the NOX and OpenFlow system supports a virtualization technique, organizing multiple logical networks from a single unique physical network. Therefore, the MIM-capable OpenFlow network and the MIM-incapable OpenFlow network can be managed separately. Also, this orthogonal trait of virtualized network supports adaptive activation of MIM scheduling according to the capability or status of the network. We do not deal with the re-routing and virtualization issues and focus on MIM scheduling and association in this thesis.

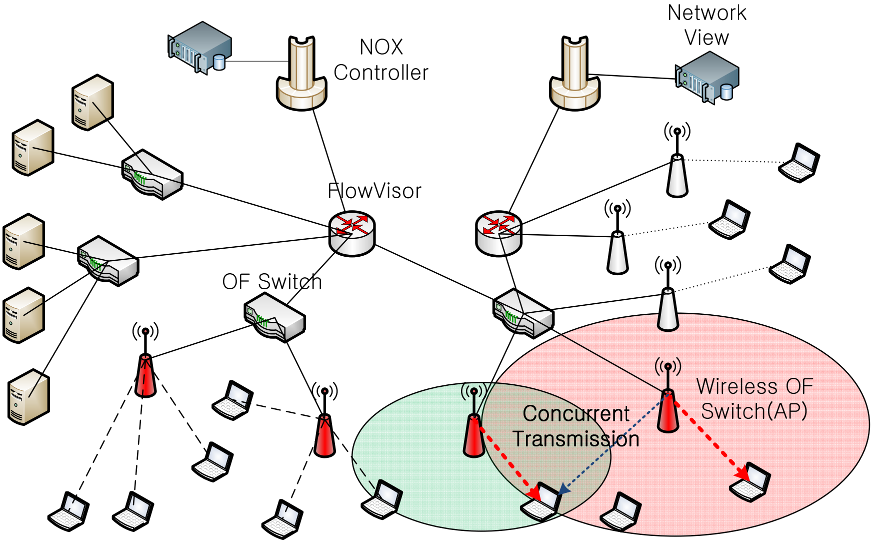


Fig. 7.3 Adoption of MIMAC on the NOX/OpenFlow AP Architecture.

7.4 Performances on a simple two APs scenario

To show the performance of MIMAC on a simple topology with two APs, we have compared MIMAC with Shuffle and NoControl (i.e., DCF). Note that while MIMAC employs both MIM scheduling and association control, Shuffle exploits MIM scheduling only. The operation of NoControl is equivalent to the standard DCF. We implemented MIMAC, Shuffle and NoControl using the MATLAB simulator. We have performed simulations using the simple topology as shown in Fig. 7.1 with IEEE 802.11a environments. Each AP is connected to its clients with CBR traffic over TCP and has packets in its queue all the time (i.e., saturated). The packet length is 1500 bytes. APs only transmit packets to the clients (i.e., downlink). Simulations continued for 100sec.

Fig. 7.4 shows the throughput performance of MIMAC, Shuffle and NoControl. Shuffle shows the same throughput gain with NoControl since there is no MIM opportunity under the topology as shown in Fig. 7.1(a). In contrast, MIMAC adjusts the association of a client R2 from AP1 to AP2 as shown in Fig. 7.1(b), so that it produces a new MIM opportunity, thus enables concurrent transmissions (i.e., AP2→R2, AP1→R1). Note that this concurrency improves not only the throughput of R1 and R2 but also that of R3. In addition, the reduced contentions among the links help the overall back-off be smaller. Consequently, MIMAC achieves higher throughput improvement over Shuffle and NoControl by up to 160%. Next, we extend the simulations in larger topologies with various parameters.

Fig. 7.4 Throughputs of MIMAC, Shuffle and NoControl in a simple 2 APs scenario

7.5 Performances on large scale topologies

We conduct extensive simulations in larger topologies with varying the number of APs and STAs to verify the effectiveness and feasibility of MIMAC. We compare the performances of the following four schemes; MIMAC, Shuffle, Association and NoControl. Association, in this comparison, has an ability to change the associations even though it already associates with an AP with the strongest signal in order to maximize the spatial reuse (however, it does not take MIM scheduling into account). In our evaluation environments, APs are linearly deployed with the same distance (50*m*) between adjacent APs to avoid biased performance results. STAs are deployed randomly around the APs. The evaluation results are averaged after 10 runs.

First, we set the number of APs 10 and vary the number of STAs from 5 to 25. Fig. 7.5 shows the evaluation results. As the number of STAs increases, the number of concurrent links also increases as expected. The performance metric, the number of concurrent (i.e., active) links, means that the sum of the links that could be scheduled simultaneously in a unit schedule. MIMAC finds out the highest number of concurrent links thanks to the power of association control and MIM scheduling. NoControl (i.e., DCF) shows the worst performance since it only utilized unintended spatial reuse. Shuffle increases the concurrency with MIM scheduling and shows fair performance. However, the performance gain of Shuffle is limited due to the underlying network topologies. The concurrency gain of Association is comparable to Shuffle. This can be an evident that association control can be a good knob to enhance the spatial reuse even without MIM functionality.

Fig. 7.5 Concurrency gains (# of AP = 10, # of STA varies from 5 to 25)

Next, we set the number of APs 25 and vary the number of STAs from 5 to 25, and Fig. 7.6 shows the results. Other settings are all the same as in Fig. 7.5. We can observe that the overall performances are similar to the results in Fig. 7.5. However, Association shows better performance than Shuffle regardless of the number STAs. This result can be interpreted as the concurrency gains from association control can be greater than those from the MIM scheduling. Of course, we notice that the results could be changed in other network environments since the parameter such as interference is tightly coupled with network conditions.

