Enhanced Coordinated Spatial Reuse: Bidirectional Multiple AP Coordination for IEEE 802.11be

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***Abstract*—The popularity of WiFi keeps increasing because of its capability to deliver a cost-efficient broadband Internet connection. However, a new problem emerges when many basic service sets (BSSs) are deployed in the same area, which increases inter-access point (AP) contention and co-channel interference. Inter-AP contention will decrease the overall throughput in the area and cause long application delay. The rise of bandwidth-hungry and low-latency applications like virtual and augmented reality, online gaming, and video streaming makes it urgent to solve this problem. The IEEE 802.11be Working Group (TGbe) proposes a new feature, coordinated spatial reuse (CSR). This feature allows concurrent transmissions of multiple APs through coordination between APs, reducing inter-AP contention and co-channel interference. However, existing proposed CSR algorithms use one-way coordination where the AP that initiates the CSR transmits at its maximum power and other APs optimize their transmit (TX) power accordingly, resulting in poor throughput for other APs. To solve this problem, we propose a new bidirectional CSR algorithm, Enhanced Coordinated Spatial Reuse (ECSR), which collaboratively determines the TX power for all APs by setting an appropriate interference tolerance limit. To the best of our knowledge, this is the first work that proposes bidirectional multiple AP coordination for CSR. We evaluate our proposed algorithm in dense enterprise scenarios. Simulation results show that our proposed design achieves three times higher throughput than the traditional carrier sense multiple access (CSMA) technique and four times more than the existing one-way CSR. Our experimental results also show that none of the stations participating in ECSR transmissions have low throughput.**

I. Introduction

The number of WiFi users keeps rising because of its capabilities to deliver cost-efficient broadband Internet connection. However, this expanding popularity has led to many basic service sets (BSSs) deployed in the same overlapping area with co-channel interference [1]. An example of such dense WiFi deployment is illustrated in Fig. 1, where stations in the overlapping zones face severe co-channel interference, affecting the overall throughput and increasing channel access delay. However, existing commercially available IEEE 802.11 products cannot solve this problem, as the conventional channel access technique based on carrier sense multiple access (CSMA) cannot accommodate many competing devices simultaneously. Additionally, the proliferation of bandwidth-hungry and low-latency applications such as virtual and augmented reality, gaming (e.g., latency below 5 ms for online gaming), 4K and 8K video streaming, and online video conferencing poses a new challenge for current IEEE 802.11 standards because they cannot reduce the inter-access point (AP) contention in dense environments, which makes latency worse [2].

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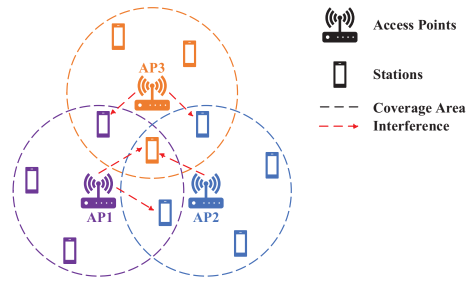

Fig. 1. Example of dense WiFi deployment in which one AP's service area overlaps with another.

To address this issue, IEEE 802.11ax introduces spatial reuse (SR) [3], which increases the number of concurrent transmissions in overlapping regions by optimizing the transmit (TX) power of APs. Thus, 802.11ax can reduce interference and improve spectral efficiency. However, the main problem of SR is that when one AP transmits data with its maximum TX power, other APs decrease their TX power uncoordinatedly. Hence, some stations (STAs) get too low signal-to-noise-ratio (SNR), resulting in poor throughput [4]. To solve these problems, IEEE 802.11be (WiFi 7) proposes coordinated spatial reuse (CSR), the low-complexity multiple AP coordination system where APs mitigate interference by cooperatively controlling their TX power to ensure adequate SNR at all STAs [5].

