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Improving Spatial Reuse of Wireless LAN Uplink Using BSS Color and Proximity Information

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Abstract: With the density of wireless networks increasing rapidly, one of the major goals in next-generation wireless LANs (Local Area Networks) is to support a very dense network with a large number of closely deployed APs (Access Points) and crowded users. However, the CSMA (Carrier-Sense Multiple Access)-based medium access control of current wireless network systems suffers from significantly degraded performance when the network becomes dense. Recent WLAN (Wireless Local Area Networks) standards include measures for increasing spatial reuse such as BSS (Basic Service Set) coloring, but the schemes based on BSS coloring such as OBSS/PD (Overlapping BSS/Preamble Detection) have limitations in improving spatial reuse. In this paper, we propose a spatial reuse method for uplink which can utilize BSS color and proximity information to improve the efficiency of carrier sensing and thus spatial reuse. Specifically, through the BSS color and the proximity information, a node receiving a preamble can figure out how far the receiver of the ongoing traffic is located. This information is used to determine whether the node should aggressively start transmitting or defer its transmission to protect the ongoing transmission. Simulation results show that the proposed method outperforms existing methods in terms of throughput and fairness.

Keywords: wireless LAN; spatial reuse; medium access control; BSS color; proximity information

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1. Introduction

In recent years, WLANs have become an essential part of everyday life in most places. The density of users has grown at a fast rate, because most people use phones, pads, laptops, and other devices that connect to WLANs whenever available, mostly while indoors. The traffic demand of each user is also rapidly increasing due to applications such as video streaming, video conferencing, and automatic backup services. On the other hand, the density of WLAN APs has also increased in recent years. We can easily find tens of WLAN APs accessible from a single indoor location. The cost of WLAN APs has become cheap enough to equip many APs in a room in order to support users in a crowded place. However, deploying more APs does not translate into providing more bandwidth, because the available bandwidth is decided by the frequency spectrum, not the density of APs. To support the ever-increasing traffic demand, an efficient use of frequency resource is very important.

The earlier versions of the IEEE 802.11 WLAN standard did not pay much attention to supporting dense scenarios due to natural reasons. The DCF (Distributed Coordination Function), which is the fundamental medium access control protocol of WLANs, suffers from significantly degraded performance in dense environments due to collisions and hidden/exposed terminal effects. In the latest and upcoming versions of the standard such as IEEE 802.11ax and 802.11be, efficient utilization of the medium is gaining much attention due to increased traffic demand and network density [1,2]. The goal of efficient channel utilization is to maximize "spatial reuse", or number of parallel transmissions in a given area.

IEEE 802.11ax, the most recent WLAN standard, incorporates a feature called BSS coloring [3], as well as two spatial reuse methods called OBSS/PD and PSR (Parameterized Spatial Reuse) [4]. Although these mechanisms can help increase spatial reuse and thus improve the overall performance in dense environment, they have their limitations as discussed in the next section.

In this paper, we propose a method called PSC-UL (Proximity-based Sensitivity Control for UL) which uses BSS color and proximity information to dynamically control the carrier sense threshold of the nodes. In addition to differentiating between intra- and inter-BSS communication, the idea of PSC-UL is to locate the position of OBSS AP using the BSS color. Furthermore, proximity information is used to predict the position of the transmitting STA. Using this information, a node receiving a preamble can estimate whether its transmission can take place in parallel to the ongoing transmission. This method leads to a more accurate decision compared to OBSS/PD and PSR, and thus can improve spatial reuse further. Simulation results show that the proposed method achieves increased UL throughput compared to existing methods such as OBSS/PD, both for STAs close to the APs as well as STAs in the edge of their BSSes. Packet delivery ratio is also improved, showing that the proximity information can be used to more accurately determine whether a node can successfully transmit a packet in parallel to the ongoing transmission. In the following are the contributions of this paper.

- We show that the BSS color can be used to predict the location of other APs, which can be used to estimate the interference received by the other AP when the node transmits a packet. Furthermore, we introduce the "proximity information" that can be included in the preamble. This proximity information together with the BSS color can be used to determine whether a node receiving the preamble can start a parallel transmission or not.
- We propose a new method called PSC-UL that uses the BSS color and proximity information to dynamically control carrier sense threshold of the STAs. The proposed method improves spatial reuse for UL communications.
- We conduct extensive simulations to evaluate performance of the proposed method under various environments and parameters, comparing with other existing methods such as OBSS/PD, PSR and Dual-CST [5].

The rest of the paper is organized as follows. In Section 2, we survey existing work on improving the efficiency of WLANs and discuss how the proposed scheme is different from other methods. In Section 3, we present the proposed method PSC-UL in detail with example scenarios to illustrate its operation. In Section 4, we evaluate performance of the proposed method comparing with other state-of-the-art mechanisms. Finally, in Section 5, we conclude the paper with remarks for possible future work.

2. Related Work

From the early days of IEEE 802.11 WLAN, it was well known that the performance of WLAN degrades significantly in dense scenarios, mainly due to the fact that its medium access control method, DCF, is based on CSMA/CA (Carrier-Sense Multiple Access/Collision Avoidance). As collision avoidance is based on random backoff, the probability of collision increases with node density, leading to packet loss and frequent retransmissions. Furthermore, the fact that carrier sensing is done by the transmitter leads to the hidden and the exposed problems, resulting in further performance loss and unequal share of channel bandwidth between the nodes [6].

Naturally, a significant research effort was made to improve the spectral efficiency of DCF. One of the goals was to find an optimal CST for the nodes, because using a fixed CST is the problem that leads to hidden and exposed terminal problems [7]. For example, Jiang et al. [8] studied the conditions for setting the CST to eliminate hidden terminals. However, such CST can increase exposed terminal that result in wasted channel bandwidth. Nakahira et al. [9] proposed a centralized method for controlling CST. The proposed algorithm measures SINR at the stations when two neighboring APs transmit in parallel and adjusts CST based on the information in order to increase number of parallel transmissions. Chakraborty et al. [10] proposed a method where hidden and exposed terminals are identified through RTS (Request-To-Send) and CTS (Clear-To-Send) packets. Specifically, if a node overhears and RTS but not the corresponding CTS, the node thinks that the RTS sender is an exposed terminal and transmits its packet concurrently.

Vutukuru et al. [11] proposed a method where each node maintains a CMAP (Conflict Map) which records which nodes should not transmit together. The CMAP is constructed by observing packet collisions and exchanging messages with neighbor nodes and is used along with the carrier sensing to avoid hidden and exposed terminal problems. Chau et al. [12] proposed a method for dynamically adapting its CST. If a node cannot transmit for a long time, it increases CST to mitigate the exposed terminal problem. On the other hand, if the node fails to receive ACK (Acknowledgement) multiple times, it decreases CST to mitigate hidden terminal problem. Hosseinabadi et al. [13] proposed Concurrent-MAC, where a transmitting node can select one of its neighboring nodes as a "privileged node" which can transmit a packet concurrently. In order to do so, information on who can transmit in parallel is collected by a central coordinator and disseminated throughout the nodes.

Eliab et al. [14] proposed G-DCF, where nodes form groups in a distributed manner if they can successfully transmit in parallel. Once one of the nodes transmits a packet, it triggers other nodes in the group to transmit their packets together. So et al. [5] proposed a method where two CSTs are used instead of one. When a node transmits a packet, it includes an "advertised CST" in the preamble, which should be obeyed by the neighbors to protect the ongoing transmission. Nodes hearing the preamble use their own CST as well as the advertised CST to determine whether to transmit or not. The CSTs are dynamically chosen to protect the transmissions by estimating the SNR (Signal-to-Noise Ratio) at the receivers. Although this method uses dynamic CST to improve spatial reuse, the method is still conservative in choosing CSTs because it assumes that the transmitters are in the closest position to the other receivers. The CST are chosen so that the packets can be received even in the worst case.

When developing the most recent standard, IEEE 802.11ax, spatial reuse has gained significant attention, due to its potential of considerably improving perceived quality of service [1]. One of the earlier proposals was DSC (Dynamic Sensitivity Control) [15], which selects CST based on the proximity between the sender and the receiver. Specifically, a node close to its AP uses a high CST so that it transmits aggressively, while a node far away from its AP uses a low CST so that it transmits conservatively. Evaluation of DSC shows that while it can increase throughput, DSC can causes severe unfairness among nodes; nodes closer to their APs get much larger share of the channel bandwidth, while nodes far away from their APs can be starved [16–20]. Many proposals were proposed aiming to address the problem of DSC. For example, Afaqui et al. [21] proposed a method where edge nodes that experience high FER (Frame Error Rate) use RTS/CTS to protect their packets from hidden terminals. Ropitault et al. [22] propose a technique where both transmit power and CST are adjusted based on ETX (Expected Transmission Count). A node with high ETX increases transmit power and CST to increase SNR as well as transmission opportunity.

Through these efforts, two spatial reuse schemes were included in the IEEE 802.11ax standard: OBSS/PD and PSR. In OBSS/PD, a node can use different CST depending on whether the ongoing communication is an intra-BSS or inter-BSS communication. For an intra-BSS communication, the node uses the default CST, or CST_{min} (e.g., −82 dBm). However, for an inter-BSS communication, the node can increase the CST up to CST_{max} (e.g., −62 dBm). However, when the node increases CST, it should also use a lower transmit power in order to protect the ongoing communication. Equation (1) is used to find the upper bound of the CST for inter-BSS communications. In the equation, TX_PWR_{ref} is the maximum transmit power, whereas TX_PWR is the reduced transmit power to protect the ongoing transmission. The allowable CST region according to the transmit power is shown in Figure 1.

$$CST \leq \max(CST_{min}, \min(CST_{max}, CST_{min} + (TX\_PWR_{ref} - TX\_PWR))) \quad (1)$$

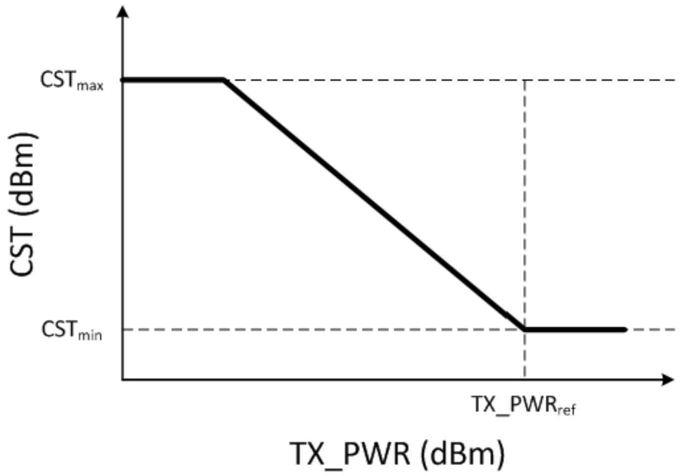


Figure 1. CST selection with transmit power control in the OBSS/PD method.

