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Probe/PreAck: A Joint Solution for Mitigating Hidden and Exposed Node Problems and Enhancing Spatial Reuse in Dense WLANs

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ABSTRACT In dense wireless local area networks (WLANs), the primary causes of interference and hindrance to spatial reuse are the well-known hidden node problem (HNP) and the exposed node problem (ENP). In this paper, we propose a joint solution to these problems. The proposed mechanism, referred to as Probe/PreAck (PR/PA), utilizes the concept of a two-way handshake for efficient channel reservation and spatial reuse by means of two control frames called PR and PA. The PR frame is designed for the *semi-reservation* of a channel initiated by a transmitting node, while the PA frame is used for the *receiver-oriented permission* of a channel reservation. Once a transmitting node advertises a PR frame, the channel is temporarily reserved, and the channel reservation is finally completed after the node receives the corresponding PA frame. Otherwise, the channel reservation is immediately released. Unlike the ready-to-send/clear-to-send mechanism, which is a well-known solution to HNP, the proposed mechanism does not unnecessarily prevent nodes from accessing the channel but selectively blocks transmitting and receiving nodes when they overhear the PA and PR frames transmitted by neighboring nodes, respectively. In this way, the proposed PR/PA mechanism effectively deals with both HNP and ENP in a unified framework. We further enhance the PR/PA mechanism by devising an *immediate destination switching* scheme, which is implemented in access points (APs) to improve the downlink throughput. If an AP fails to complete the exchange of PR and PA frames with a specific destination, it sends another PR frame to a different destination node without performing a new back-off procedure. Moreover, we adopt the transmission time control scheme to assure successful spatial reuse in multiple basic service set (BSS) WLANs. By adjusting the transmission time of the data frames simultaneously transmitted in different BSSs, severe interference between the data and acknowledgment frames can be avoided. The results of a simulation study confirmed that the proposed mechanism outperformed conventional mechanisms in dense multi-BSS WLANs; the downlink throughput was increased by more than 10 times while the overall network throughput was increased by approximately 50%.

INDEX TERMS Dense networks, exposed node, hidden node, IEEE 802.11, spatial reuse, RTS/CTS.

I. INTRODUCTION

In recent years, data traffic over wireless local area networks (WLANs) has increased by orders of magnitude as access points (APs) have been widely deployed and many WLAN-equipped devices have emerged. The growth in the number of WLANs is continuing due to the various services and devices in the Internet-of-Things [1], [2] and device-to-device communications [3]–[5] and the density of nodes is expected to increase dramatically. These changes have led to the emergence of the next-generation WLAN standard, IEEE 802.11ax [6], with the aim of improving area throughput and spectral efficiency in dense WLANs. In this upcoming standard, the value of the carrier sensing threshold (CSTH) is expected to increase so that multiple stations (STAs) or APs in different basic service sets (BSSs) are allowed to transmit data frames simultaneously through spatial reuse. There are several challenges associated with an increase in CSTH, e.g. severe interference from hidden nodes, unfair coexistence between legacy STAs and 802.11ax-capable STAs, and collisions between data frames and acknowledgment (ACK) frames [7], [8]. Meanwhile, the hidden node problem (HNP) is a well-known challenge in WLANs. Among various solutions to this problem, the ready-to-send/clear-to-send (RTS/CTS) mechanism (often referred to as virtual carrier sensing) is the most conventional and widely-implemented solution. However, it has been revealed that this approach has several drawbacks, e.g. unavoidable large signaling overhead, false blocking or partial deadlock, and the masked node problem [9]–[11]. In addition to HNP, the exposed node problem (ENP) is another main obstacle for improving spatial reuse because several nodes in different BSSs are unnecessarily prevented from accessing the channel. This problem is exacerbated as the density or number of nodes increases and it cannot be adequately dealt with or is made even worse by the RTS/CTS mechanism.

In this paper, we propose the *Probe/PreAck (PR/PA)* mechanism to enhance spatial reuse in dense WLANs. The proposed mechanism can successfully handle both HNP and ENP by means of two control frames: PR and PA. The key ideas are two-fold: the *sender-initiated semi-reservation* of a channel and the *receiver-oriented permission* of the channel reservation. By advertising a PR frame before the transmission of a data frame, the sender first attempts to reserve the channel. In response to the PR frame, the receiver transmits a PA frame as long as the transmission is allowed. Once PR and PA frames have been successfully exchanged, the channel is entirely reserved and the sender can transmit a data frame. Otherwise if the sender does not receive the corresponding PA frame, the semi-reserved channel is immediately released. Moreover, the neighbor nodes are not unnecessarily blocked even if they overhear the PR frame indicating the semi-reservation; they are only blocked if overhearing the PA frame confirming the full reservation of the channel. The proposed mechanism is similar to the RTS/CTS mechanism in that it employs two control frames; however, it is free from the false blocking and masked node problems and jointly deals with both HNP and ENP in a unified framework.

We further enhance the PR/PA mechanism by proposing an *immediate destination switching* (IDS) scheme. We consider that the traffic volume in real WLANs is asymmetric; in order words, the downlink traffic transmitted from an AP to STAs is mostly larger than the uplink traffic transmitted from STAs to the AP. The IDS scheme is designed to improve the downlink throughput and is implemented in the AP. If the AP does not receive the PA frame after sending the PR frame, the IDS scheme allows the AP to immediately send another PR frame to a different destination node without performing a new back-off procedure. Therefore, the possibility of spatial reuse can be increased and the channel access delay can be decreased. Moreover, we additionally incorporate the scheme of *transmission time control* (TTC) into the PR/PA mechanism, the basic idea of which we proposed in our previous work for successful spatial reuse in multi-BSS WLANs [8]. We showed that the transmission of an ACK frame is prone to failure because of the asynchronous concurrent transmission of data frames. Note that if the ACK frame is corrupted, not only the data frame should be retransmitted but also the channel access delay probably increases due to the binary exponential backoff (BEB) mechanism of IEEE 802.11 WLANs. The TTC scheme combined with the PR/PA mechanism estimates the transmission time of the primary data frame, which is indicated in either the PR or the PA frame. Subsequently, it adjusts the transmission time of the secondary data frame so that the ACK frames can be transmitted without severe interference. The results of a simulation study confirmed that compared to the conventional mechanism, the proposed PR/PA mechanism increased the downlink throughput and the total network throughput by up to 10 times and 50%, respectively.

The rest of the paper is organized as follows. In Section II, we state the problem and discuss related work in the literature. Next, we describe the proposed PR/PA mechanism in Section III and report the results of its performance evaluation via an extensive simulation study in Section IV. Conclusions on the study follow in Section V.

II. STATEMENT OF THE PROBLEM

HNP occurs when two or more nodes that cannot sense each other's transmissions send frames at the same time, which leads to transmission failure due to severe interference. On the other hand, ENP occurs when one or more nodes that sense the transmission of a neighbor node are unnecessarily prevented from sending frames, thus degrading the opportunity of spatial reuse. There exists a fundamental and inevitable trade-off in dealing with HNP and ENP, i.e. improving spatial reuse by exposed nodes tends to increase interference and transmission failure due to hidden nodes, or mitigating interference may worsen spatial reuse. Both problems occur in a combined way, and they coexist temporally or spatially depending on the locations of the nodes, which are neither predictable nor controllable. Moreover, these problems become more severe as WLANs become more densely deployed with many nodes and the areas of the BSSs overlap. Therefore, it is imperative to deal with these two problems together in a unified framework. In the following two subsections, we first discuss several drawbacks of the RTS/CTS mechanism and later introduce existing solutions from the literature. We will also verify the problems of the RTS/CTS mechanism in depth through simulation in Section IV-B and IV-C.

A. THE DRAWBACKS OF RTS/CTS

1) FALSE BLOCKING AND THE MASKED NODE PROBLEM

In multi-BSS WLANs, the RTS/CTS mechanism cannot effectively handle HNP and worsens ENP. Accordingly, any node overhearing an RTS or CTS frame should defer accessing the channel during the duration specified in the control frames. Subsequently, some nodes exposed to the sender or receiver are unnecessarily blocked and it is possible

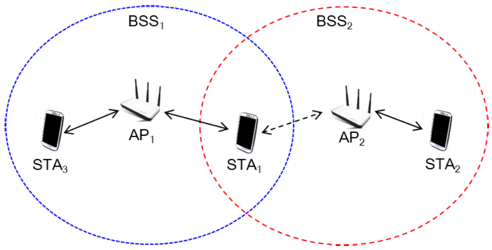


FIGURE 1. A simple scenario of hidden and exposed nodes in two overlapping BSSs.

that none of the nodes in the network can transmit frames at all for a long period of time; these scenarios are referred to as *false blocking* and a *partial deadlock*, respectively [10]. In addition, the RTS/CTS mechanism is vulnerable to *virtual jamming* [12]; i.e. a malicious node blocks neighbor nodes for a long time by deliberately sending fake RTS frames. The primary cause of these problems is that the channel is unconditionally reserved by the advertisement of the RTS frame regardless of whether the exchange of the RTS and CTS frames is successful or not. Furthermore, the RTS/CTS mechanism has another severe issue, referred to as the *masked node problem* [11]; a node is said to be masked if it is incapable of decoding or interpreting the RTS or CTS frame due to another ongoing transmission. It was shown in [11] that a masked node leads to data frame transmission failures even when the RTS and CTS frames have been successfully exchanged.