Fig. 7.6 Concurrency gains (# of AP = 25, # of STA varies from 5 to 25)

At this time, we set the number of STAs 10 and vary the number of APs from 5 to 25 and Fig. 7.7 shows the results. As shown in Fig. 7.7, MIMAC achieves the best performance result compared to other schemes as expected. Shuffle may not find the concurrent links due to the topology limitation. In contrast, Association enhances the concurrency with the power of association control.

Fig. 7.7. Concurrency gains (# of STA = 10, # of AP varies from 5 to 25)

Finally, we set the number of STAs 25 and vary the number of APs from 5 to 25. The results are shown in Fig. 7.8. The overall performance results are similar to the previous results shown in Fig. 7.7.

Consequently, throughout the various evaluations, our key findings are as follows; (i) MIMAC outperforms other schemes since it exploits both the power of MIM scheduling and association control. (ii) In contrast, Shuffle and Association have the limited concurrency gains from MIM scheduling and association control, respectively. (iii) Association shows better performance than Shuffle. It means that association control is more powerful than MIM scheduling in our test environments.

Fig. 7.8 Concurrency gains (# of STA = 25, # of AP varies from 5 to 25)

In this section, we have proposed MIMAC to supplement the current MIM-aware concurrent transmission systems. Our proposed scheme, MIMAC, regulates the association among OpenFlow APs to increase the concurrent transmission opportunities. We formulated MIMAC algorithm as a Mixed Integer Programming (MIP) to compute the maximum of concurrent links satisfying the MIM capture threshold requirements. The extensive performance evaluations verify that MIMAC outperforms other legacy systems significantly thanks to both MIM scheduling and association control. In our future work, we will implement MIMAC on NOX/OpenFlow system to verify the performance of MIMAC in a larger real-time testbed.

Chapter 8 Conclusion

In this thesis, we proposed a distributed opportunistic MIM-aware concurrent transmission protocol (DOMCT) for IEEE 802.11 WLANs to improve the system throughput. DOMCT increases the concurrency by opportunistically transmitting a frame immediately after the MAC header of an ongoing frame if the MIM capture threshold requirements are satisfied. As shown in our ns-2 simulations, DOMCT increases the system throughput by up to 61% higher compared to DCF and achieves close throughput performance compared to Shuffle, the state-of-the-art centralized solution. We are planning to implement DOMCT in a real test-bed to verify the feasibility of DOMCT in practice. Also, we will extend DOMCT to be integrated with ad-hoc and mesh networks. We expect DOMCT will enlarge the concurrent transmission chances in ad-hoc and mesh networks since DOMCT is not limited to the downlink traffic only in these networks.

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초 록

IEEE 802.11 DCF 는 프레임 충돌을 막기 위해서 채널 감지 기법을 이용한다. 그러나, 최근의 실험결과는 물리 계층의 프레임 캡쳐가 빈번하게 일어남을 확인시켜준다. 즉, 프레임들이 충돌할 경우에도 이들 프레임들 중 상대적인 신호세기가 충분히 큰 하나의 프레임은 성공적으로 수신이 된다. 더욱이, 메시지-인-메시지라 불리는 새로운 물리계층 기술은 진화된 프리엠블(preamble) 탐지기능을 이용하여 물리계층의 캡쳐효과를 증대시키다. 이러한 메시지-인-메시지 기술을 다중 충돌 환경에서 최대한 많이 활용하기 위해서는 프레임 전송순서가 세심하게 스케줄링 되어야 한다. 또한, 다중 AP 들 사이의 견고한 시간 동기화가 필요하고 이로 인해 상당한 오버헤드를 유발하게 된다.

본 논문에서는 분산적으로 동작하여 중앙제어를 통한 스케줄링의 필요성을 제거한 기회적 동시 전송 기법인 DOMCT 를 제안한다. DOMCT 의 동작은 다음과 같다. 각각의 AP 는 동시전송이 가능한 기회를 찾기 위해서 간섭맵(Interference MAP)을 만든다. 그 이후, 주변 AP 로부터의 프레임 전송을 감지한 AP 는 자신의 프레임과 현재 전송되고 있는 프레임이 메시지-인-메시지 캡쳐가 가능하다는 것을 간섭맵을 통해 확인하면 의도적인 동시 전송을 진행한다.

DOMCT 의 추가적인 성능향상을 위해서 스테이션단위 큐 전략 및 전송 순위 기법을 도입하였다. 스테이션단위 큐를 이용하여 DOMCT 는 메시지-인-메시지 기반의 동시전송이 가능한

프레임을 실시간으로 선택해서 전송한다. 한편, 전송 순위 기법은 동시전송 가능한 기회를 증가시켜 성능 향상을 가져온다.

수학적 분석과 시뮬레이션을 통한 성능 검증 결과 DOMCT 는 기존의 DCF 에 비해 처리량이 61% 정도까지 향상되었고, 중앙제어 방식의 스케줄링 기법과도 동등한 수준의 성능을 보여주었다.

주요어: IEEE 802.11 무선랜, 스케줄링, 매체 접근 제어, 메시지-인-메시지, 물리 계층 캡쳐, 메시지-인-메시지 캡쳐

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