To support CSR, several algorithms are proposed in recent years. In [6], sharing AP, an AP that wins the channel, initiates the CSR and regulates the TX power of other APs, known as "shared APs," to avoid co-channel interference. However, when the STA associated with the shared AP is close to the sharing AP, the shared AP either cannot participate in CSR transmissions or transmits at a reduced data rate. In [7], CSR first ensures the target SNR of at least one STA that the sharing AP wishes to serve before satisfying the SNR of other STAs connected to the shared APs. However, focusing more on securing the transmission of the sharing AP does not make this approach ideal for dense deployment circumstances because it can reduce the number of concurrent transmissions. In [8], the sharing AP utilizes the received signal strength indicator (RSSI) reported by the STA associated with it to determine the acceptable interference level. Then, it calculates the TX power for shared APs based on this interference level. Nevertheless, when all APs are close to one another, the interference level rises, which reduces the shared AP's TX power and impacts the throughput. Furthermore, existing techniques favor one-way coordination, in which the sharing AP determines its own TX power without a coordinating mechanism and limits shared APs' TX power to safeguard the sharing AP's transmissions.

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Therefore, developing a bidirectional coordination algorithm for CSR in which the sharing AP and shared APs collaborate to determine the optimal TX power for all APs is highly desirable.

In this paper, we present a new bidirectional CSR algorithm in which a sharing AP determines an appropriate interference tolerance limit (CSR Threshold) for all participating APs by collecting information (RSSI and TX power) from shared APs, which allows multiple APs to transmit simultaneously without interfering each other's transmission. Then, the sharing AP calculates CSR TX power for all APs based on this CSR Threshold. In each transmission opportunity (TXOP), the value of CSR Threshold is fixed for all APs, but it may be different in another TXOP depending on several factors including the distance between APs and the distance between an AP and the STAs associated with neighboring APs, and the TX power of the APs. For a successful transmission, the RSSI coming from a neighboring AP must be greater than the CSR Threshold. When the CSR Threshold is low, all APs reduce their TX power; in contrast, all APs transmit at the maximum power when the CSR Threshold is high. A possible issue is that interference in overlapping regions may increase if the CSR Threshold is too high, forcing some APs to defer their transmissions. To prevent this problem, we propose that, in each TXOP, the sharing AP sets this threshold for all APs by checking the interference level of every STA participating in enhanced coordinated spatial reuse (ECSR) transmissions. Instead of reducing the transmission range in which some STAs may have a low SNR, as with the IEEE 802.11ax SR, we determine a suitable CSR Threshold for all APs, which ensures an appropriate SNR for every STA participating in ECSR transmissions.

Contributions: We summarize our unique contributions as follows:

- We develop a novel low-complexity bidirectional CSR algorithm, ECSR, for next-generation WiFi 7, which can maximize the number of parallel transmissions per TXOP while maintaining adequate SNR for STAs joining CSR data transmissions. Thus, our proposed algorithm increases the area throughput, i.e., the total throughput of all APs.
- We thoroughly explain how, in ECSR transmissions, the sharing AP and shared APs jointly determine the TX power and CSR Threshold for all APs. Currently, no prior work covers all aspects of CSR transmission for WiFi 7; they provide ideas and do simulations on a limited scale for CSR. To the best of our knowledge, this is the first work that proposes bidirectional multiple AP coordination and evaluates it in different simulation setups.
- We demonstrate the efficacy of our proposed algorithm in dense deployment situations. To do this, we test our algorithm in dense enterprise scenarios by randomly generating the position of the APs and STAs. We also compare our proposed algorithm with existing one-way CSR and the traditional CSMA-based access technique. Simulation results show the effectiveness of our algorithm in highly congested environment.

II. Related Work

Recent studies on CSR mostly come from the IEEE 802.11be Working Group (TGbe) documents. To maintain less than 10% packet error rate (PER) for the sharing AP and shared APs, shared APs optimize their TX power following the sharing AP's instructions [9]. However, if the distance between the shared AP and its associated STA is high, the modulation and coding scheme (MCS) will move downward to maintain the 10% PER, which impacts the data rate of the shared AP. The use of the acceptable receiver interference level (ARIL) at the STA the sharing AP intends to serve, to calculate the TX power for all shared APs, is proposed in [6]. However, limiting shared APs' TX power and utilizing the maximum TX power at the sharing AP may lower the number of parallel transmissions in each TXOP. CSR is combined with coordinated time division multiple access (C-TDMA) in [10], which boosts area throughput by 140%. Here, CSR plays a vital role for improving throughput, but how it makes sure that all APs have sufficient TX power is not covered. Therefore, finding a suitable TX power management method for CSR is still necessary.