To illustrate this problem, we consider the simple configuration in Fig. 1. In this study, we consider infrastructure WLANs where each STA communicates with an AP. Here, STA_1 and STA_3 are associated with AP_1, and STA_2 is associated with AP_2. Consider that AP_1 and AP_2 are hidden from each other whereas STA_1 and AP_2 are exposed to each other. First, we consider Case1 in the timing diagram in Fig. 2(a); STA_1 becomes blocked after overhearing the RTS frame transmitted by an exposed neighbor node AP_2 (denoted as $\mathtt{RTS}_1$) and so does not respond to the RTS frame transmitted by its intended sender AP_1 (denoted as $\mathtt{RTS}_2$). It is worthwhile noting that the incomplete exchange of the RTS and CTS between AP_1 and STA_1 falsely blocks STA_3. If AP_1 retries to transmit another RTS frame ($\mathtt{RTS}_3$) to STA_1 that is still in a deferred state due to $\mathtt{RTS}_1$, the false blocking situation lasts longer and eventually leads to a partial deadlock.

The masked node problem is shown in Case2 (Fig. 2(a)). After overhearing the RTS frame transmitted by AP_1 ($\mathtt{RTS}_1$), STA_1 is blocked and consequently becomes a mask node; that is to say, it cannot correctly decode the CTS frame ($\mathtt{CTS}_2$) transmitted by AP_2 due to interference by the data frame ($\mathtt{DATA}_1$) transmitted by AP_1. The masked node STA_1 becomes unaware of the transmission of the data frame ($\mathtt{DATA}_2$). After the channel has been released, STA_1 transmits its RTS frame ($\mathtt{RTS}_3$) and both $\mathtt{RTS}_3$ and $\mathtt{DATA}_2$ collide. As a result, AP_2 fails to receive the $\mathtt{DATA}_2$ frame correctly. Note that even though AP_2 and STA_2 successfully exchanged the RTS and CTS frames, the transmission between them may fail due to the masked node problem.

2) UNFAIRNESS DUE TO RTS COLLISIONS

The exchange of RTS and CTS may be unsuccessful because of collisions or interference between the control frames (RTS, CTS, and ACK) [13]. The success or failure of an RTS/CTS exchange occurs in an asymmetric way among multiple BSSs, which can lead to a biased and unfair result in the network performance.

First, we consider Case3 in Fig. 2(b) where two RTS frames transmitted from AP_1 and AP_2 collide. In this case, the RTS collision has an asymmetric effect in BSS_1 and BSS_2, i.e. STA_1 may not correctly decode its intended RTS frame transmitted by AP_1 ($\mathtt{RTS}_1$) due to the severe interference of the RTS frame transmitted by AP_2 ($\mathtt{RTS}_2$), but STA_2 may succeed in decoding $\mathtt{RTS}_2$.

Therefore, even in the presence of a collision between $\mathtt{RTS}_1$ and $\mathtt{RTS}_2$, $\mathtt{RTS}_2$ can be successfully delivered but the transmission of $\mathtt{RTS}_1$ not only fails but also falsely blocks STA_3, leading to poor BSS_1 throughput.

Similarly, we consider the collision of RTS frames transmitted by STA_1 and STA_2 in Case4 (Fig. 2(b)). Since STA_1 and STA_2 are hidden from each other, STA_1 may transmit $\mathtt{RTS}_1$ to AP_1 while STA_2 is transmitting $\mathtt{RTS}_2$ to AP_2. In contrast to the RTS collision in the downlink transmission from the APs to the STAs in Case3, the one in the uplink transmission from the STAs to the APs in this case ends up with the opposite result, i.e. the transmission of $\mathtt{RTS}_2$ fails but the transmission of $\mathtt{RTS}_1$ succeeds. It is noteworthy that the situation of unfairness deteriorates in Case3 and Case4 if the node that failed to transmit the RTS frame (e.g. $\mathtt{AP}_1$ in Case3 and $\mathtt{STA}_2$ in Case4) retransmits another RTS frame ($\mathtt{RTS}_3$). This is because the retransmission of the latter ($\mathtt{RTS}_3$) may still fail due to the interference of the data frame. These observations confirm that an RTS collision leads to biased and unfair results in different BSSs, which agrees with the analysis and experimental results in [14] and [15].

B. RELATED WORKS

HNP and ENP are well-known issues in wireless networks based on carrier sense multiple access (CSMA) and many solutions to these problems have been proposed in the literature. The approaches to dealing with HNP in early studies mostly relied on a hand-shaking mechanism consisting of several control frames like RTS and CTS [16] or a busy-tone mechanism with a dedicated control channel to notify the status of a data channel [17]. Thereafter, many variants of these approaches have been proposed [18]. In addition, HNP can be handled in various ways including the controlling CSTH, scheduling, rate control, directional antenna, full duplex transmission, and so on [19]–[22]. On the other hand, the approaches to overcome ENP can be largely categorized into (1) tuning CSTH or controlling the transmission power or rate [23]–[26] and (2) identifying exposed nodes [27]–[30]. These approaches were intended to improve spa-

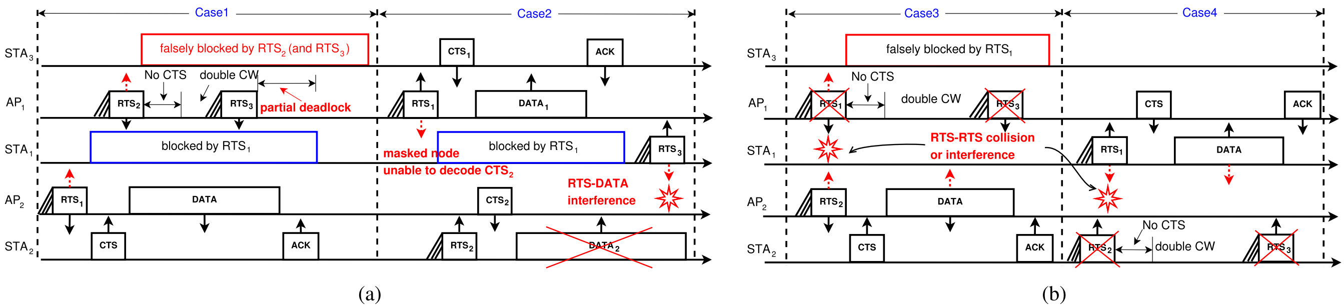


FIGURE 2. An illustration of the drawbacks of the RTS/CTS mechanism in the presence of hidden and exposed nodes. (a) False blocking and the masked node problem. (b) Unfairness due to RTS collision.

tial reuse by allowing concurrent transmissions by exposed nodes. Note that most of these existing studies exploit the exchange of RTS/CTS frames.

Recently, many studies have investigated HNP and ENP together [14], [31], [32] and proposed a joint solution [33]–[36]. The study in [31] analyzed the optimal transmission power of data and ACK frames to balance HNP and ENP by considering a tolerable interference level, carrier sensing range, and interference range. The theoretical analysis in [14] showed that ENP causes the network throughput to be non-scalable and HNP leads to unfair throughput distribution. In [32], a sophisticated analytical model was established to evaluate the network performance when both hidden and exposed nodes coexist, and the optimal value of the carrier sensing range was derived and discussed in depth. The distribution power control mechanism was proposed to deal with ENP and HNP in [33] where the carrier sensing and interference ranges are adjusted by means of an adaptive transmission power control. The interference-aware power control (IAPC) mechanism in [34] was also proposed to improve network throughput in the presence of hidden and exposed nodes, in which the CTS frame conveys information on the transmission power so that the neighbor nodes can determine their transmission power for successful concurrent transmission. Furthermore, the mechanism in [35] proposed jointly controlling the transmission rate and power; the transmission rate of RTS and CTS frames is determined to eliminate HNP and the transmission power of the data and ACK frames is controlled to avoid ENP. Meanwhile, the opportunistic collision avoidance (OCA) mechanism in [36] aimed to mitigate HNP and ENP by exploiting the frame aggregation and block acknowledgment (BACK) capabilities of IEEE 802.11 WLANs.

Compared to these existing joint solutions to HNP and ENP, our work is different in the following aspects. Since our mechanism does not resort to controlling CSTH or transmission power, it does not require an estimation or calculation of interference or distance between the transmitter and the receiver, which is difficult to accurately obtain due to the nature of the dynamic change of signal strength in the wireless channel. Therefore, our mechanism does not incur any additional signaling overhead for delivering the information between the transmitter and the receiver, which would be undesirable in a dense network. In contrast to the previous approaches, our mechanism can be simply incorporated into the current MAC protocol of IEEE 802.11 without any major modification, so it maintains backward compatibility. As well as HNP and ENP, our mechanism can resolve the masked node problem, which was not considered in the previous studies. Moreover, most of the previous studies assumed that the ACK frame is successfully delivered as long as the transmission of the corresponding data frame succeeds. However, this is not the case in an environment of multiple overlapping BSSs, which was verified via a simulation. Our work considers the possible corruption of an ACK frame due to interference from a data frame transmitted concurrently, which is another contribution of our work.

III. THE PROBE/PREACK MECHANISM

We designed an effective joint solution to HNP and ENP with the following objectives.

1) In resolving HNP, false blocking should be avoided and the cost of incomplete channel reservation should be minimized.
2) In mitigating ENP, concurrent transmission should be allowed with a minimal overhead and its probability of success should be maximized.