In order to distinguish inter-BSS communications from intra-BSS communications, each BSS chooses a BSS color (an integer), and a node includes the BSS color in the preamble of the packet. OBSS/PD is shown to achieve higher throughput compared to the legacy scheme with fixed CST [23]. However, as OBSS/PD still relies on channel status measured at the transmitter, it suffers from hidden and exposed terminals similar to the legacy scheme.

PSR is another method for spatial reuse. It can be used when uplink communication is scheduled by a trigger frame sent from the AP. In the trigger frame, the AP includes a PSR value which is calculated as in Equation (2). In Equation (2), I_{AP}^{max} is the acceptable interference level calculated as in Equation (3). In Equation (3), UL_Target_RSSI is the expected receive power of the UL packet, set by the AP and included in the trigger frame. Furthermore, min_SNR_MCS is the minimum SNR required for receiving the highest MCS (Modulation and Coding Scheme) among the scheduled UL traffic with less than 10% PER (Packet Error Rate).

$$PSR = TX\_PWR_{AP} + I_{AP}^{max} \quad (2)$$

$$I_{AP}^{max} = UL\_Target\_RSSI - min\_SNR\_MCS - margin \quad (3)$$

When a node receives a trigger frame from an AP that the node is not associated with, it looks at the PSR value and checks whether it can transmit concurrently with the scheduled UL traffic of the other BSS. Specifically, the node estimates the interference it will cause at the other AP and determines whether the UL packet will be successfully received at the AP even if the node transmits concurrently. If the estimated interference is less than the acceptable interference level at the AP, the node ignores the UL traffic that follows the trigger frame and transmits its packet after counting the backoff counter to zero. Rodrigues et al. [24] show that PSR has advantages over the legacy scheme, especially in reducing packet latency of uplink traffic [24]. However, as PSR only protects the UL traffic by advertising the PSR value, the node transmitting concurrently with the UL traffic may fail to send the packet if its receiver is close to the node sending uplink traffic [25]. In our proposed method, a node considers the SNR at both receivers when deciding to transmit a packet concurrently or defer its transmission.

There are other schemes that try to improve spatial reuse under various assumptions. For example, Murakami et al. [26] proposed a CST control scheme based on node locations, assuming nodes know their locations through devices like GPS. Furthermore, Adere et al. [27] proposed a scheme using directional antennas, while Wang et al. [28] proposed a method that requires devices with full-duplex capability.

With the recent advance of artificial intelligence, machine learning techniques were applied to the problem of spatial reuse. Jamil et al. [29] proposed a centralized approach where a central coordinator collects information and runs a neural network to find the best transmit power and CST to use. Wilhelmi et al. [30,31] proposed a distributed method where each node runs multi-armed bandits to find the best channel and transmit power. The authors showed that each node acting in a selfish way can still result in better spatial reuse as a system. Wang et al. [32] proposed an approach where a single user dynamically selects the best channel to transmit its packet among many available channels. The user uses a DQN (Deep Q Network) to learn the optimal policy of selecting the channel without knowing the system statistics. Naparstek et al. [33] extended this work to address the environment where multiple nodes are running DQN to select the best channel, while there are other nodes running different protocols like TDMA and ALOHA.

Yu et al. [34] proposed a method called DLMA (Deep reinforcement Learning Multiple Access), which replaces CSMA for channel access in a single wireless LAN. Instead of measuring channel status as in CSMA, DLMA uses ACK feedbacks to determine when to transmit its packet. Ak et al. [35] proposed a two-scale method for controlling CST using MLP (Multi-Layer Perceptron). While the local scale control is used to adjust CST to reduce interference and increase parallel transmissions, the global scale control is used to improve fairness among nodes. Yin et al. [36] proposed a scheme where interferers are recognized based on reinforcement learning and decisions to transmit concurrently are made accordingly. Reinforcement learning techniques are used for topics other than spatial reuse, such as channel bonding, network monitoring, and link configuration. These works are summarized in the survey paper by Szott et al. [37].

Finally, note that rate control is an important factor that needs to be considered when nodes dynamically select parameters like CST and transmit power. If a node finds out that the SNR at the receiver is not high enough for a certain MCS level, it can choose to wait or send the packet using a lower MCS level. Huang et al. [38] proposed a rate adaptation scheme where nodes transmitting in parallel adjust their MCS levels so that the colliding packets are safely received at their receivers. Krotov et al. [39] proposed a rate control algorithm that can be used with IEEE 802.11ax spatial reuse features. In our paper, we do not consider rate control and assume nodes use a fixed MCS level. Further improvements may be possible by applying rate control with the proposed method, and we leave this issue as a future work.

3. Proposed Method

3.1. Idea Overview

The main idea behind the proposed method is to estimate SNR at the receivers assuming the transmissions take place in parallel. While currently the BSS color is used to distinguish between intra-BSS frames and inter-BSS frames, we further use the BSS color to estimate where the inter-BSS AP is located. Furthermore, nodes include proximity information in the preamble which indicates how far the transmitter is located from its AP. Using this information, a node receiving a preamble can predict whether the packets will be successfully received at the receivers if the node concurrently transmits its packet.

When a node receives a preamble from another node, it has to decide whether it should defer its transmission by pausing the backoff countdown, or ignore the ongoing transmission, continue the backoff countdown, and potentially transmit its packet in parallel with the ongoing transmission. In the legacy scheme, a fixed threshold of −82 dBm is used to determine this, regardless of if the preamble belongs to an intra-BSS frame or an inter-BSS frame. In a dense network, this approach creates a lot of hidden and exposed terminals and leads to inefficient channel usage.

In OBSS/PD, a node can find out whether the preamble belongs to an inter-BSS frame by checking the BSS color. Even if the RSSI (Received Signal Strength Indicator) exceeds −82 dBm, the node can still transmit provided that it reduces its transmit power. This approach may allow exposed terminals to concurrently transmit packets and increase spectrum efficiency. However, still neither of the concurrently transmitted packets is guaranteed to be received at the receiver, because the decision is based on channel status of the transmitter.

In PSR, the AP protects the UL packets by broadcasting acceptable interference level to the inter-BSS nodes through trigger frames. However, the inter-BSS node transmitting concurrently does not know whether its packet will be successfully received at the receiver. It is possible that if its receiver is close to the transmitter of the ongoing communication, the packet may get lost due to low SNR. The key is that before a node decides to transmit its packet concurrently with the ongoing transmission, it must make sure both packets will have sufficient SNR at their respective receivers. The challenge is that while the location of a stationary AP can be estimated through beacons, the location of a mobile STA is hard to track.

We first consider the hidden terminal scenario described in Figure 2. In the scenario, node A is associated to AP_1, and node B is associated to AP_2. Node A begins to transmit its packet to AP_1, and its preamble is heard by node B. However, because the distance between node A and B is great, the received power at node B is lower than −82 dBm. With the legacy DCF, node B can transmit in parallel and cause collision at AP_1. OBSS/PD also cannot avoid this problem. Suppose node B receives node A's preamble at −72 dBm. Even if node B reduces its transmit power by 10 dB, it can be close enough to AP_1 so that there is still a collision at AP_1.

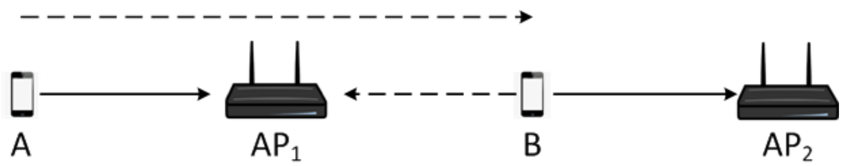


Figure 2. A hidden terminal scenario. Node B is hidden to node A, and the packet at AP_1 is lost when both node A and B transmit together.

When node B receives node A's preamble, it should transmit its packet in parallel only if it is certain that the ongoing transmission will not be lost. Node B needs to estimate the SNR at AP_1. As APs transmit beacons periodically, node B can predict the interference level at AP_1, assuming there is no other source of interference. What node B does not know is the signal level at AP_1. This cannot be known to node B unless node A gives the information to node B. In other words, node A must provide the "proximity information" that indicates how far node A is from AP_1. For example, node B knows that the received power from AP_1 to B is −70 dBm. (Here we assume that all APs and stations are transmitting at the same transmit power.) If node A "tells" node B that the received power from AP_1 to A is −50 dBm, node B knows that the SNR at AP_1 will be approximately 20 dB if both node A and node B transmits. If that SNR is not enough to receive A's packet, node B must defer its transmission.

Next, we consider the exposed terminal scenario described in Figure 3. Similar to the previous scenario, node A is associated to AP_1 and node B is associated to AP_2. Node A begins to transmit its packet to AP_1, and its preamble is heard by node B. As node B is close to node A, the received power at node B can be above the CST. In legacy DCF, node B unnecessarily defers its transmission, although both packets can be successfully received at their respected receivers.

Figure 3. An exposed terminal scenario. Node A is exposed to node B, so node B unnecessarily defers its packet even both transmissions can take place in parallel.

In PSR, if AP_1 sends a trigger frame to schedule UL transmission, node B can find out the acceptable interference level at AP_1 using the PSR value in the preamble. Thus, node B can transmit its packet if node B's interference at AP_1 is expected to be lower than the acceptable interference level. However, PSR cannot guarantee that node B's transmission will be successfully received at AP_2. Suppose AP_2 was in a location close to node A, as in Figure 4. In this scenario, node B should actually defer its transmission, but transmits aggressively according to PSR and fails.

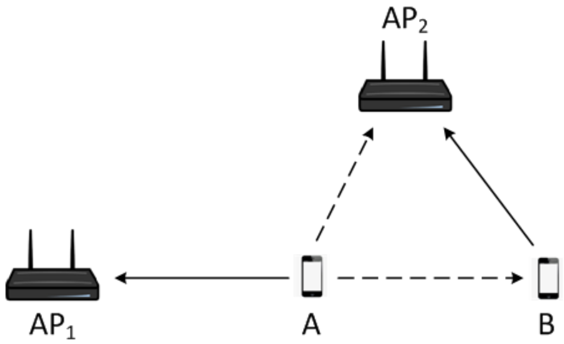


Figure 4. A scenario where node B transmits in parallel with node A according to PSR, but node B's packet is lost due to low SNR at AP_2.