To increase the number of simultaneously transmissions in overlapping regions, some studies propose transmission power control mechanisms by adjusting the carrier sensitivity threshold (CST). To find the optimal transmission power configuration, [11], [12], and [13] use machine learning (ML) techniques and achieve a significant improvement in area throughput by maximizing the number of parallel transmissions. However, these techniques are centralized by design; therefore, they cannot be employed when several APs maintained by different owners conflict with one another's transmission. How to choose the best sensitivity threshold and create a closed-form formula for the threshold that optimizes throughput is investigated in [14]. However, to make the issue tractable, only one MCS is employed and, as a result, only one fixed target SNR is considered.

Our work is unique in that we propose a bidirectional TX power control algorithm where the sharing AP determines the TX power for all APs who want to join the CSR transmission. Our proposed algorithm ensures the maximum parallel transmission by setting an appropriate CSR Threshold for all APs. Instead of having a fixed sharing AP, we propose that the AP that accesses the channel first as the sharing AP. Simulation results show that our proposed algorithm can significantly increase the area throughput in dense WiFi networks without affecting the data rate of shared APs.

III. The Proposed ECSR Protocol

To increase the number of concurrent transmissions by alleviating the inter-AP contention, we propose a new CSR algorithm, ECSR. In ECSR, the sharing AP collects information from all the APs that want to participate in ECSR to figure out the CSR Threshold and TX power for all the APs. It not only optimizes the TX power of the sharing AP, but also optimizes the TX power of shared APs, so that every ECSR-enabled AP participates in the transmission. Therefore, we refer to our proposed model as "bidirectional multiple AP coordination."

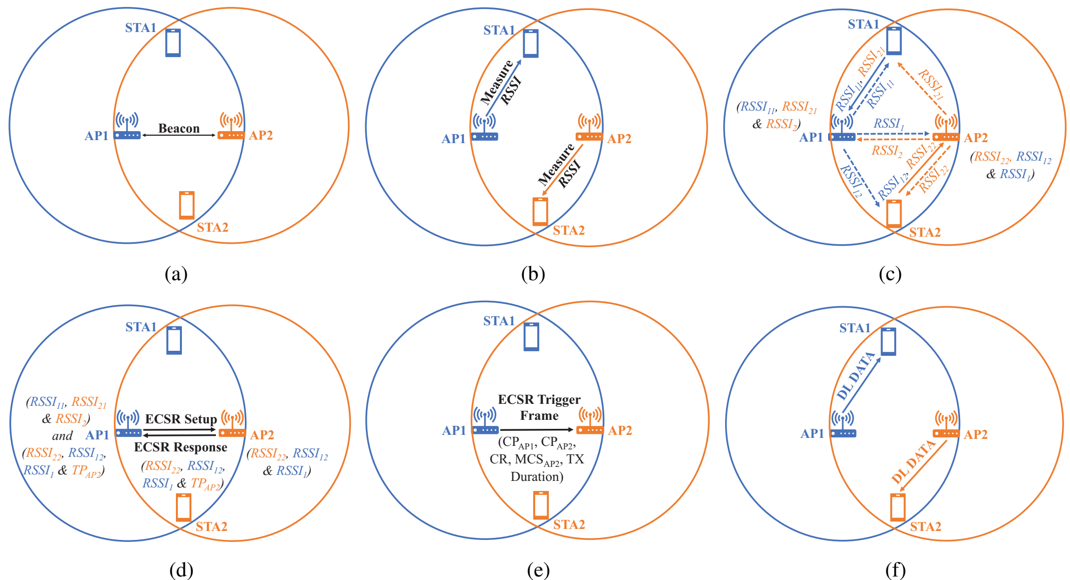

Fig. 2. The operation of the proposed ECSR: (a) ECSR capability announcement; (b) RSSI measurement instruction; (c) RSSI measurement and report; (d) ECSR announcement; (e) ECSR trigger and (f) ECSR data transmission.

A. ECSR Operation

In this section, we describe the operation of ECSR in detail. Each AP broadcasts a control message after joining a network to find other ECSR-enabled APs in its transmission range. Then, the AP, who accesses the channel first, initiates the ECSR. Each AP only follows the ECSR protocol when it detects an overlapping BSS (OBSS) transmission from another AP. The OBSS packet detection is specified in IEEE 802.11ax [15]. An AP follows the traditional CSMA-based channel access mechanism when no overlapping region exists.