To achieve the first objective, we introduce a novel two-step procedure of channel reservation: *sender-initiated semi-reservation* and *receiver-oriented permission*. This procedure can be realized by two control frames `Probe (PR)` and `PreACK (PA)`, which is similar to the RTS/CTS exchange but free from its disadvantages described in Section II-A. By avoiding false blocking, the chance of spatial reuse can be increased, thus ENP can be alleviated to some extent. The second objective is established to further improve successful spatial reuse and can be achieved by the two key ideas of *immediate destination switching* (IDS) and *transmission time control* (TTC); it is worth noting that these two schemes can be simply implemented in the framework of PR/PA without any significant changes or an additional signaling overhead. The following subsections describe the details of the design and operation of the proposed mechanism and discuss its several issues.

A. THE DESIGN RATIONALE AND BASIC OPERATION OF PROBE/PREACK

The proposed PR/PA mechanism employs a two-way handshake procedure of channel reservation in advance of data transmission. The sender initiates the procedure of semi-reservation by advertising a PR frame, while the receiver grants the reservation by sending a PA frame back to the sender in response to the PR frame. We assume that the PR and PA frames have the same fields as the RTS and CTS frames, respectively, including the MAC address of the sender and/or receiver and the transmission duration.

The unique and key features of PR/PA compared to RTS/CTS are two-fold:

- The channel is temporarily reserved by the PR frame and is immediately released unless it is completely reserved by the PA frame.
- Neighbor nodes overhearing the PR or PA frame are not always blocked but selectively blocked depending on the type of control frame overheard.

The flow chart in Fig. 3 illustrates the operation of the PR/PA mechanism. Let us denote `my_PR` and `my_PA` as the PR and PA frames exchanged between an intended sender and receiver, and `oth_PR` and `oth_PA` as those transmitted by neighbor nodes in different BSSs. We first focus on the sender-side operation (Fig. 3(a)). If a sender detects an `oth_PR` frame in the backoff procedure, it freezes the backoff procedure and waits for the corresponding `oth_PA` frame. It defers the channel access for the duration indicated in the `oth_PA` frame (denoted as D_{PA}) only if the sender detects the latter within the expected time. The underlying principle of this operation is as follows. The channel is not fully reserved due to the `oth_PR` frame, and so there may exist a chance of spatial reuse, i.e. it is desirable not to block the transmission of `my_PR`. Unlike the `oth_PR` frame, the `oth_PA` frame indicates the completion of the channel reservation by a neighbor node, so the concurrent transmission should be blocked to avoid interference. In this way, the PR/PA mechanism effectively deals with HNP and ENP and thus can avoid the problem of false blocking and improve spatial reuse. After the backoff procedure has finished (i.e. the backoff counter becomes zero), the sender transmits `my_PR` and waits for `my_PA`. If `my_PA` does not return within the expected time,[1] the channel is released and the sender repeats the procedure for channel reservation. Here, the important point is that the size of the contention window is not doubled according to the binary exponential backoff (BEB) mechanism due to the incomplete exchange of PR and PA frames, which is not in the RTS/CTS mechanism. The reason is that the BEB mechanism is an effective way of dealing with severe collisions among intra-BSS STAs, but the main cause of the incomplete exchange of PR/PA frames is the interference due to the inter-BSS STAs rather than the collision itself.

[1] We assume that the modulation and coding scheme (MCS) of the PR and PA frames is the most robust one (e.g. BPSK 1/2) similar to RTS and CTS frames. Under this assumption, we can calculate the fixed transmission time of the PR or PA frames.

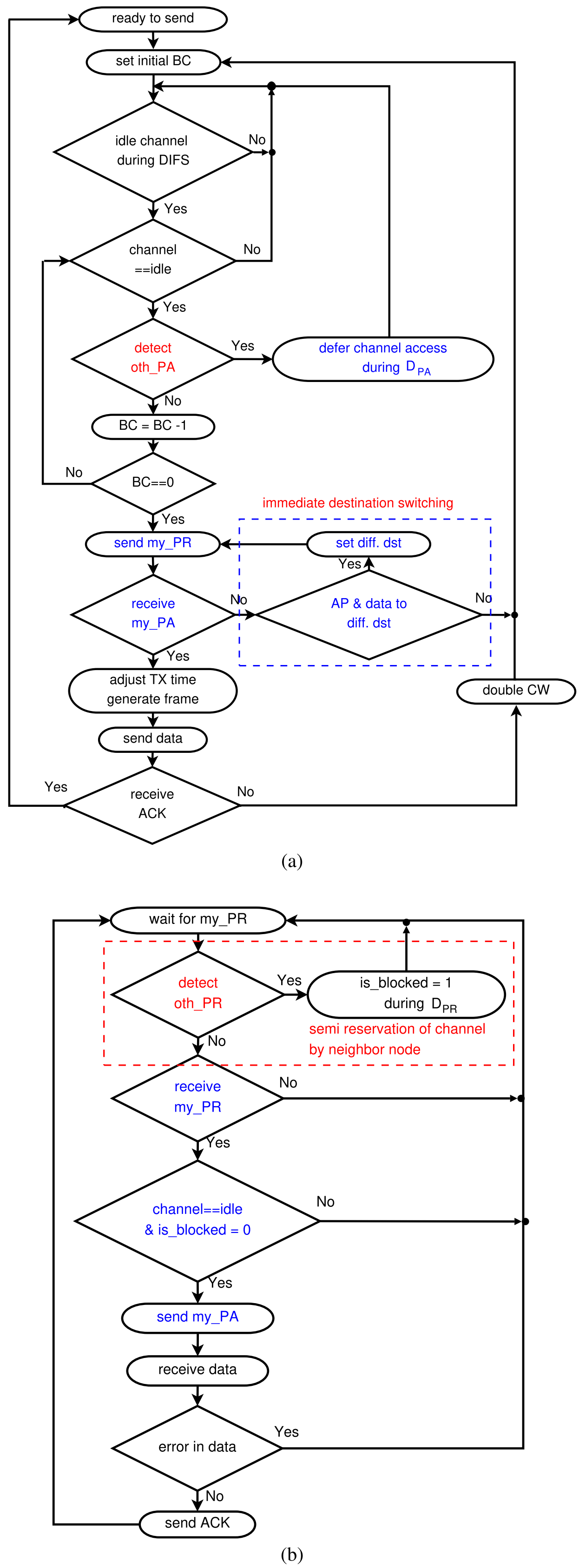


FIGURE 3. A flow chart illustrating the operation of the PR/PA mechanism. (a) Transmitter-side operation. (b) Receiver-side operation.

Next, we explain the receiver-side operation of PR/PA mechanism as shown in Fig. 3(b). We introduce a state variable is_blocked in a receiver node. This is used for virtual channel sensing and has a binary value of one or zero, each of which indicates whether the receiver node is blocked or not, respectively. Whenever the receiver detects oth_PR, it sets is_blocked as one during the period of D_{PR}. Note that the value of D_{PR} is comparable to the transmission time of oth_PA but quite a bit smaller than the transmission time of the data frame. Here, we consider two cases. In the first one, the neighbor node that sent oth_PR actually transmits its data frame after receiving its corresponding oth_PA. Subsequently, the receiver detects that the channel is busy by means of physical channel sensing and its state is maintained as blocked until the channel becomes idle after the neighbor node finishes transmitting its data frame. On the other hand, in the second case, the neighbor node is not allowed to transmit the data frame because the channel is not fully reserved, and so the channel becomes idle and the value of is_blocked is returned to zero, indicating that the node can receive a data frame from its intended sender. To maximize the opportunity of spatial reuse, the receiver does not set is_blocked as one even though it detects oth_PA. On receiving my_PR, the receiver transmits my_PA as long as the following two conditions are satisfied: (1) the channel is sensed as idle by means of physical channel sensing and (2) the variable of is_blocked is zero, which is managed by the virtual channel sensing in the PR/PA mechanism.

B. IMMEDIATE DESTINATION SWITCHING FOR ADDITIONAL SPATIAL REUSE

The IDS scheme was designed to increase the downlink throughput by boosting the opportunity of spatial reuse in APs. If there is no response to the PR frame sent by an AP, the IDS scheme allows the AP to switch its destination instantly by transmitting another PR frame to a different destination. In doing this, the AP neither doubles its contention window nor starts a new backoff procedure for channel access. Therefore, the IDS scheme decreases the channel access delay and increases the downlink throughput accordingly.

Fig. 4 depicts the operation of IDS under the configuration in Fig. 1(a). Consider that AP_2 sends a PR frame (PR_1) to STA_2 and that STA_1 overhears it. To avoid HNP, STA_1 needs to be blocked during D_{PR} time by setting is_blocked to one. Now consider that AP_1 sends its PR frame (PR_2) to STA_1. Since STA_1 is in the blocked state (due to either virtual or physical channel sensing), it does not reply by transmitting the corresponding PA frame. After transmitting the PR_2 frame, AP_1 sets a timer whose value is D_{PR}. If there is no response before the timer expires, AP_1 immediately generates a new PR frame (PR_3) with the different destination of STA_3 and sends it without additional backoff time. Therefore, as well as increasing the downlink throughput, the IDS scheme can mitigate the unfairness between downlink transmissions in different BSSs, as explained in Case3 (Fig. 2(b)). Selecting the alternative destination depends on

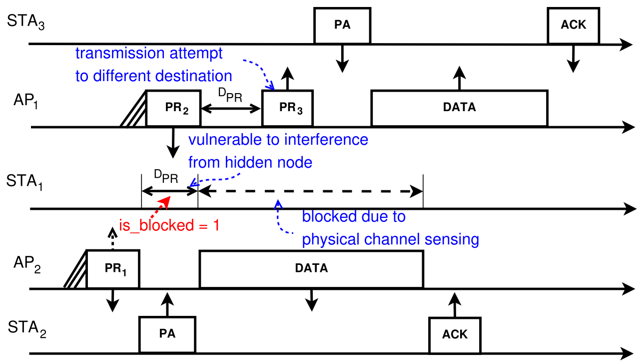


FIGURE 4. The immediate destination switching in the PR/PA mechanism.

the specific scheduling or queuing policy, e.g. first-come-first-served, round-robin, or weighted fair queuing. If no frame in the buffer has a different destination or the exchange of the PR/PA frames fails consecutively up to the maximum retry limit, the IDS scheme ceases to work.