When node B transmits its packet in parallel with node A, node B should be confident that its transmission is successfully received at AP_2. The signal level at AP_2 can be predicted because B is receiving beacons from AP_2. Predicting the interference level at AP_2 is not trivial, because we do not know how far node A is from AP_2. Although node A may know the proximity between itself and AP_2 through beacons, it is impractical for node A to include proximity information with non-associated APs in the preamble. We need to estimate the interference level with other information.

As APs are mostly stationary, an AP can keep track of the proximity between itself and other neighboring APs. For example, in Figures 3 or 4, AP_2 maintains a neighbor table, where it records the average RSSI for its neighboring APs. The RSSI can be obtained by listening to the beacons. Furthermore, AP_2 sends the table to node B, so that it knows the proximity between AP_2 and AP_1. When node B receives preamble from node A, it can estimate the distance between node A and AP_2 using the proximity between AP_2 and AP_1, as well as the proximity between node A and AP_1.

Let us denote the distance between AP_1 and AP_2 as d_{12}, and the distance between node A and AP_1 as d_{1A}. Then, the distance between node A and AP_2, d_{2A}, is less than or equal to $d_{12} - d_{1A}$. The placement of nodes in Figure 3 is the worst case, where $d_{2A} = d_{12} - d_{1A}$. Using this information, we estimate the interference level at AP_2 and determine whether node B can transmit concurrently with node A. As we do not know exactly where node A is located in vicinity of AP_1, we consider the worst case and assume that node A is in the position closest to AP_2, in order to avoid collisions caused by the hidden terminal problem.

We summarize the idea of the proposed method with the scenario shown in Figure 5. In the scenario, node A is transmitting its packet to AP_1, and its preamble is received by node B. Node B needs to decide whether it can transmit its packet concurrently with node A. In order to do so, node B needs to find out the following values.

- S_1: received power of the signal from node A to AP_1.
- I_1: received power of the interference from node B to AP_1.
- S_2: received power of the signal from node B to AP_2.
- I_2: received power of the interference from node A to AP_2.

Among the four values, S_2 and I_1 are directly known to node B, because node B is receiving beacons from AP_2 and AP_1. S_1 is also known to node B, because node A includes the proximity information in the preamble which indicates the received power of the signal from AP_1.

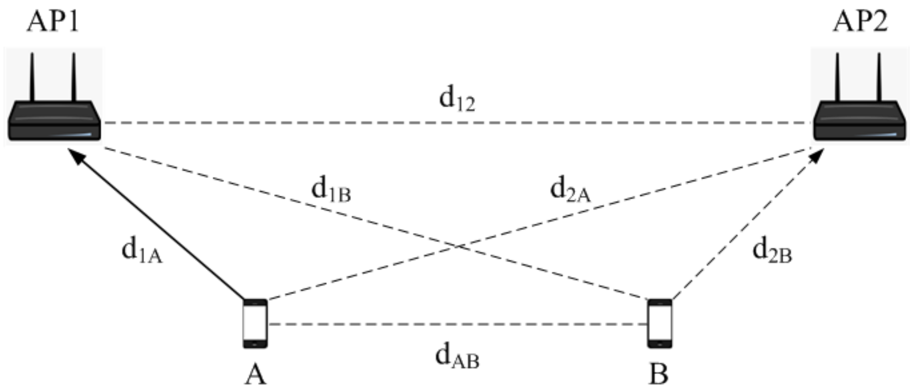


Figure 5. A scenario illustrating how a node determines concurrent transmission in the proposed method.

In order to estimate I_2, we use the triangle inequality to estimate the "distance" between node A and AP_2. Note that the concept of distance we use here is a notion of signal attenuation, rather than the exact physical distance. If there is an obstacle between the transmitter and the receiver, the distance between the two points will be estimated longer than the actual physical distance. When maintaining RSSI obtained from beacons, weighted moving average is used to smooth out variations caused from multi-path fading. According to triangle inequality, the following inequalities hold:

$$d_{2A} + d_{AB} \geq d_{2B} \tag{4}$$

$$d_{2A} + d_{2B} \geq d_{AB} \tag{5}$$

$$d_{2A} + d_{12} \geq d_{1A} \tag{6}$$

$$d_{2A} + d_{1A} \geq d_{12} \tag{7}$$

Combining these equations, we get the minimum distance between node A and AP_2, which can be used to estimate I_2.

$$d_{2A} \geq \max(|d_{AB} - d_{2B}|, |d_{12} - d_{1A}|) \tag{8}$$

d_{AB}, d_{2B}, d_{12}, and d_{1A} are all obtainable through BSS color, proximity information, and neighbor tables maintained at APs and STAs. Next, we describe the details on how the proposed method is designed and implemented.

3.2. Protocol Details

In this section, we describe the details of the proposed method, PSC-UL. This method is used to improve spatial reuse of uplink traffic. In other words, when a UL transmission is in place, a station in a different BSS can use the method to transmit its packet in parallel. It does not mean that downlink traffic cannot co-exist in the same channel. DL (Downlink) traffic may co-exist, but its cannot benefit from proximity information to start a concurrent transmission, unless APs maintain proximity information of stations in its own BSS as well as other neighboring BSSes.

3.2.1. Neighbor Table

In PSC-UL, APs and stations maintain neighbor tables where the RSSI of neighboring APs are stored. An example neighbor table is shown in Table 1. The neighbor table stores the RSSI of neighboring APs, measured using beacons sent from the APs. Each entry of the table stores BSSID, BSS color, and the RSSI value. The RSSI value of each AP is updated using EMA (Exponential Moving Average) as shown in Equation (9). In the equation, R_t is the average RSSI at time t, S_t is the RSSI sampled from a beacon at time t, and α is a value between 0 and 1.

$$R_t = \alpha \cdot S_t + (1 - \alpha) \cdot R_{t-1} \tag{9}$$

Table 1. Neighbor table of node B and AP_2. APs periodically send its neighbor table to the stations, so node A will have both the tables. (**a**) Neighbor table of B. (**b**) Neighbor table of AP_2.

(**a**)			(**b**)		
Neighbor_Table of B			**Neighbor_Table of AP_2**		
BSSID	**Color**	**RSSI**	**BSSID**	**Color**	**RSSI**
00:00:00:00:00:01	1	−76	00:00:00:00:00:01	1	−72
00:00:00:00:00:02	2	−44	00:00:00:00:00:03	3	−63
00:00:00:00:00:03	3	−68	00:00:00:00:00:04	4	−88
00:00:00:00:00:05	5	−87	00:00:00:00:00:05	5	−83

In Table 1a, node B has four entries in its neighbor table, including its associated AP, AP_2. In Table 1b, AP_2 has four entries from which it can receive beacons. While AP_4 (BSSID: 00:00:00:00:00:04) appears in the neighbor table of AP_2, it is too far from node B such that node B cannot hear its beacon. Periodically, an AP sends its neighbor table to all the associated stations. Thus, the stations have two neighbor tables: one that stores RSSI of APs measured at the node, and one that stores RSSI of APs measured at its AP.

3.2.2. Proximity Information

When a node transmits a UL packet to its AP, it includes the proximity information in the preamble, along with the BSS color. The proximity information is basically the RSSI of the associated AP, measured from the node. Suppose node A receives beacons from AP_1 at an average RSSI of −40 dBm. Then, −40 dBm is the proximity information node A includes in the preamble of its packets.

The proximity information should be included in the signal field of the preamble, such as HE-SIG-A (High-Efficiency SIG-A) of 802.11ax. In HE-SIG-A, 6 bits are allocated for BSS color, which allows up to 64 unique colors for representing a BSS. The proximity information can be encoded into 4 bits, similar to the Spatial Reuse field in the HE TB PPDU (HE Trigger-Based PLCP Protocol Data Unit) which is used for sending PSR values. An example field encoding for proximity information is shown in Table 2. Using more bits allows sending a fine-grained proximity information which can increase spatial reuse, but at the same time increases the overhead of sending more bits in the preamble. For example, in Table 2, the proximity information is encoded in steps of 4 dB. To encode the proximity information, the RSSI of the AP is quantized to a lower value. For example, if RSSI of the AP is −74 dBm, then the proximity information field is set so '2', which means −76 dBm.

Table 2. Proximity information field encoding. The RSSI of the AP is quantized to a lower value.

Value	**Meaning**	**Value**	**Meaning**
0	PI_UNKNOWN	8	PI = −52 dBm
1	PI $\leq$ −80 dBm	9	PI = −48 dBm
2	PI = −76 dBm	10	PI = −44 dBm
3	PI = −72 dBm	11	PI = −40 dBm
4	PI = −68 dBm	12	PI = −36 dBm
5	PI= −64 dBm	13	PI = −32 dBm
6	PI = −60 dBm	14	PI = −28 dBm
7	PI = −56 dBm	15	PI $\geq$ −24 dBm

3.2.3. Protocol Operation

To describe the operation of PSC-UL, we consider the scenario in Figure 5. In the scenario, node A transmits a packet to AP_1, which is also received by node B. We assume that node A and AP_1 are using BSS color 1, while node B and AP_2 are using BSS color 2. By reading the BSS color field in the preamble, node B finds out that the packet belongs to a different BSS. Node B needs to decide whether it should pause the backoff countdown or continue. If it continues to countdown the backoff counter, node B may transmit if packet concurrently with the ongoing transmission.