We divide the operation of ECSR into six different steps. The details of each step are described below:

1) ECSR capability announcement: After joining the network, each AP broadcasts a beacon frame to find other ECSR-enabled APs. Thus, each AP gets its neighbor's AP list. In Fig. 2(a), AP1 and AP2 exchange a beacon frame with each other and share their ID in response. Thus, both APs identify each other as its neighboring ECSR-enabled AP.

2) RSSI measurement instruction: Each AP now shares the neighboring AP's list with their associated STAs and instructs them to measure the RSSI from their associated AP and neighboring APs. When a new AP joins the network, it follows the same procedure described above, and all APs update their neighbor list and share it with their associated STAs. If any AP leaves the network, the remaining APs again update the neighbor list and inform their associated STAs. In Fig. 2(b), AP1 shares AP1 and AP2's ID with STA1 and instructs it to measure the RSSI from AP1 and AP2. AP2 follows the same procedure and instructs STA2 to measure the RSSI.

3) RSSI measurement and report: Now, STAs start to measure the RSSI from all APs included in the list. The STAs measure the RSSI from ongoing transmissions of the APs. When APs request their associated STAs for RSSIs, STAs report all the measured RSSIs to their associated AP. When a significant change occurs in the RSSI due to the movement of STAs or any AP leaving the network, STAs share this updated RSSI with their associated AP. Each AP also measures RSSIs from its neighboring APs. In Fig. 2(c), STA1 measures RSSIs from AP1 and AP2; similarly, STA2 measures RSSIs from AP2 and AP1. Here, $RSSI_{11}$ denotes the RSSI at STA1 for AP1, $RSSI_{21}$ is the RSSI at STA1 for AP2, $RSSI_{22}$ is the RSSI at STA2 for AP2, and $RSSI_{12}$ is the RSSI at STA2 for AP1. On the other hand, $RSSI_1$ denotes the measured RSSI at AP2 for AP1, and $RSSI_2$ is the RSSI at AP1 for AP2. Then, STA1 and STA2 both share their measured RSSIs with the associated AP.

4) ECSR announcement: When an AP wins the channel, it initiates the ECSR transmission by sending a ECSR Setup frame to adjacent ECSR-enabled APs. Those APs, ready to join ECSR, respond by sending a ECSR Response frame. The AP who wins the channel is the sharing AP, and the other APs who reply are the shared APs. ECSR Response frame contains all the measured RSSIs by its associated STAs and the TX power of APs. Thus, the sharing AP collects all the link information (RSSIs) and the TX power of shared APs. In Fig. 2(d), when AP1 sends a ECSR Setup frame to AP2, in response, AP2 shares all the measured RSSIs by STA2 and its own TX power information.

5) ECSR trigger: After receiving all the RSSIs and TX power information from shared APs, the sharing AP calculates the CSR Threshold (CR) for all AP-STA pairs, which keeps the same for all AP-STA pairs in each TXOP. Then, the sharing AP determines the new TX power, called CSR TX power (CP), for all APs joining the ECSR transmission based on the CR so that they can transmit simultaneously without interfering each other. It also calculates the MCS and TX durations for all APs. Then, it sends a ECSR Trigger frame to all shared APs, which includes the ID of the sharing AP and shared APs, CP of the sharing AP, CP for shared APs, CR, MCS for shared APs, and TX duration. In Fig. 2(e), AP1 is the sharing AP, and it sends a ECSR Trigger frame to AP2 including all necessary information (CP_{AP1}, CP_{AP2}, CR, MCS_{AP2} and $TXDuration$) required for the ECSR transmission.

6) ECSR data transmission: Now, shared APs set their transmission parameters (TX power, MCS, and TX duration) as per instructions given by the sharing AP through the ECSR Trigger frame and start data transmissions. In Fig. 2(f), AP2 sets its transmission parameters after receiving the ECSR Trigger frame from AP1 and starts the data transmission to STA2. On the other hand, AP1 starts its data transmission to STA1 after sending the ECSR Trigger frame.