C. TRANSMISSION TIME CONTROL FOR SUCCESSFUL SPATIAL REUSE

The proposed PA/PR mechanism allows concurrent transmissions by means of spatial reuse; however, the transmissions are not always successful. Here, we introduce the TTC scheme to assure successful spatial reuse. We first investigate why and how concurrent transmissions by the exposed nodes fail and then explain how the TTC scheme can solve this problem.

We consider a typical situation of concurrent transmissions in Fig. 5 for the configuration in Fig. 1. We define a *primary transmission* as the transmission preceding the other overlapping transmission, and a *secondary transmission* as the transmission following the primary transmission.[2] As shown in the left part of Fig. 5, AP_2 starts the primary transmission after exchanging PR/PA frames with STA_2. We assume that STA_1 is exposed to AP_2 but hidden from STA_2 so that STA_1 detects the PR frame (PR_1) sent by AP_2 but cannot detect the PA frame (PA_1) sent by STA_2. Consequently, STA_1 can transmit its PR frame (PR_2) to AP_1 and starts the secondary transmission after receiving the PA frame (PA_2) from AP_1. In this case, it is possible that the duration of the secondary transmission of the data frame (represented as the dotted line of $DATA_2$ in Fig. 5) overlaps with that of the ACK (ACK_1) transmission for the primary transmission. Thus, the transmission of ACK_1 may fail because of the interference due to the secondary transmission of the data frame ($DATA_2$).

The failure of the ACK transmission leads to two significant costs: (1) the data frame should be unnecessarily retransmitted even though it was successfully delivered and (2) when retransmitting the data frame, the backoff time is probably increased because of the BEB mechanism, which

[2]It is possible that there exist multiple secondary transmissions and that the secondary transmission may start at the same time as the primary transmission.

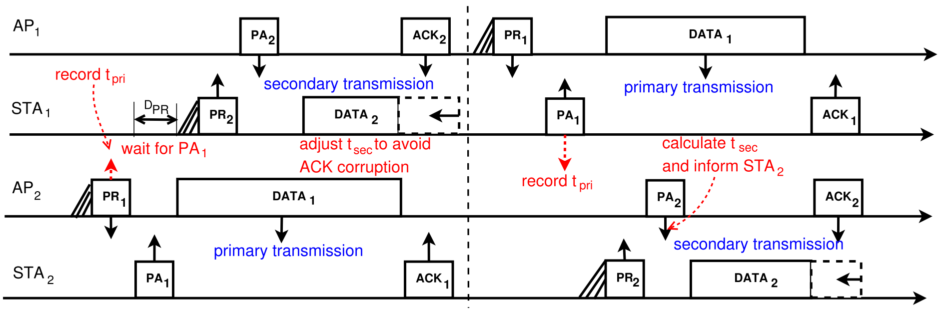


FIGURE 5. The transmission time control in the PR/PA mechanism to avoid interference between the data and ACK frames.

leads to a further decrease in throughput.

A simple solution to avoid the ACK failure is to adjust the duration of the secondary transmission so that it is terminated at the same time as the primary transmission (represented as the solid line of $\mathtt{DATA}_2$ in Fig. 5), which is the main idea of TTC and was introduced in our previous work [8]. Let us denote t_{pri} and t_{sec} as the duration of primary and secondary transmissions, respectively. The original version of the TTC scheme in [8] easily estimates t_{pri} from the physical layer header of the overheard frame. In this study, we need to incorporate the TTC scheme into the framework of the PR/PA mechanism and the key issue is how to estimate t_{pri}. The information on the transmission duration is delivered in the PR and PA frames similarly to the RTS and CTS frames.[3] We consider two cases of estimating t_{pri}. In the first case (the left part of Fig. 5), the sender of the secondary transmission (STA_1) estimates t_{pri} from the overheard PR frame ($\mathtt{PR}_1$) of the primary transmission. Note that STA_1 is not sure that the primary transmission actually occurs by overhearing the $\mathtt{PR}_1$ frame. By taking this into account, STA_1 adjusts t_{sec} only if it detects the data frame ($\mathtt{DATA}_1$) of the primary transmission.

In the second case (the right part of Fig. 5), the receiver of the secondary transmission (AP_2) estimates t_{pri} and informs the sender of this information. On overhearing the PA frame ($\mathtt{PA}_1$) of the primary transmission, AP_2 first records t_{pri}. After receiving the PR frame ($\mathtt{PR}_2$) of the secondary transmission from STA_2, AP_2 calculates t_{sec} such that both the primary and secondary transmissions end at the same time and delivers this information to STA_2 via the $\mathtt{PA}_2$ frame. Finally, STA_2 adjusts t_{sec}. Note that t_{sec} can be adjusted by means of frame aggregation, frame fragmentation, and/or zero-padding.

D. A DISCUSSION OF PR/PA

We compare the cost of channel reservation in the RTS/CTS mechanism and the proposed mechanism. Let us define D_{RTS} and D_{CTS} as the time interval in the blocked state (i.e. unable to access the channel) when a node detects an RTS frame and a CTS frame, respectively. They can be represented as

$$D_{RTS} = 3\,T_{SIFS} + T_{CTS} + T_{data} + T_{ACK},$$
$$D_{CTS} = 2\,T_{SIFS} + T_{data} + T_{ACK}, \qquad (1)$$

where T_{SIFS}, T_{CTS}, T_{data} and T_{ACK} are the time for the short inter-frame space (SIFS) and the transmission times of the CTS, data, and ACK frames, respectively. We assume that the transmission rate of the control frame (e.g. RTS, CTS, and ACK) is fixed, then the values of T_{CTS} and T_{ACK} are fixed. However, the value of T_{data} increases as the size of the data frame increases or its transmission rate decreases. Similarly, we define D_{PR} and D_{PA} as the time interval in the blocked state when a node detects an `oth_PR` frame and an `oth_PA` frame, respectively, and we set their values as

$$D_{PR} = 2\,T_{SIFS} + T_{PA},$$
$$D_{PA} = 2\,T_{SIFS} + T_{data} + T_{ACK}, \qquad (2)$$

where T_{PA} is the transmission time of the PA frame. It is noteworthy that D_{PR} is used to block the node due to the semi-reservation, while D_{PA} $(= D_{CTS})$ is used for the full-reservation of a channel. We can see from (1) and (2) that D_{RTS} and D_{CTS} increase with respect to T_{data}, but D_{PR} is much smaller than D_{RTS} or D_{CTS} and independent of T_{data}.[4]

Table 1 contains a comparison of the blocking time when a node detects a specific control frame in the RTS/CTS mechanism and the PR/PA mechanism. In the case of the RTS/CTS mechanism, the blocking time is irrelevant to the node type (sender or receiver). On the other hand, the PR/PA mechanism differentiates the blocking times depending on the type of control frame detected and the type of node. From (1) – (2)

TABLE 1. A comparison of blocking times due to channel reservation.

Mechanism		RTS/CTS		PR/PA	
Frame type		RTS	CTS	PR	PA
node type	sender	D_{RTS}	D_{CTS}	D_{PR}	D_{PA}
	receiver				0

[3] For this purpose, we make use of the `duration` field in the PR and PA frames. However, unlike the RTS/CTS mechanism, this field is not used to block the node by setting the network allocation vector (NAV), but only used to deliver the information on the transmission duration.

[4] Under a typical WLAN configuration based on the IEEE 802.11n or IEEE 802.11ac standards, the values of D_{RTS} and D_{CTS} are approximately several hundred microseconds and that of D_{PR} is less than one hundred microseconds.

and Table 1, we can derive the following conclusions, which confirm the advantage of PR/PA mechanism compared to the RTS/CTS mechanism:

- In the RTS/CTS mechanism, the time wasted due to false blocking is D_{RTS} or D_{CTS} and increases as the size of the data frame increases or its transmission rate decreases.
- The PR/PA mechanism is completely free from false blocking when a receiver detects a non-intended PA frame (`oth_PA`) transmitted by a neighbor node. This contributes to spatial reuse by mitigating ENP. Although false blocking may occur in the PR/PA mechanism on detecting `oth_PR`, its cost is fixed and minimized due to the semi-reservation, i.e. the blocking time is $D_{PR}(\ll \min(D_{RTS}, D_{CTS}))$.
- If the sender in the PR/PA mechanism detects `oth_PA`, it is necessary to block the channel access to avoid HNP, and the blocking time D_{PA} is the same as D_{CTS} in the RTS/CTS mechanism.