First, node B reads the proximity information field also in the preamble. If the proximity information is unknown (value 0 in the field), then it means node B cannot use the PSC-UL method for parallel transmission. This may be because the ongoing communication is a downlink traffic, or PSC-UL is disallowed by operator decisions. If the proximity information field is some other encoded value, node B decodes the value. We denote the decoded value as P_{1A}. Suppose in our scenario that P_{1A} is −40 dBm. Now, from node B's neighbor table, we read the average RSSI of the beacon from AP_1 to node B. This value is P_{1B}, and suppose it is −76 dBm in our scenario. We check whether Equation (10) is true. In the equation, SNR_{min} is the minimum SNR for successfully receiving the packet, and m is the margin. If Equation (10) is false, node B decides the channel is busy and pauses its backoff. If Equation (10) is true, then we continue. In our example scenario, SNR_{min} is 23 dB and m is 5 dB, which makes the equation true. It means that when node B transmits its packet concurrently, AP_1 can still successfully receive the packet sent by node A.

$$P_{1A} - P_{1B} \geq SNR_{min} + m \tag{10}$$

Now, we need to check whether the packet sent by node B will be successfully received by AP_2. To do that, we need to check whether Equation (11) is true. In the equation, P_{2B} can be obtained by reading node B's neighbor table. Suppose P_{2B} is −44 dBm.

$$P_{2B} - P_{2A} \geq SNR_{min} + m \tag{11}$$

To calculate P_{2A}, we need to known the pathloss between node A and AP_2, and we do this by estimating the distance between node A and AP_2, d_{2A}. We consider two cases: In the first case, we estimate the distance between AP_1 and AP_2 (d_{12}), as well as the distance between node A and AP_1 (d_{1A}). As we do not exactly know where node A is located, we consider the worst case and assume that node A is on the line between AP_1 and AP_2, which puts node A in the closest position to AP_2. Then, the distance between node A and AP_2 is $d_{12} - d_{1A}$.

We estimate the distance from RSSI using a pathloss model. Specifically, we use a log-distance model which is frequently used for indoor environment. Equation (12) shows the equation for calculating pathloss from distance using the log-distance model. In the equation, PL is the pathloss, PL_0 is the reference pathloss, d is the distance between the source and the destination, and d_0 is the reference distance. Furthermore, γ is the pathloss exponent and X_g is a random variable that models channel variations such as fast fading. We set X_g to zero, and use the margin parameter to account for channel variations.

$$PL = PL_0 + 10\gamma log_{10}\frac{d}{d_0} + X_g \tag{12}$$

Using Equation (12), we can calculate the distance if we know the pathloss, as in Equation (13).

$$d = d_0 \times 10^{\frac{PL - PL_0}{10\gamma}} \tag{13}$$

Using Equation (13), we convert P_{12} and P_{1A} to d_{12} and d_{1A}. We can obtain P_{12} from the neighbor table of AP_2 which is periodically sent to node B. Furthermore, we can obtain P_{1A} through proximity information. Once we get d_{12} and d_{1A}, we estimate d_{2A} as Equation (14), which is the worst case in terms of interference at AP_2.

$$d_{2A} = d_{12} - d_{1A} \tag{14}$$

Once we get d_{2A}, we convert it back to pathloss P_{2A} using Equation (12). Then, by subtracting the pathloss from transmit power, we get P_{2A}. Finally, we can use Equation (11) to determine whether the packet transmitted from node B will be successfully received at AP_2. If Equation (11) is true, then AP_2 can successfully receive the packet from node B. If Equation (11) is false, then AP_2 will not have sufficient SNR to receive the packet from node B.

In the second case, we estimate d_{2A} using the distance between two senders (d_{AB}) and the distance between node B and AP_2 (d_{2B}). In this case, the worst case would be when AP_2 is located on the line connecting node A and node B. Then, the distance between node A and AP_2 is $d_{AB} - d_{2B}$. Similar to the previous case, we convert P_{AB} and P_{2B} to d_{AB} and d_{2B}. P_{AB} can be obtained by measuring signal strength of the packet from node A, and P_{2B} can be obtained from B's neighbor table. We convert these values to distances using the pathloss model, estimate the worst-case distance d_{2A} using Equation (15), and convert the value back to pathloss to get P_{2A}. In this case as well, we can use Equation (11) to determine whether AP_2 can successfully receive the packet from node B.

$$d_{2A} = d_{AB} - d_{2B} \tag{15}$$

In summary, when node B receives preamble from node A, node B calculates d_{2A} according to Equations (14) and (15). Then, according to Equation (8), we choose the final d_{2A} as the maximum of the two. Then, we convert d_{2A} into the P_{2A} and apply Equation (11) to determine whether the packet transmitted by node B will be successfully received at AP_2. If Equation (11) is true, the node B can continue its backoff countdown and transmit concurrently with the ongoing communication. If Equation (11) is false, node B must pause its backoff and defer its transmission. The whole process of the proposed scheme is described as a flow diagram in Figure 6.

In the beginning of the section, we assumed that the nodes transmit packets at the same transmit power. However, it is possible that a user station could reduce the transmit power in order to reduce interference or other reasons such as energy conservation. In this case, the transmit power must be taken into account when calculating the interference at the receivers. In the proposed scheme, the only term affected by the transmit power of the user station is d_{AB}, which is the distance between the two user stations. All the other distances are calculated from RSSIs measured from beacons that are transmitted using a fixed transmit power. In order to correctly estimate d_{AB}, node B needs to know the transmit power of node A.

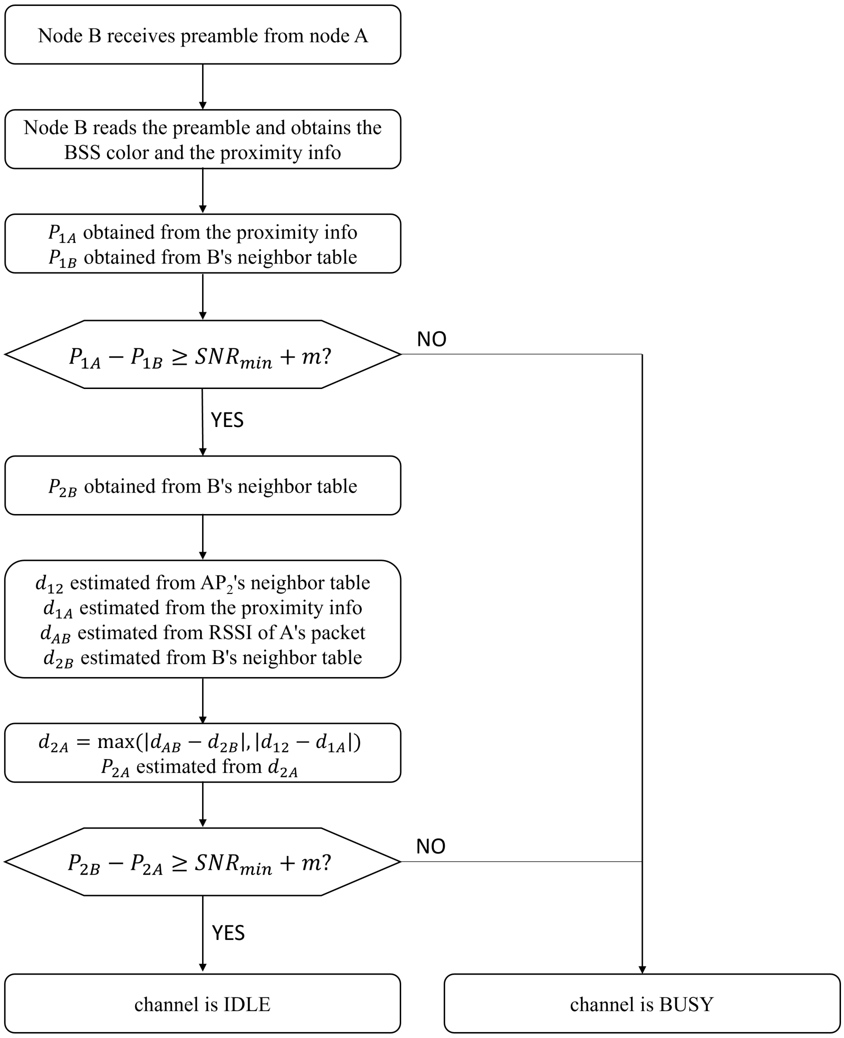


Figure 6. A flow diagram illustrating the operation of the proposed method.

There are two ways to address this problem. First, node A encodes its transmit power into the preamble, similar to the proximity information. This will require several bits in the preamble, which is an overhead. An alternative is to just assume that node A is transmitting at the maximum transmit power. Then, the calculation of d_{AB} will result in a larger value when node A is transmitting at a reduced power. In turn, d_{2A} will be estimated as a larger value, and P_{2A} will be estimated as a smaller value. As node A is transmitting at a reduced power, P_{2A} will actually be smaller than when node A is transmitting at the maximum power. Although estimation errors will increase because pathloss is a nonlinear function, we do not need to explicitly send transmit power in the preamble in this scheme.

When calculating SNR in Equations (10) and (11), we use the margin parameter m to account for channel variation due to fading, as well as errors made from the pathloss model. A large margin makes nodes conservative, which reduces collisions but at the same time reduces parallel transmissions. On the other hand, a small margin makes nodes more aggressive, which increases parallel transmissions but also collisions. In the simulations, we study the impact of margin on the protocol performance. There are methods to improve the accuracy of a pathloss model, such as tuning the pathloss exponent to better reflect the current environment [40]. With a more accurate model we may choose a smaller margin and further improve the protocol performance. It is out of scope of this paper and left as a future work.

4. Performance Evaluation

4.1. Simulation Setup

We have evaluated the performance of PSC-UL using a simulator implemented in Python. In the default setting, a 100 m $\times$ 100 m simulation area is divided into 100 cells, where an AP is placed at the center of each cell. One-hundred user stations are randomly deployed in the area, and each station associates with the closest AP. The simulation environment is illustrated in Figure 7. We assume that all user stations are backlogged with packets to send to the AP, so they contend for the channel constantly. We use UDP (User Datagram Protocol) traffic with 1472 bytes of packet size, and the MCS is set so that the link speed is 65 Mbps for 20 MHz channels. We use the log-distance model as the pathloss model. In the model, the reference distance d_0 is 1 m, the reference pathloss (PL_0) is 46.67 dB, and the pathloss exponent (γ) is 3. The transmit power is set to 25 dBm for both APs and stations, and the noise floor is set to -93.97 dBm. The minimum SNR required for successfully receiving a packet is set to 23 dBm, and we use 5 dB as margin, unless otherwise specified.