In addition to HNP and ENP, the proposed PR/PA mechanism can cope with the masked node problem. Assume that in Case2 (Fig. 2(a)), the RTS ($\mathtt{RTS}_1$ and $\mathtt{RTS}_2$) and CTS ($\mathtt{CTS}_1$ and $\mathtt{CTS}_2$) frames are replaced by the PR ($\mathtt{PR}_1$ and $\mathtt{PR}_2$) and PA ($\mathtt{PA}_1$ and $\mathtt{PA}_2$) frames, respectively, in the proposed mechanism. On overhearing $\mathtt{PR}_1$ transmitted by AP_1, STA_1 sees that the channel is first semi-reserved but released after D_{PR} if STA_1 does not detect $\mathtt{PA}_1$; that is to say, STA_1 is not blocked due to $\mathtt{PR}_1$, but it is blocked due to $\mathtt{PA}_2$ transmitted by AP_2. Accordingly, the PR/PA mechanism is simply free from the masked node problem without any additional operations being required.

We discuss the implementation issues of the proposed mechanism. The state diagram in Fig. 6 shows the full operation of the PR/PA mechanism including the two add-on schemes: IDS and TTC. Note that a node can be a sender at a certain time and a receiver at another time. Each node runs two independent processes for the sender-side and receiver-side operations depicted in Fig. 6. The sending process is invoked whenever a data frame to transmit is delivered from the upper layer protocol whereas the receiving process is always executed as a background service. Compared to the conventional RTS/CTS mechanism, the PR/PA mechanism does not incur any significant computational complexity or additional signaling overhead. Moreover, it can be incrementally deployed and coexist with legacy devices for which our mechanism is not implemented, implying that backward compatibility is maintained. The IDS and TTC schemes work independently and can be selectively integrated into the basic framework of the PR/PA exchange without any major modifications. The IDS scheme needs to be implemented only in the APs; the STAs do not require any additional operations or implementation of the IDS scheme. On the other hand, the TTC scheme requires that a node estimates the primary transmission time or calculates the secondary transmission time whenever detecting the PR or PA frames. It is possible that the node detects more than one PR or PA frame especially when many BSSs are densely deployed. In this case, the TTC scheme determines the termination time of secondary transmission as the earliest termination time among the estimated primary transmission times. Consequently, the TTC scheme usually decreases the secondary transmission time, which is a cost of TTC.

TABLE 2. The set of transmission rates and the minimum required SINR.

Data rate (Mb/s)	Modulation	Coding rate	SINR (dB)
6.5	BPSK	1/2	
13	QPSK	1/2	3.8
19.5	QPSK	3/4	6.3
26	16QAM	1/2	9.3
39	16QAM	3/4	12.6
52	64QAM	2/3	16.8
58.5	64QAM	3/4	18.2
65	64QAM	5/6	19.4
78	256QAM	3/4	23.5

IV. PERFORMANCE EVALUATION

In this section, we report on an evaluation of the performance of the PR/PA mechanism via extensive simulations. We first focused on validating the effectiveness of the PR/PA mechanism and then compared the performances of it and several other mechanisms under various configurations.

A. THE SIMULATION CONFIGURATION

We established simulation configurations by following the evaluation methodology and simulation scenario of IEEE 802.11ax, the standard of the next-generation WLANs [37], [38]. We built the simulator with MATLAB and implemented all the necessary functions in IEEE 802.11 physical (PHY) and medium access control (MAC) layers. We considered several PHY layer parameters as follows. We used the TGax channel model (Channel B) [39] for the log-distance path loss and set the carrier frequency and channel bandwidth as 5.3 GHz and 20 MHz, respectively, and the transmission power of STA and AP as 15 dBm and 20 dBm, respectively. The carrier sensing threshold was set to -72 dBm. We considered that the control frames (i.e. RTS, CTS, ACK, PR, and PA) as well as the data frame could be corrupted depending on the probability of frame error, which was calculated based on the effective signal-to-interference-plus-noise ratio (SINR). We also implemented a link adaptation mechanism such that the target frame error rate was lower than 1% for the given value of SINR. We implemented a set of transmission rates, the modulation and coding scheme, and the minimum SINR to attain each transmission rate, as listed in Table 2. Other key parameters of the MAC layer were set as follows. The minimum and maximum contention windows were set to 15 and 1023, respectively, and the maximum retry limit was set to 4. We set the transmission rate of all of the control frames as the most conservative one, i.e. 6.5 Mb/s, which agreed with the common assumption in the literature and the recommendation in [38]. We set the transmission rate of the data frames as 26 Mb/s if the link adaptation was disabled; otherwise, it is determined among the transmis-

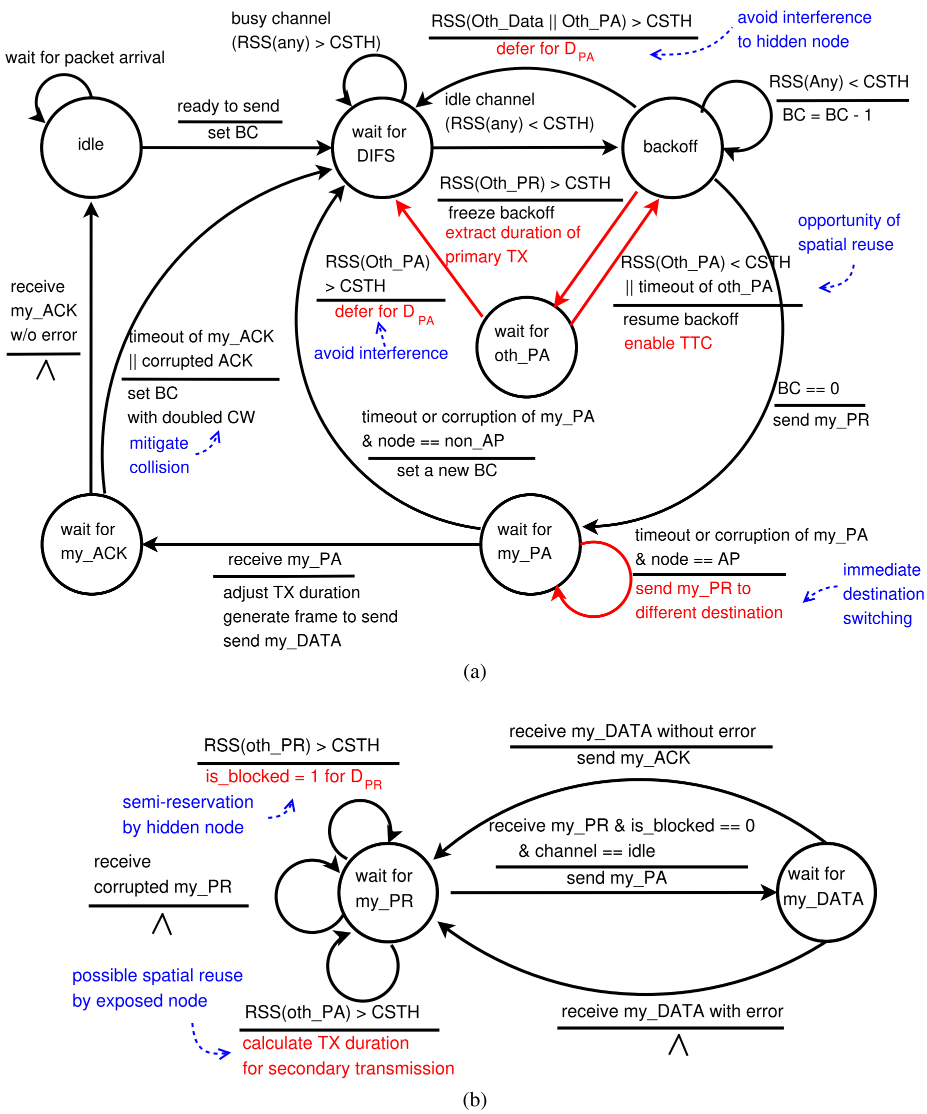


FIGURE 6. **State diagrams illustrating the full operation of PR/PA with the IDS and TTC schemes. (a) Transmitter-side operation. (b) Receiver-side operation.**

sion rates listed in Table 2. We set the data frame size as 1,500 bytes. We assumed that all the nodes always have data frames to transmit and that all the BSSs have the same channel. We set the simulation time to 1 million time slots. We considered the following mechanisms for the performance comparison:

- BASE: As a baseline scheme, this implemented only the basic channel access mechanism of IEEE 802.11, i.e. distributed coordination function (DCF).
- RTS/CTS: This is the conventional RTS/CTS mechanism.
- A_RTS/CTS: This is the *asymmetric RTS/CTS* mechanism aimed at mitigating both HNP and ENP as proposed in [23]. The transmission power of the RTS frame was decreased to 10 dBm but that of the CTS frame was not changed; thus, the RTS frame had a smaller coverage than the CTS frame.
- PR/PA: This implemented the IDS scheme over the framework of the PR/PA exchange but without the TTC scheme.
- PR/PA+: This is the full version of the proposed mechanism implementing all of the components described in Section III.

B. THE VALIDATION OF PR/PA WITH THE EXISTENCE OF HNP

The simulation in this section was designed to validate the basic operation of PR/PA with IDS in the simple topology shown in Fig. 1. The locations of the nodes represented as sets of Cartesian coordinates were $AP_1 = (-25, 0)$, $AP_2 = (25, 0)$, $STA_1 = (-11, 0)$, $STA_2 = (50, 0)$, and $STA_3 = (-50, 0)$. This setting agrees with the relationship between the hidden and exposed nodes described in Section II-A.

TABLE 3. The comparison of various performance indices in the presence of HNP.

Mechanism		BASE		RTS/CTS		PR/PA	
BSS		BSS_1	BSS_2	BSS_1	BSS_2	BSS_1	BSS_2
Throughput (Mb/s)	STA_1	3.34	/	1.89	/	0.69	/
	STA_2	/	18.39	/	14.85	/	15.81
	STA_3	5.81	/	7.27	/	14.68	/
	per-BSS	9.14	18.39	9.16	14.85	15.37	15.81
Total throughput (Mb/s)		27.53		24.01		31.18	
Number of accesses	STA_1	7875	/	11501	/	5705	/
	STA_2	/	13792	/	11137	/	11860
	STA_3	4354	/	5454	/	6175	/
	per-BSS	12229	13792	16955	11137	11883	11860
Number of successes	STA_1	2502	/	1419	/	515	/
	STA_2	/	13791	/	11136	/	11859
	STA_3	4354	/	5454	/	11012	/
	per-BSS	6856	13791	6873	11136	11527	11859
Success ratio		0.56	1.00	0.41	1.00	0.97	1.00
Average back-off time		26.7	8.5	35.8	8.5	8.7	8.5

Recall that BSS_1 consists of AP_1, STA_1, and AP_3, and BSS_2 consists of AP_2 and STA_2. To validate correctly, we set the destination node of AP_1 as either STA_1 or STA_3 with the same probability and intentionally disabled the link adaptation. To focus on the effect of HNP, we considered only downlink traffic.

Table 3 lists several performance indices for the three mechanisms: BASE, RTS/CTS, and PR/PA. Note that the ideal operation of PR/PA was identical to that of PR/PA+ in this simulation. Here, we define three performance measures: th_i, TH_{BSS_j}, and TH_{total}, as the per-STA throughput of STA_i, the per-BSS throughput of BSS_j, and the total network-wide throughput, respectively. We also define $n_{acc,i}$ and N_{acc,BSS_j} as the number of channel access attempts by the AP for transmitting frames to STA_i and to all the STAs in BSS_j, respectively, during the whole simulation time. Similarly, we define $n_{suc,i}$ and N_{suc,BSS_j} as the number of successful channel access to STA_i and to all the STAs in BSS_j, respectively.

We first investigated the performance of BASE. Since AP_1 and AP_2 are hidden from each other and STA_1 is located between these two APs, it is susceptible to frequent interference from AP_2. However, STA_3 associated with AP_1 is located far away from AP_2, so the interference from AP_2 is mostly tolerable in STA_3. As a result, th_1 was about half of th_3 in the case of BASE. It is interesting that $TH_{BSS,1}$ was also half of $TH_{BSS,2}$ because AP_1 made lots of retransmission attempts to STA_1 that mostly failed due to severe interference, which could be confirmed from the fact that $n_{acc,1} \gg n_{acc,3}$ and $n_{suc,1} \ll n_{suc,3}$. Thus, the average backoff time was somewhat increased in AP_1 compared to AP_2 and $TH_{BSS,1}$ became quite a bit smaller than $TH_{BSS,2}$.

All of the problems in BASE primarily result from HNP, and we expected that they could be alleviated in RTS/CTS. However, the results in Table 3 are counter-intuitive; th_1 of RTS/CTS was rather decreased compared to BASE and $TH_{BSS,1}$ was still considerably smaller than $TH_{BSS,2}$. In our simulation, AP_2 always had data frames to send, so it continuously transmitted RTS frames, which blocked STA_1 for most of the time. Accordingly, STA_1 could not respond to its RTS frame transmitted from AP_1, i.e. STA_1 could not transmit the CTS frame. This could be verified from the result that $n_{acc,1}$ was larger than 11,000 but $n_{suc,1}$ was at most 1,400. Last, note that RTS/CTS increased $n_{acc,1}$ compared to BASE, the reason being that the transmission time of the RTS frame was quite a bit shorter than that of the data frame in BASE, so AP_1 made more retransmission attempts to STA_1, leading to a further increase in the average backoff time in AP_1. Meanwhile, $TH_{BSS,2}$ and TH_{total} of RTS/CTS were somewhat smaller than those of BASE, which resulted from the overhead of the RTS and CTS frames.

Next, we observed the performance of PR/PA. Although th_1 was close to zero, th_3 was more than double compared to the other mechanism[5] and $TH_{BSS,1}$ became comparable to $TH_{BSS,2}$. Note that, in PR/PA, $n_{acc,i}$ was counted for every transmission attempt to STA_i but $n_{suc,j}$ was calculated with the final successful (re)transmission to STA_j. Therefore, $n_{suc,i}$ could be greater than $n_{acc,i}$ due to the destination switching in PR/PA. By comparing $n_{acc,1}$, $n_{acc,3}$, $n_{suc,1}$, and $n_{suc,3}$, we can see that most of the channel access opportunities for STA_1 were successfully conceded to STA_3 by means of IDS. Consequently, the success ratio (defined as the ratio of the total number of successful channel accesses to total number of channel accesses) was almost close to the ideal value of one in AP_1 and the average backoff time of AP_1 was not increased much and almost equal to that of AP_2. These results confirm the effectiveness of IDS combined with the semi-reservation of channels in the PR/PA mechanism.

C. THE VALIDATION OF PR/PA WITH THE COEXISTENCE OF HNP AND ENP

Here, we extended the simulation in Section IV-B by considering both uplink and downlink traffic. Unlike the previous simulation that was free from ENP, both HNP and ENP coexisted and the problem of false blocking might happen in this simulation. The pairs of hidden nodes were (AP_1, AP_2) and (STA_1, STA_2) and exposed nodes was (STA_1, AP_2).

Fig. 7(a) and Fig. 7(b) show the per-BSS throughput and per-node throughput for the several mechanisms: BASE, RTS/CTS, PR/PA, and PR/PA+, respectively. Here, the per-node throughput was measured as the total bits of data frames successfully transmitted by the given node divided by the whole simulation time. As shown in Fig. 7(a), RTS/CTS had the lowest throughput in both BSSs, which was mainly due to the false blocking problem due to the exposed nodes. For example, if a transmission is initiated by either STA_1 or AP_1 in BSS_1, AP_2 exposed to STA_1 may overhear the RTS of CTS frame transmitted by STA_1. Consequently, AP_2 will be blocked and can neither transmit nor receive a data frame with STA_2. This is the reason why the

[5]In this intentional simulation configuration, the desirable operation of PR/PA in BSS_1 was that STA_1 hardly achieved throughput but most of the throughput was obtained by STA_3. However, this is not a typical case and rarely happens in real WLANs where many nodes are randomly located and many BSSs overlap arbitrarily.

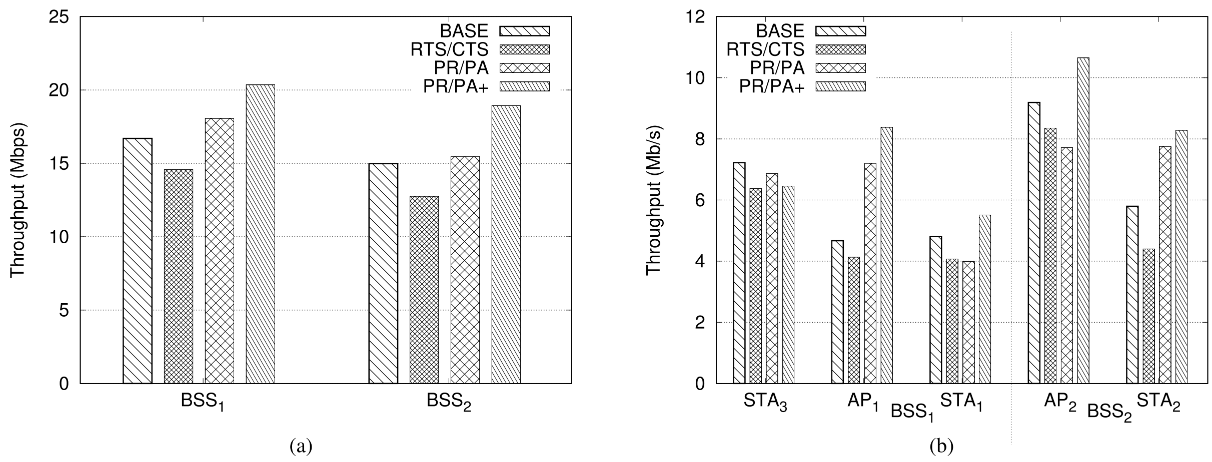


FIGURE 7. The throughput comparison with the coexistence of HNP and ENP. (a) Per-BSS throughput. (b) Per-node throughput.