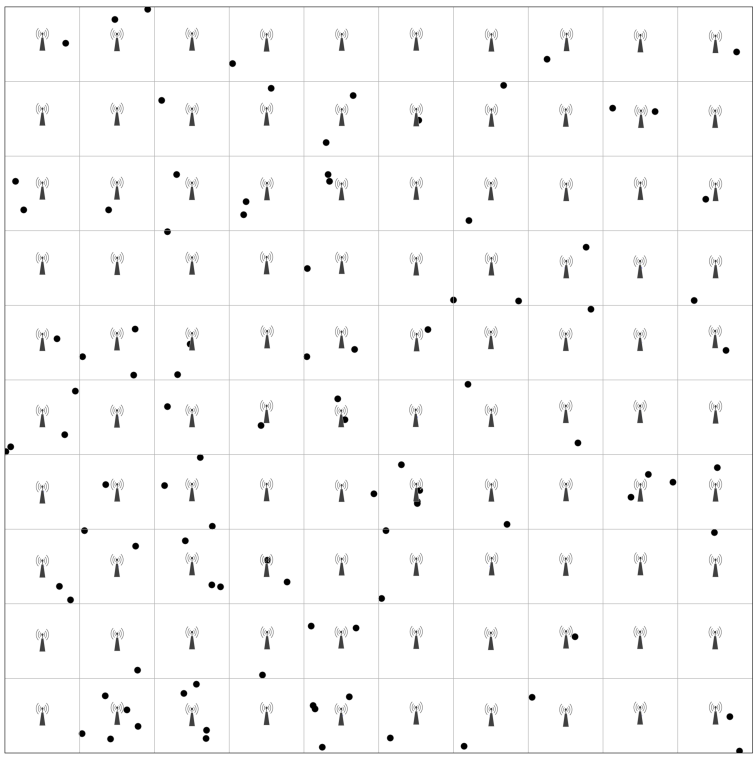


Figure 7. The default simulation environment. One-hundred APs are placed in a 100 m $\times$ 100 m area, and 100 user stations are randomly deployed inside the area.

We use six metrics to evaluate the performance. The first metric is 'network throughput', which indicates the number of data bits successfully transferred in the network per second. With the same environment and configuration parameters, a method with higher spatial reuse will achieve higher throughput. However, just measuring the network throughput may mislead the results, because high throughput can also be achieved by having a small number of nodes dominate the channel and starving all other nodes. A notion of fairness should also be measured. For that we use 'bottom 50% throughput' and 'bottom 25% throughput'. For these metrics, we sort the node throughput in the ascending order, and select 50% and 25% of the nodes with the least throughput. Then, we aggregate their throughput to obtain the results. If a method achieve a high network throughput but a low bottom 50% or bottom 25% throughput, it means the method is favoring only a few nodes in the network while starving all others. We also measure Jain's fairness index, which is a more direct metric used to measure fairness of a system. The equation for Jain's fairness index is shown in Equation (16). In the equation, x_i is the throughput of node i, and n is the total number of nodes.

$$J(x_1, x_2, ..., x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \times \sum_{i=1}^{n} {x_i}^2} \tag{16}$$

As the fifth metric, we measure the 'non-starvation ratio', which is the percentage of nodes that transmitted at least one packet successfully during the simulation time, which can be another indication of fairness. Finally, we measure the 'packet delivery ratio'. Packet delivery ratio reveals how aggressively nodes transmitted their packets. If a method has a low delivery ratio, it means a lot of collisions occurred due to aggressive transmissions.

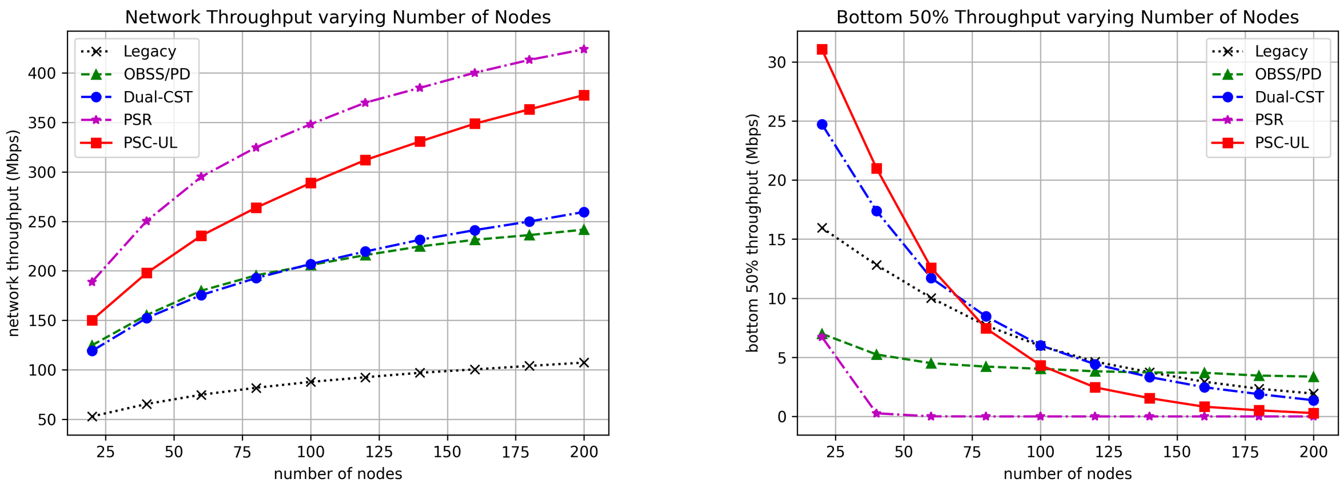
Using these evaluation metrics, we compare the performance of five different methods. The first method, "legacy" is the original 802.11 DCF with fixed CST. The default CST is set to −82 dBm. The second method is "OBSS/PD", where a node may decide to transmit with a lower transmit power when the sensed interference is between CST_{min} and CST_{max}. In the simulations, CST_{min} is −82 dBm and CST_{max} is −62 dBm. The third method is "Dual-CST", which is a method proposed in [5] and uses "advertised CST" in addition to the original CST. The fourth method is "PSR", where an AP advertises acceptable interference in the preamble, and a node in a different BSS may choose to transmit if its interference will not exceed the acceptable interference level at the AP. In PSR, we set UL_Target_RSSI to −32 dBm. (OBSS/PD, PSR, and Dual-CST were discussed earlier in the related work section.) Finally, "PSC-UL" is the proposed method.

To obtain each point in the graphs, we ran 100 simulations with different topology and different random number generator seeds, and averaged the results.

4.2. Simulation Results

4.2.1. Varying Number of Nodes

In the first experiment, we have varied the number of user stations in the network to study the impact of node density on the protocol performance. The number of stations was varied from 20 to 200. The results are shown in Figure 8.



(a) **(b)**

Figure 8. *Cont.*

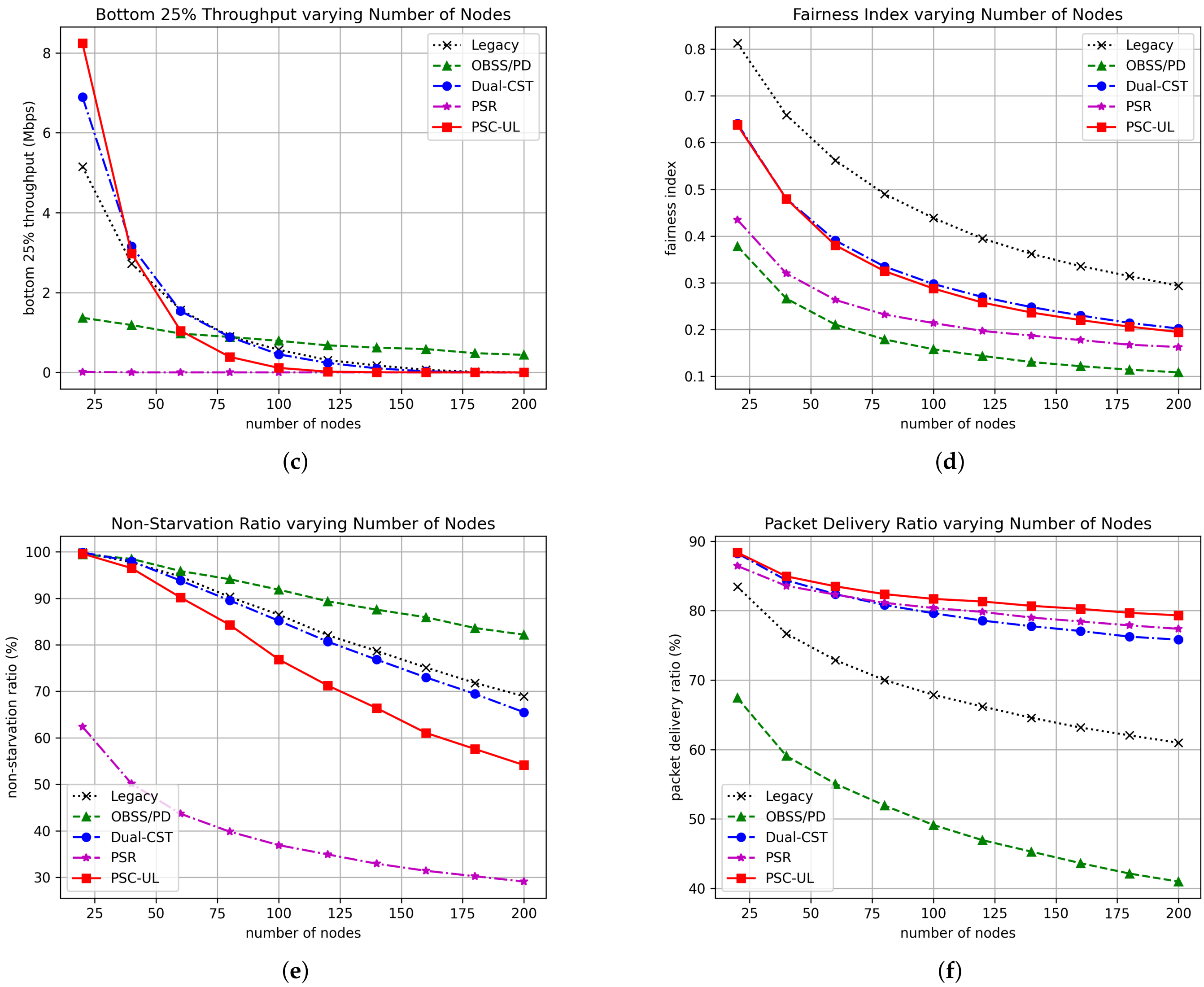
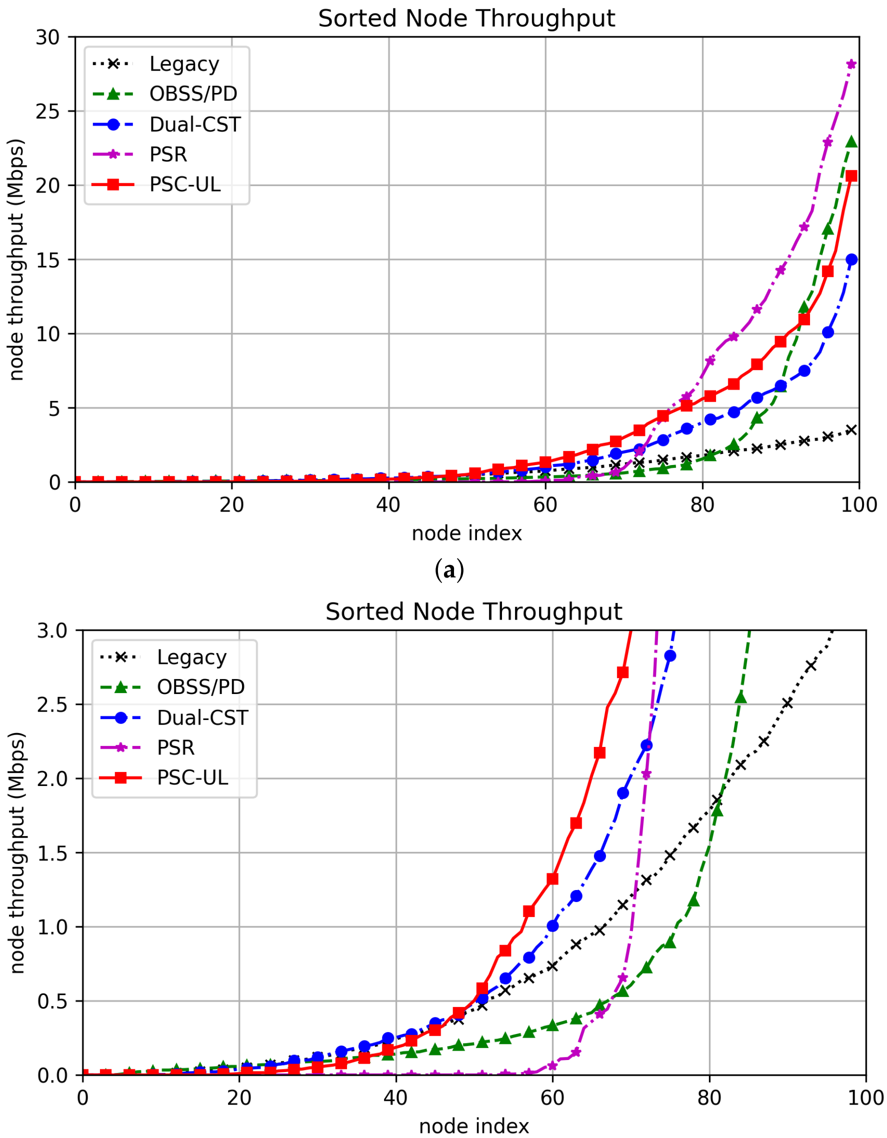