per-BSS throughput was decreased in RTS/CTS (Fig. 7(a)) and the STA_2 of RTS/CTS maintained quite a low throughput compared to the other mechanisms (see Fig. 7(b)). However, BASE is free from the false blocking problem because it does not work in a reservation-based manner. On the other hand, the false blocking problem can be resolved in PR/PA in two ways: (1) semi-reservation and (2) destination switching. We consider two examples. In the first example, AP_1 initiates the transmission by sending the PR frame to STA_1 and AP_2 may overhear the PA frame transmitted by the exposed node STA_1. However, as long as AP_2 works as a receiver, it is not blocked, and STA_2 can send a frame to AP_2, while AP_1 is transmitting. This explanation supports the result in Fig. 7(b) that PR/PA increased the throughput of STA_2 considerably (by more than 70%) compared to RTS/CTS. In the second case, AP_1 attempts to transmit a data frame after AP_2 transmits a PR frame to STA_2. If the destination of AP_1 is STA_1, this transmission is not possible because STA_1 is blocked due to the transmission by the exposed node AP_2. Even in this case, AP_1 is allowed to transmit a data frame to STA_3 thanks to the IDS scheme. Therefore, the throughput of AP_1 in PR/PA was remarkably increased compared to BASE and RTS/CTS (by approximately 54% and 74%, respectively). In addition, the throughput was further increased in PR/PA+; compared to RTS/CTS and PR/PA, PR/PA+ increased $TH_{BSS,1}$ by around 40%, and 13%, $TH_{BSS,2}$ by around 48% and 22%, respectively. As well as the two cases of simultaneous transmissions in PR/PA addressed previously, PR/PA+ supports another case of successful spatial reuse among exposed nodes (i.e. STA_1 and AP_2) at the aid of TTC. While there is an ongoing primary transmission by STA_1 (or AP_2), the secondary transmission is allowed by AP_2 (or STA_1), and both transmissions can be successful due to the TTC scheme, which is not possible in PR/PA. Therefore, PR/PA+ notably increased the throughput of STA_1 and AP_2, as confirmed in Fig. 7(b). The results in Fig. 7 can be summarized as follows:

- The false blocking related to ENP in RTS/CTS hinders spatial reuse and decreases the network-wide throughput.
- The semi-reservation of the channel in PR/PA contributes to an increase in throughput by avoiding the false blocking problem. Besides, the destination switching scheme of PR/PA is effective in increasing the downlink throughput.
- The TTC scheme in PR/PA+ further increases throughput by assuring successful spatial reuse among the exposed nodes.

D. THE VALIDATION OF THE TRANSMISSION TIME CONTROL IN PR/PA

In this simulation, we focused on the effect of TTC by comparing the performances of PR/PA and PR/PA+, and we observed how effectively the TTC scheme increased the probability of successful spatial reuse. We considered a more realistic simulation configuration as follows. We placed N_{STA} STAs at random positions within a square area of 200 m × 200 m, and increased N_{STA} from 20 to 100. We also placed four APs at the positions of (d,d), $(-d,d)$, $(-d,-d)$, and $(d,-d)$ and set $d = 30$ m such that each AP could not sense the other APs but their carrier sensing areas partially overlapped. Moreover, we enabled the link adaptation so that each STA and AP might have different data frame transmission rates among the set given in Table 2. To evaluate the performance of TTC, we defined R_{fail} and ρ_{int} as the rate of ACK transmission failure and the rate of ACK failure due to the interference of data or ACK frame among the failed ACKs only, i.e.

$$R_{fail} = \frac{N_{fail}}{N_{ACK}}, \quad \rho_{int} = \frac{N_{int}}{N_{fail}}, \tag{3}$$

where N_{ACK}, N_{fail}, and N_{int} are the total number of ACK frames transmitted by all of the nodes, the total number of ACK frames unsuccessfully delivered, and the total number of ACK frame transmission failures due to the interference of data or ACK frame transmission overlap only (see Fig. 5). Note that the ACK frame is not transmitted for the corrupted data frame and that the ACK frame may be corrupted for several reasons including collision or interference

TABLE 4. The comparison of the ratio of ACK failures with PR/PA and PR/PA+.

Mechanism	PR/PA		PR/PA+	
Ratio of ACK failure (%)	R_{fail}	ρ_{int}	R_{fail}	ρ_{int}
N_{STA} = 20	10.94	47.58	5.81	0
N_{STA} = 60	19.80	71.98	6.46	0
N_{STA} = 100	21.06	76.40	7.47	0

from data, ACK, PR, and/or PA frames being concurrently transmitted.

Table 4 reports a comparison of the performances of PR/PA and PR/PA+ in terms of R_{fail} and ρ_{int} when N_{STA} varied. As N_{STA} increased from 20 to 100, the R_{fail} of PR/PA increased from around 0.1 to 0.2 because the degree of collision or interference increased with respect to the increase in N_{STA}. It should be noted that the ρ_{int} of PR/PA exceeded 0.7 when $N_{STA} = 100$, meaning that most of the ACK corruptions in PR/PA originated from the interference between the data or ACK frames as N_{STA} increased. This result strongly supports the necessity for mitigating such interference in the PR/PA mechanism. The results in Table 4 confirm the effectiveness of the TTC scheme incorporated into the PR/PA mechanism; PR/PA+ decreased R_{fail} by 2 - 3 times compared to PR/PA, so that the R_{fail} of PR/PA+ was at most 8% even in the worst case. From this result, we can infer that the synchronized transmission of ACK frames in the primary and secondary transmissions is also helpful in decreasing the probability of ACK failure due to collisions with PR or PA frames. More importantly, the ρ_{int} of PR/PA+ was absolutely zero regardless of N_{STA}, i.e. no ACK frames were corrupted at all because of interference between the overlaid data and the ACK frames. In conclusion, the TTC scheme plays a key role in improving the throughput of the PR/PA mechanism.

E. THE PERFORMANCE COMPARISON AT VARIOUS NETWORK DENSITIES

We compared the performance of several mechanisms when the density of the network changes. We performed a simulation under the same configurations as in Section IV-D. Here, we denote TH_{DL} and TH_{UL} as the total downlink and uplink throughput measured by considering the frame successfully transmitted from all of the APs and STAs, respectively. Fig. 8 represents TH_{DL}, TH_{UL}, and $TH_{total} (= TH_{DL} + TH_{UL})$ when N_{STA} was 20, 60, and 100.

We observed the following from the results in Fig. 8.

- The increase in N_{STA} resulted in a decrease in TH_{total} for all of the mechanisms; as N_{STA} increased from 20 to 100, TH_{total} was seriously decreased by around 5 times for BASE and by 25% - 30% for the other mechanisms. This is because the increase in N_{STA} worsened both HNP and ENP and the transmission mostly failed in BASE due to severe collisions or interference.
- The gain in A_RTS/CTS over RTS/CTS was marginal; A_RTS/CTS increased TH_{total} by 6% - 16%, compared to RTS/CTS, which implies that although A_RTS/CTS may alleviate the false blocking problem in RTS/CTS, it cannot assure successful spatial reuse.
- For RTS/CTS and A_RTS/CTS, the APs hardly achieved throughput; TH_{DL} was smaller than TH_{UL} by more than 10 times. One of the main reasons for the imbalance between TH_{DL} and TH_{UL} is that according to the CSMA mechanism, each node (AP or STA) has a comparable chance of channel access and the probability of channel access by the AP decreases as N_{STA} increases. This imbalance was significantly eased in PR/PA and PR/PA+. Thanks to the IDS scheme, the transmissions made by the AP were mostly successful, which helped not to increase the contention window of the AP unnecessarily. At the same time, the semi-reservation scheme does not allow the transmission by the STA that is vulnerable to interference. As a result, PR/PA and PR/PA+ increased the transmission opportunities by the APs and increased TH_{DL} by more than 10 times compared to RTS/CTS and A_RTS/CTS.
- PR/PA+ outperformed the other mechanisms in terms of TH_{total}, which was higher by 22% - 54% compared to RTS/CTS, A_RTS/CTS, and PR/PA.

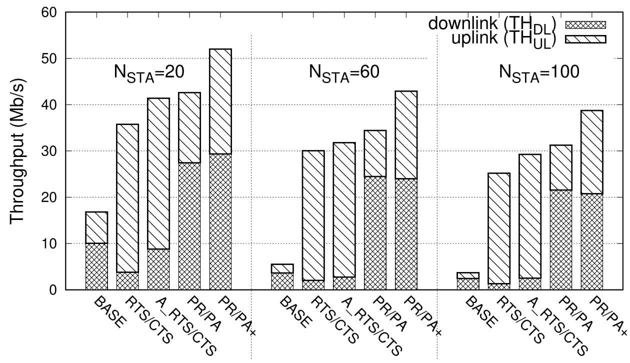
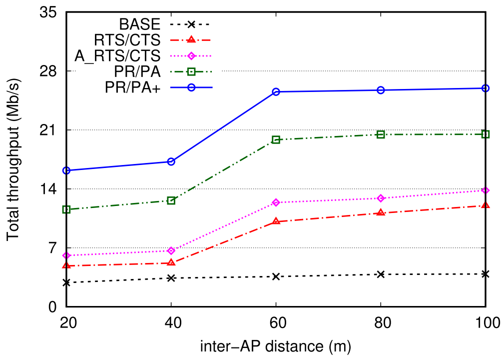


FIGURE 8. The comparison of throughput with different numbers of STAs.