Figure 8. Performance of methods varying number of nodes. (**a**) Total throughput; (**b**) Bottom 50% throughput; (**c**) Bottom 25% throughput; (**d**) Fairness; (**e**) Non-starvation Ratio; (**f**) Delivery Ratio.

In Figure 8a, we can see that the PSR achieves the highest total throughput, followed by PSC-UL. PSC-UL achieves higher throughput compared to Legacy, OBSS/PD, and Dual-CST. As the number of stations increases, the difference of throughput between PSR, PSC-UL, and the other three methods increases, meaning that PSR and PSC-UL find more opportunities for parallel transmission compared to other methods. Although PSR achieves higher total throughput compared to PSC-UL, PSR suffers from significant unfairness, as can be observed from the other graphs. Figure 8b,c shows bottom 50% throughput and bottom 25% throughput. As the number of stations increase, these values decrease for all methods. Especially for PSR, almost no throughput is gained for bottom 50% nodes. This is also reflected in Figure 8d,e, which shows the Jain's fairness index and non-starvation ratio. While the fairness index of PSC-UL is similar to Dual-CST, a much lower fairness index is achieved by PSR and OBSS/PD.

This occurs because the fairness index is low for SNR, as shown in Figure 8e; too many nodes are starved. PSR is designed so that the spatial reuse opportunity is taken only when the on-going communication can be protected. It does not guarantee that the parallel communication will succeed. Naturally, nodes that are far away from their APs tend to lose packets in parallel transmission, while nodes close to their APs have their packets successfully received. This is because OBSS/PD has low fairness index as can be seen in Figure 8f, which shows the delivery ratio. With OBSS/PD, nodes attempt to transmit their packets too aggressively, which results in a lot of packet losses due to collision. PSC-UL shows lower fairness index compared to Legacy. This is due to the fact that in PSC-UL, stations that are in proximity to their APs gain more throughput compared to Legacy, while the throughput of stations that are far from their APs is comparable to Legacy. It is natural that stations that have higher SNR margin at their receivers have higher chance of initiating a parallel transmission.

To take a deeper look, we have plotted the throughput of each node, sorted in the ascending order of throughput. Figure 9a,b shows the result of simulations using the default configuration. They are the same graph, except that the range of the y-axis was adjusted in Figure 9b to get a better look at nodes with lower throughput. We can see that the throughput of all methods except PSR starts to grow at similar times. Furthermore, the throughput of PSC-UL grows faster than other protocols. On the other hand, the throughput of PSR stays near zero until index 60, and then starts to grow. This is consistent with the earlier observation that a lot of stations are starved in PSR.

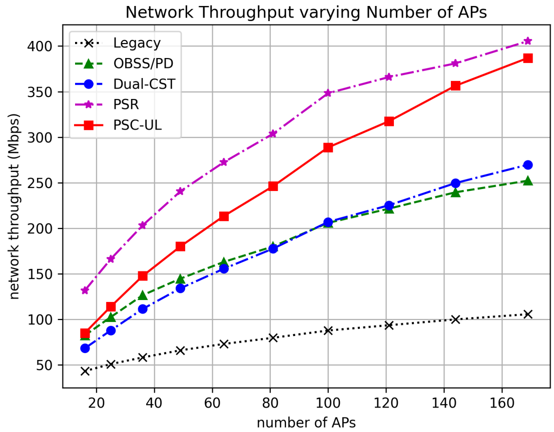


(**b**)

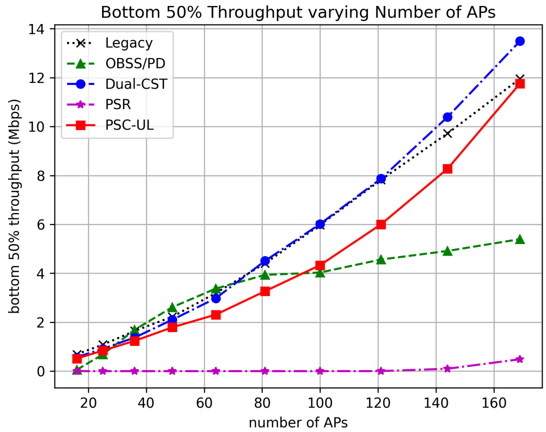
Figure 9. Sorted node throughput. Panel (**a**) is the full graph whereas panel (**b**) is a partial graph where the y-axis is from 0 to 3 Mbps.

4.2.2. Varying Number of APs

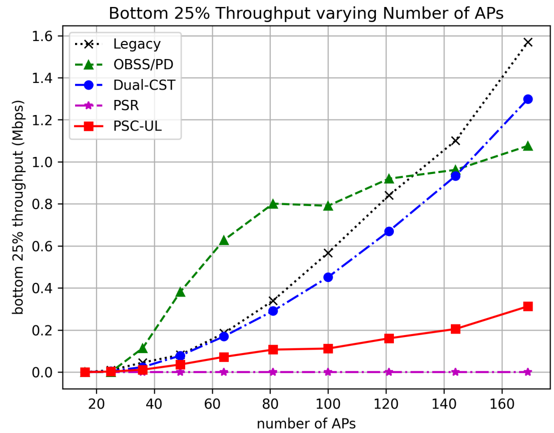
In the second experiment, we have varied the number of APs in the network while keeping the number of stations fixed. The area size is also fixed to 100 m × 100 m. Thus, when the number of APs is increased, the average distance between a station and its AP decreases. The number of APs is varied from 16 to 169. The results are shown in Figure 10.



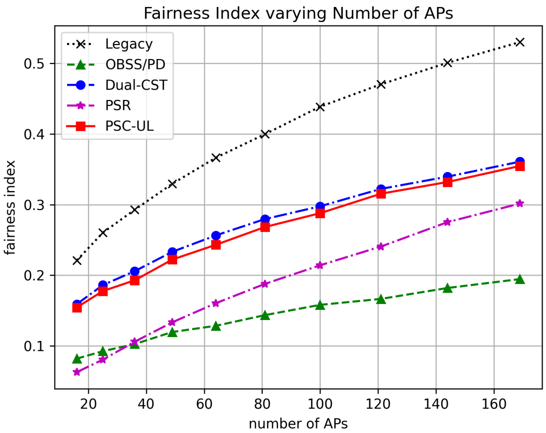
(**a**)



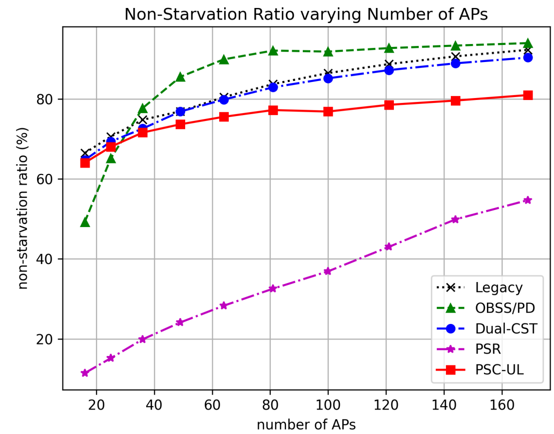
(**b**)



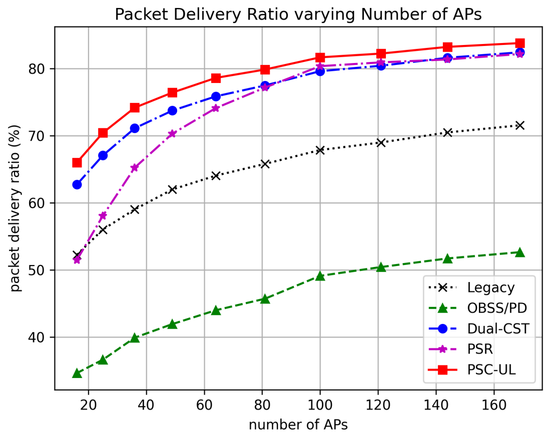
(**c**)



(**d**)



(**e**)



(**f**)

Figure 10. Performance of methods varying number of APs. (**a**) Total throughput; (**b**) Bottom 50% throughput; (**c**) Bottom 25% throughput; (**d**) Fairness; (**e**) Non-starvation Ratio; (**f**) Delivery Ratio.

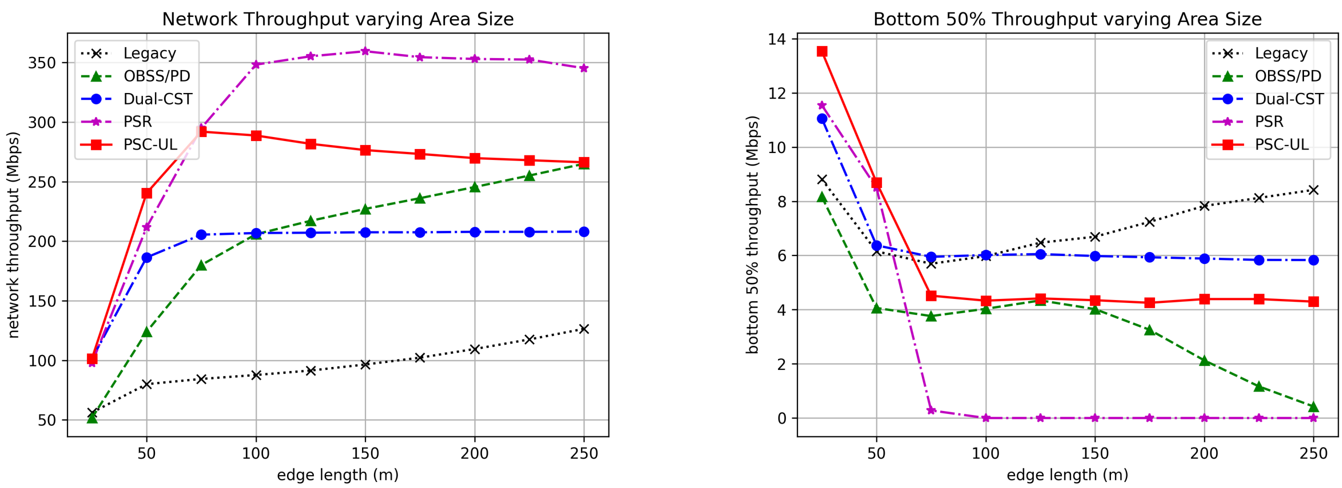
The total throughput shown in Figure 10a shows a similar trend to the previous experiment. In this case, the throughput increases with number of APs because more parallel transmission can be initiated when the distance between a station and its associated AP is shorter. The PSR and PSC-UL increase the gap with other methods as the number of APs grow larger, because they use a more fine-grained information to determine whether parallel transmission will be successful. Similar to the previous experiment, the PSR achieves higher total throughput compared to PSC-UL, but its fairness and non-starvation ratio are much lower than PSC-UL.

When the number of APs becomes large, we can observe that the bottom 25% throughput as well as the non-starvation ratio of PSC-UL is lower than other compared methods except PSR. This means that stations at the edge experience very low throughput and some may even starve. This is because when PSC-UL estimates SNR at the receivers, only the two potentially parallel transmissions are considered. If there exists additional interference at the receivers, the SNR can become lower than expected, and to the point where packet losses occur. One solution to address this problem is to control the margin parameter based on density. A larger margin value can be used for a very dense network to account for additional interference. We use a fixed margin in this paper, and finding the optimal margin for the environment is left as a future work.

4.2.3. Varying Area Size

In the previous experiment, we have increased the number of APs while keeping the area size fixed. In the third experiment, we vary the area size while keeping the number of APs and stations fixed. It is true that both changing the number of APs and changing the area size affect the cell size. The difference is that with fixed number of stations, increasing the number of APs lead to smaller number of stations per cell, and vice versa. On the other hand, increasing area size while keeping the number of APs and number of user stations fixed will only increase the average distance between user stations and their associated APs, while keeping the number of user stations per cell the same.

In this experiment, the area size is varied from 25 m × 25 m to 250 m × 250 m. As we increase the area size, the size of each cell increases, meaning that the average distance from a station to an AP will be longer. The result is shown in Figure 11. In the figure, the X-axis is the edge length, which is the length of an edge in the square-shaped area.



(a) (b)

Figure 11. *Cont.*

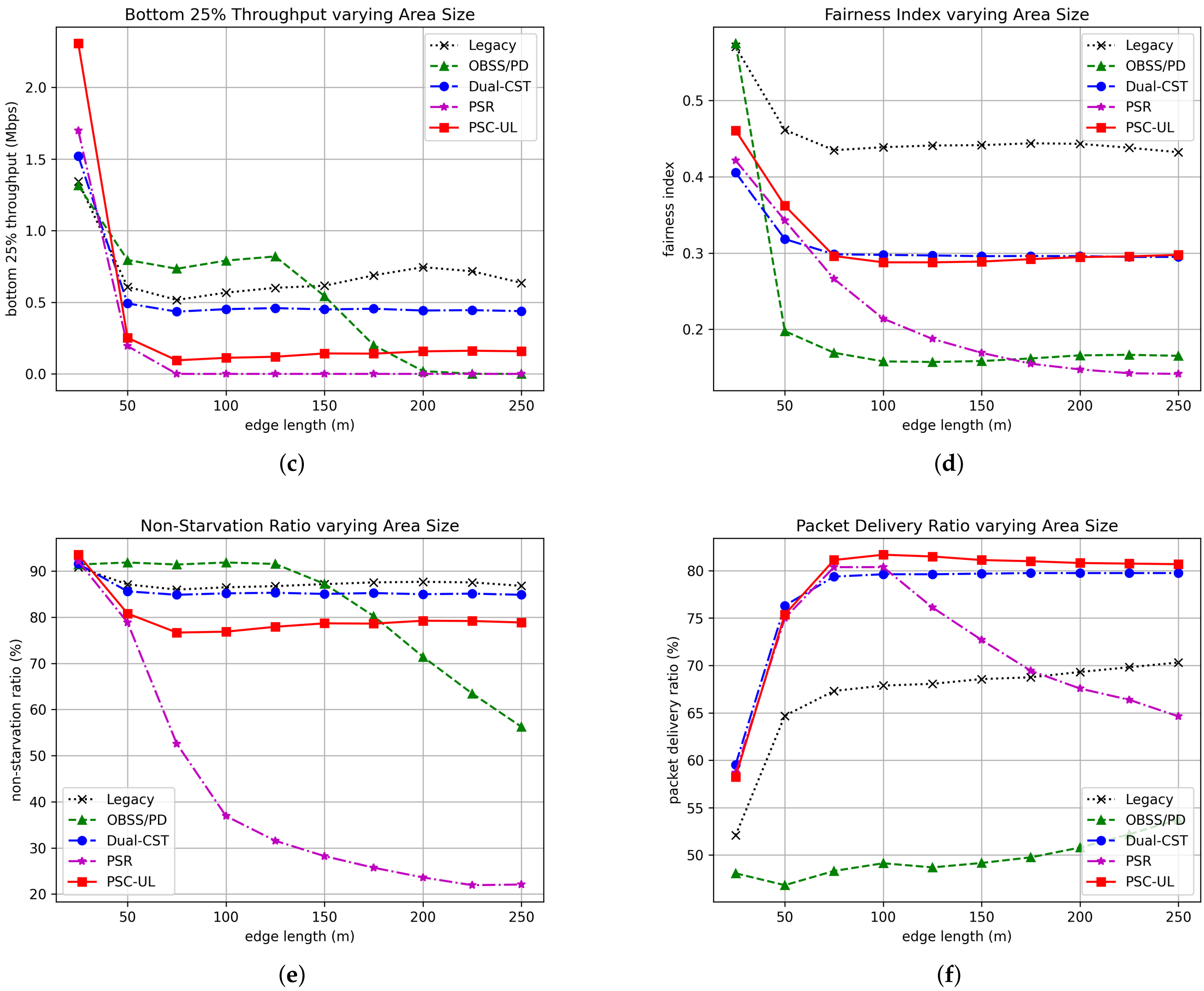


Figure 11. Performance of methods varying area size. (**a**) Total throughput; (**b**) Bottom 50% throughput; (**c**) Bottom 25% throughput; (**d**) Fairness; (**e**) Non-starvation Ratio; (**f**) Delivery Ratio.

When the area is very small, the spatial reuse opportunity is rare, and therefore the throughput is low. As the area size increases to some extent, the network throughput increases because more parallel transmission can take place in the area. However, if the area becomes larger while the number of APs is fixed, the average distance between a station and its associated AP increases. Because of that, the acceptable interference level at the receivers decreases, and the throughput starts to decrease as shown in Figure 11a.

The pattern is different for OBSS/PD. The total throughput continues to increase, while the fairness measures start to drop rapidly, as shown in Figure 11b–e. This is because OBSS/PD does not consider SNR at the receiver, but only uses signal strength measured at the sender to determine whether a node should start a concurrent transmission. When the distance between nodes increases, nodes tend to transmit more aggressively in OBSS/PD. As a result, nodes at the edge fail to have their packets received, while the nodes closer to their APs enjoy successful communication.