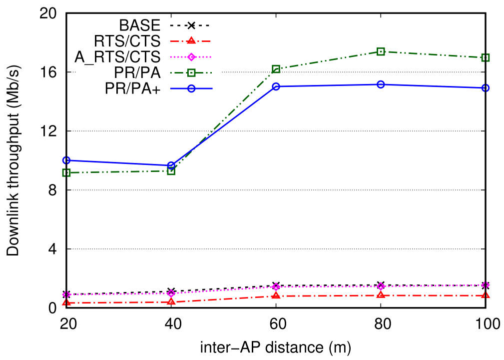
F. THE PERFORMANCE COMPARISON UNDER DIFFERENT OVERLAPPING BSS ENVIRONMENTS

In this simulation, we observed the performances when BSSs were deployed with different degrees of overlapping. For this purpose, we placed two APs at (-d,0) and (d,0) and increased the value of d from 10 m to 50 m in 10 m increments. We defined D_{AP} as the distance between two APs, i.e. $D_{AP} = 2d$ and D_{CS}^{max} as the maximum distance at which the AP's transmission can be detected, which was around 47 m in our simulation. Depending on the value of D_{AP} (or d), we considered three cases:

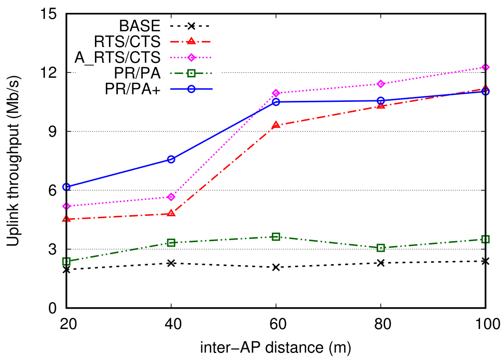
- Case1: When $D_{AP} \leq D_{CS}^{max}$ (i.e. $d = 10$ m and 20 m), the two APs can sense each other and the two BSSs overlap considerably.
- Case2: When $D_{CS}^{max} < D_{AP} \leq 2D_{CS}^{max}$ (i.e. $d = 30$ m and 40 m), the two APs are hidden from each other but the two BSSs partially overlap.
- Case3: The BSSs do not overlap at all if d (=50 m) > D_{CS}^{max}.



(a)



(b)



(c)

FIGURE 9. The performance comparison with different inter-AP distances. (a) Total throughput (TH_{total}). (b) Downlink throughput (TH_{DL}). (c) Uplink throughput (TH_{UL})

Note that, as d increases, the number of exposed nodes decreases but the number of hidden nodes increases. We set N_{STA} as 50 and placed STAs randomly within the area of the two BSSs. In addition, we fixed the transmission rate of the data frame at 26 Mb/s.

Figures 9(a), 9(b), 9(c) show TH_{total}, TH_{DL}, and TH_{UL}, respectively, when D_{AP} ranged from 20 m to 100 m. We first observe TH_{total} from Fig. 9(a). As D_{AP} increased, TH_{total} was almost constant or slightly increased in Case1 and Case3 but increased remarkably in Case2 except for `BASE`, which was due to the decrease in the number of exposed nodes. For the entire range of D_{AP}, `PR/PA+` showed outstanding performance, e.g. `PR/PA+` achieved TH_{total} higher than `BASE`, `RTS/CTS` and `A_RTS/CTS` by up to 7.1, 3.3, and 2.7 times, respectively. Compared to `PR/PA`, `PR/PA+` further increased TH_{total} by 26% - 40%, due to the TTC scheme. Meanwhile, `A_RTS/CTS` somewhat outperformed `RTS/CTS`; the TH_{total} of `A_RTS/CTS` was higher than that of `RTS/CTS` by 15% - 28%.

Figure 9(b) confirms that the superior performance of `PR/PA` and `PR/PA+` in terms of TH_{total} resulted from the increase in TH_{DL}. In the cases of `BASE`, `RTS/CTS`, and `A_RTS/CTS`, TH_{DL} was almost constant and did not exceed 1.5 Mb/s regardless of D_{AP}; however, in the cases of `PR/PA` and `PR/PA+`, it was considerably increased from 9.3 and 9.7 Mb/s to 17.4 and 15.2 Mb/s, respectively, as D_{AP} increased from 40 m to 80 m. This result proves the effectiveness of the destination switching in the PR/PA mechanism. It is of interest that `PR/PA+` attained a higher total throughput than `PR/PA` for the whole range of D_{AP} (see Fig. 9(a)), but the downlink throughput of `PR/PA+` was rather smaller than that of `PR/PA` when $D_{AP} \geq 60$ m (see Fig. 9(b)).

Next, we observe TH_{UL} from Fig. 9(c). The results of TH_{UL} were considerably different from those of TH_{DL}. While `BASE` showed the worst performance for the whole range of D_{AP}, either `PR/PA+` or `A_RTS/CTS` maintained the highest value of TH_{UL} depending on D_{AP}. Moreover, in the cases of `RTS/CTS`, `A_RTS/CTS`, and `PR/PA+`, TH_{UL} generally increased as D_{AP} increased, but `BASE` and `PR/PA` were not much affected by D_{AP}. It is important to note a trade-off in `PR/PA` in that its downlink throughput was remarkably increased, but its uplink throughput was quite poor. When $D_{AP} \geq 60$ m, the TH_{UL} of `PR/PA` was smaller than those of `RTS/CTS` and `A_RTS/CTS` by at least 2.6 times. This is because `PR/PA` is susceptible to ACK corruption due to interference with data frames. The TTC scheme effectively handles these ACK corruptions, and so compared to `PR/PA`, `PR/PA+` significantly improved the uplink throughput while maintaining a similar downlink throughput.

G. THE PERFORMANCE COMPARISON WITH DIFFERENT NUMBERS OF BSSS

In this simulation, we focused on the effect of the number of BSSs, N_{BSS}. We increased N_{BSS} from 2 to 4 and 8. When N_{BSS} was 2, two APs were located at $(-d,0)$ and $(d,0)$, and when N_{BSS} was 4, the location of APs were set as $(-d,0)$, $(d,0)$, $(0, d)$, and $(0, -d)$. Another four APs were located at (d,d), $(-d,d)$, $(-d, -d)$, and $(d, -d)$ when N_{BSS} was 8. We set the value of d as 30 m by considering the network size and the carrier sensing threshold. These configurations made the BSSs partially overlapped. On the other hand, we fixed N_{STA} as 100 and placed STAs randomly within the coverage of the BSSs. Note that as N_{BSS} increased, the density of nodes per BSS and the number of exposed nodes decreased accordingly. Other simulation configurations were the same as in Section IV-D.

The key observations from the results in Table 5 are as follows:

- TH_{total}: In most mechanisms except for `BASE`, TH_{total} increased by 4.9 - 5.9 times when N_{BSS} increased

TABLE 5. The performance comparison with different BSS numbers.

Mechanism		BASE	RTS/CTS	A_RTS/CTS	PR/PA	PR/PA+
Total throughput (TH)	$N_{BSS}=2$	1.57	11.71	11.86	13.55	16.41
	$N_{BSS}=4$	8.44	32.49	35.47	35.21	42.23
	$N_{BSS}=8$	49.71	57.06	70.22	75.88	85.84
Downlink throughput (TH_{DL})	$N_{BSS}=2$	1.10	1.01	1.41	11.26	11.44
	$N_{BSS}=4$	5.20	2.10	3.54	23.62	25.47
	$N_{BSS}=8$	17.14	4.83	4.08	33.37	47.09
Uplink throughput (TH_{UL})	$N_{BSS}=2$	0.47	10.70	10.45	2.30	4.97
	$N_{BSS}=4$	3.24	30.40	31.93	11.59	16.75
	$N_{BSS}=8$	32.57	52.23	66.14	42.51	38.74

from 2 to 8. The increase of TH_{total} is due to the increased chance of spatial reuse in different BSSs and the decreased probability of collision among STAs within a specific BSS. Moreover, PR/PA+ improved TH_{total} by 19% - 50% compared to RTS/CTS and A_RTS/CTS, and by 13% - 21% compared to PR/PA.

- TH_{DL}: RTS/CTS and A_RTS/CTS maintained poor downlink throughput, e.g. TH_{DL} was less than 5 Mb/s even when $N_{BSS} = 8$. This is because the APs were mostly blocked due to RTS or CTS frames transmitted by the STAs. However, PR/PA and PR/PA+ showed an outstanding performance in terms of TH_{DL}; they increased TH_{DL} by up to 12 times, compared to RTS/CTS and A_RTS/CTS.
- TH_{UL}: In RTS/CTS and A_RTS/CTS, most of the throughput was achieved by the STAs but the APs did little, i.e. TH_{UL} was greater than TH_{DL} by around 7 - 16 times and TH_{UL} took more than 90% of TH_{total}. This unfairness between TH_{UL} and TH_{DL} was considerably alleviated in PR/PA and PR/PA+.

V. CONCLUSIONS

In this study, we proposed a joint solution for HNP and ENP in dense WLANs. We showed that the conventional RTS/CTS mechanism faces with the false blocking problem and hinders spatial reuse among exposed nodes and that this problem originates from the unconditional full reservation of a channel on detecting the RTS or CTS frame. This problem was resolved in the proposed PR/PA mechanism by employing the *conditional semi-reservation* of the channel in response to the PR or PA frame. Furthermore, we introduced two schemes over the framework of the PR/PA exchange: IDS and TTC. The IDS scheme allows the AP to re-initiate the process of semi-reservation immediately to an alternative destination when the exchange of PR/PA frames fails at a particular destination. On the other hand, the TTC scheme adjusts the duration of the secondary transmission to avoid interference with the primary transmission. Consequently, the IDS scheme contributes to an increase in downlink throughput by decreasing the channel access delay of the AP, and the TTC scheme increases the probability of successful spatial reuse by avoiding frequent failures of the ACK frames. The results of the simulations performed on the various configurations confirmed the outstanding performance of the proposed mechanism compared to the existing ones. We expect that the performance of our PR/PA mechanism can be further improved by combining it with dynamic control of the transmission power or the carrier sensing threshold, which will be investigated in our future work.

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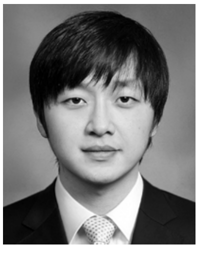

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