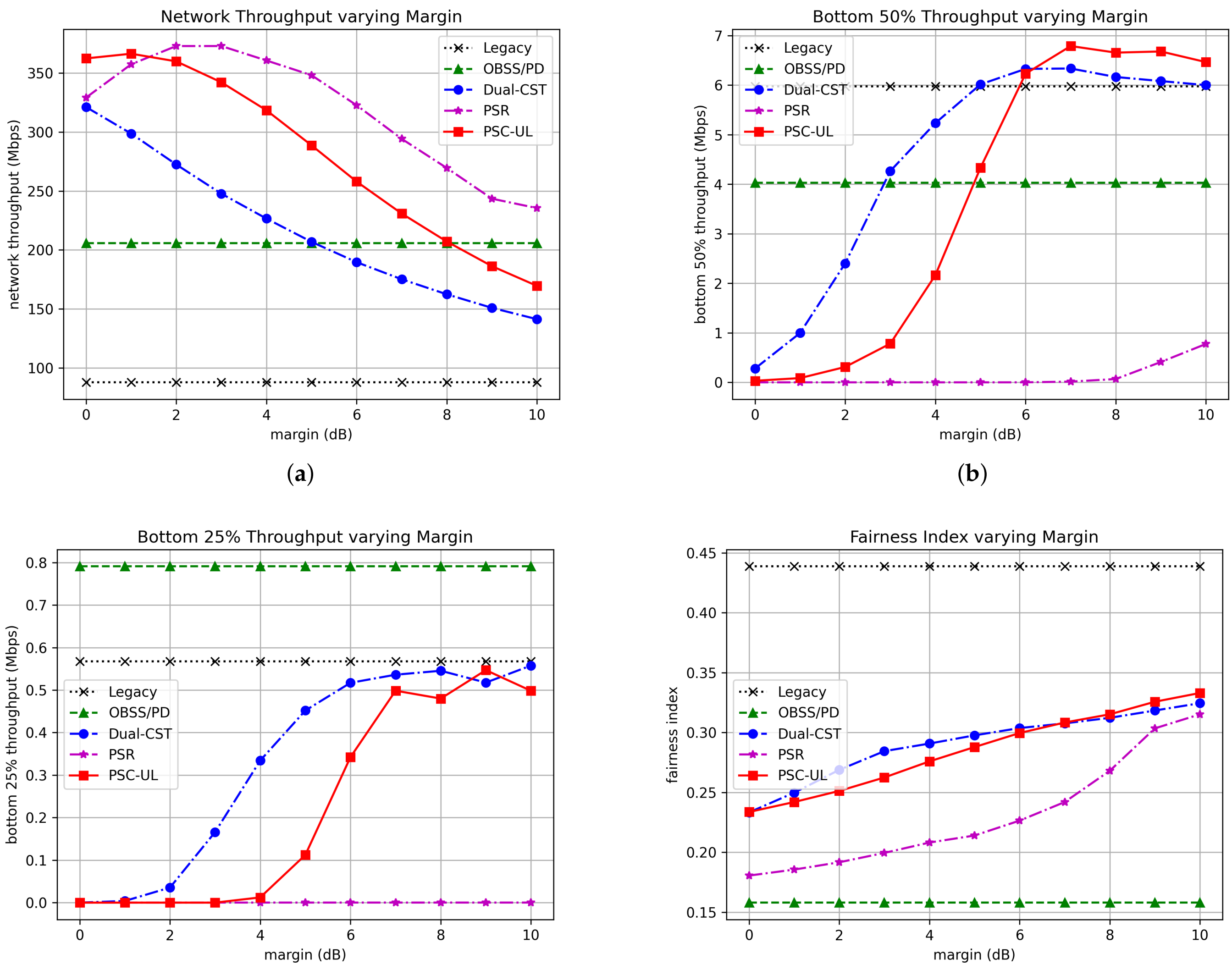
For PSC-UL, similar observations can be made in this experiment. It achieves higher total throughput than compared methods except for PSR, which shows a higher throughput than PSC-UL. However, PSC-UL achieves significantly higher measures in terms of bottom

50% and 25% throughput, Jain's fairness index, and non-starvation ratio. The performance of PSC-UL is steady with increased area size, unlike OBSS/PD and PSR.

4.2.4. Varying Margin

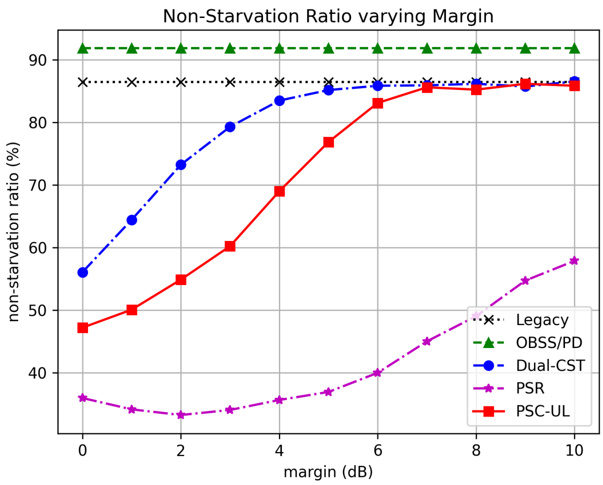
In PSC-UL as well as other methods like PSR and Dual-CST, a margin parameter is used to account for estimation errors. In the fourth experiment, we have varied the margin parameter to study its effect on protocol performance. Legacy and OBSS/PD do not use the margin parameter, so their values are constant regardless of the parameter. The margin is varied from 0 dB to 10 dB. The results are in Figure 12.

In Figure 12a, we can observe that the total throughput is reduced as we increase the margin. Increasing the margin means that the nodes transmit more conservatively, and they take the concurrent transmission opportunity only when the expected SNR at the receiver is well above the required value. With the same margin value, PSR achieves higher throughput compared to PSC-UL, which was also reflected in other experiments. However, here we can see that the peak values for the total throughput of PSR and PSC-UL are similar, achieved with different margin values. The fairness measures are improved when the margin value increases because conservative transmissions reduce collisions from hidden terminals, which is harmful for fairness. For PSR, however, the fairness measures are still much lower than other methods even with high margin values as shown in Figure 12b–e.

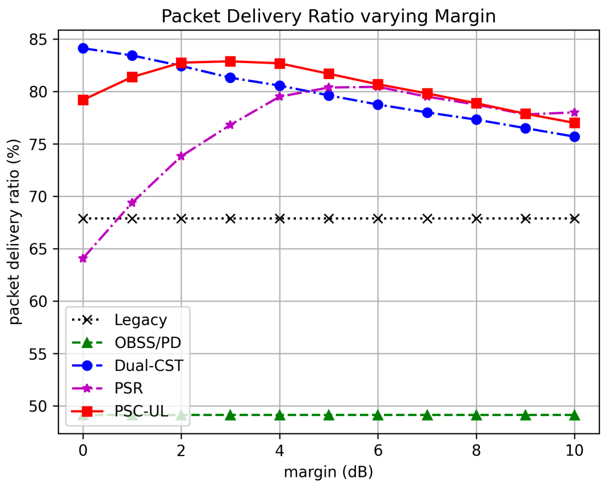


(**a**) (**b**) (**c**) (**d**)

Figure 12. *Cont.*



(**e**)



(**f**)

Figure 12. Performance of methods varying margin. (**a**) Total throughput; (**b**) Bottom 50% throughput; (**c**) Bottom 25% throughput; (**d**) Fairness; (**e**) Non-starvation Ratio; (**f**) Delivery Ratio.

In summary, PSC-UL can improve the network performance by increasing parallel transmissions. While other methods like OBSS/PD and PSR can also increase spatial reuse, these methods do not fully consider if the concurrent transmissions will be successfully received at their receivers. Therefore, lots of collisions occur which can lead to throughput degradation and unfairness. In PSC-UL, a node decides to transmit concurrently after estimating SNR at the receiver of both the ongoing transmission and the potential concurrent transmission. To estimate SNR at the receivers, nodes maintain neighbor tables that contain RSSI of APs, and include proximity information in the preamble. The experiment results show that the proposed method can significantly improve throughput over the legacy method, and shows better performance characteristics compared to other spatial reuse methods.

5. Conclusions and Future Work

In this paper, we proposed a spatial reuse method for uplink communication in wireless LANs. The proposed method, PSC-UL, allows concurrent transmissions when the estimated SNR at the receiver is sufficient to receive both the packets. In order to estimate the SNR, APs and stations maintain RSSI of neighboring APs. An AP periodically sends its neighbor table to its associated stations, so that a station has both its neighbor table and the neighbor table of the AP. When a node transmits a packet, it includes its BSS color and proximity information in the preamble. The proximity information is an indication of the distance between the transmitter and its destination AP. When a node in a different BSS receives this preamble, it uses the BSS color, the proximity information, and its neighbor tables to determine whether both packets will be successfully received at the receivers if the node chooses to transmit concurrently. If either of the packets is expected to be lost, the node pauses backoff and defers its transmission. Simulation results have shown that PSC-UL achieves a considerable amount of throughput improvement using legacy, OBSS/PD, and Dual-CST methods without causing significant unfairness as in PSR.

While the proposed method has merit, many limitations exist that need further research. First, the proposed method can only be used with UL traffic. The major reason for this is that it is difficult to estimate SNR at the receiver if the receiver is a user station. An AP cannot keep track of all user stations in the vicinity because the user stations are mobile and they do not send out beacons. Still, improving spatial reuse for DL traffic is very important. Achieving high spatial reuse for DL may require cooperation between APs, which is an important feature in the upcoming standard, IEEE 802.11be. Second, we assumed that MCS levels were fixed. However, a node may choose to send a packet using a lower MCS level if the SNR at the receiver is expected to be low. Concurrently sending a packet at a lower rate can increase the throughput by allowing more parallel transmissions, but at the same time can degrade the throughput by having lower rate transmissions occupy the channel. A spatial reuse method combined with rate control is an important topic for future study. Third, we only considered a single channel in this paper. In practice, multiple channels exist, and APs and stations can be assigned channels in a way that the spatial reuse of each channel is maximized. A spatial reuse method combined with channel assignment is another interesting topic for further study. Fourth, machine learning approaches can be used to obtain optimal parameter values, such as margin, adequate for the environment. We plan to pursue these problems in the near future.

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Abbreviations

The following abbreviations are used in this manuscript:

ACK	Acknowledgment
AP	Access Point
BSS	Basic Service Set
CA	Collision Avoidance
CCA	Clear Channel Assessment
CMAP	Conflict Map
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CST	Carrier Sense Threshold
CTS	Clear-To-Send
DCF	Distributed Coordination Function
DL	Downlink
DLMA	Deep reinforcement Learning Multiple Access
DQN	Deep Q Network
DSC	Dynamic Sensitivity Control
EMA	Exponential Moving Average
ETX	Expected Transmission Count
FER	Frame Error Rate
HE	High Efficiency
LAN	Local Area Network
MCS	Modulation and Coding Scheme
MLP	Multi-Layer Perceptron
MU-MIMO	Multi-User Multiple Input Multiple Output
NRF	National Research Foundation
OBSS	Overlapping BSS
OBSS/PD	Overlapping BSS/Preamble Detection
PPDU	PLCP Protocol Data Unit
PSC-UL	Proximity-based Sensitivity Control for UL

PSR	Parameterized Spatial Reuse
RU	Resource Unit
PER	Packet Error Rate
RSSI	Received Signal Strength Indicator
RTS	Request-To-Send
SNR	Signal-to-Noise Ratio
STA	Station
TB	Trigger-Based
TF	Trigger Frame
UDP	User Datagram Protocol
UL	Uplink
WLAN	Wireless Local Area Networks

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