B. CSR Threshold and Transmit Power Calculation

In ECSR, determining an appropriate CR is significant because it sets the interference limit for all APs so that they can transmit but without interfering with each other. Here, the sharing AP determines the CR using the RSSI and TX power information collected from shared APs. After fixing the optimal CR, the sharing AP determines the CP for all APs by using this threshold. To do this, the sharing AP follows the below steps:

1) It first uses -82 dBm as the CR and calculates the CP for all APs by

$$CP_m = TP_m - max(RSSI_{ns_m}, RSSI_{na_m}) + CR, \quad (1)$$

where TP_m is the initial TX power for AP m, $RSSI_{ns_m}$ is the RSSI of neighboring stations for AP m and $RSSI_{na_m}$ is the RSSI of neighboring APs for AP m. Here, -82 dBm is the Clear Channel Assessment Carrier Sense (CCA/CS) threshold for IEEE 802.11, and APs only decode those signals above the CCA/CS threshold [15]. Therefore, the sharing AP selects -82 dBm as the initial CR, which sets the lowest tolerance limit for all APs.

2) Then, using this CP, the sharing AP computes the new RSSI (NRSSI) for all STAs by

$$NRSSI_{as_m} = CP_m - TP_m + RSSI_{as_m}, \quad (2)$$

where $NRSSI_{as_m}$ is the new RSSI of the STAs associated with AP m and $RSSI_{as_m}$ is the previous RSSI of the STAs associated with AP m.

3) Now, the sharing AP checks the interference for all APs in the following way:

$$NRSSI_{as_m} > NRSSI_{nap_m}, \quad (3)$$

where $NRSSI_{nap_m}$ is the new RSSI at STAs associated with AP m for the neighboring APs of AP m.

4) If all APs satisfy (3), the sharing AP returns to step 1, increases the CR, and repeats steps 1 to 3 until all APs meet (3). If any AP does not satisfy (3), the sharing AP selects previous value as the final CR.

To demonstrate the significance of the CR, we conduct an experiment considering five different 4-AP simulation scenarios (SS), where the positions of APs and STAs are randomly generated. Experimental results illustrated in Fig. 3 show that the area throughput decreases when the CR is low, and after a particular CR, it saturates. When the CR is low, all APs reduce their TX power, which impacts the overall throughput.

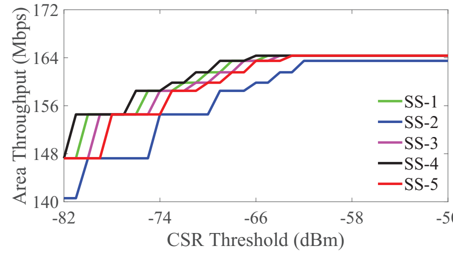

Fig. 3. The effect of CSR Threshold (CR) on area throughput.

In contrast, after a certain CR, all APs reach their optimal TX power. Therefore, the area throughput also reaches its maximum value. Fig. 3 also shows that the CR differs in different simulation scenarios. Therefore, instead of using a fixed CR, we propose that the sharing AP determines the CR in each TXOP.

IV. Throughput Analysis

To calculate the area throughput, the sum of the throughput achieved by all stations participating in ECSR transmissions, we propose an analytical model. A similar throughput analysis model is proposed in [10], but it does not consider the PER as in our model.

In traditional CSMA-based channel access (without AP coordination), when M number of APs, each has N_m associated STAs competing for accessing the channel, the throughput is

$$S = \frac{p_s N_b}{E[T]}(1 - PER), \quad (4)$$

where $p_s = M\tau(1-\tau)^{M-1}$ is the probability of a successful transmission happening in a backoff slot, τ is the transmission probability, N_b is the payload size in bits, and $E[T] = p_e T_e + \sum_{m=1}^{M}\sum_{n=1}^{N_m} w_{m,n} T_{m,n} + p_c T_c$ is the average duration of a backoff slot. Here, $p_e = (1-\tau)^M$ and T_e denote the probability and duration of an empty slot, respectively, $p_c = (1 - p_e - p_s)$ and T_c are the collision probability and duration of a collision slot, respectively. In addition, we define $w_{m,n}$ as the successful transmission probability of AP m, divided by the number of associated STAs, i.e., $w_{m,n} = \frac{\tau(1-\tau)^{M-1}}{N_m}$. We also designate $T_{m,n}$ as the successful transmission duration from AP m to its associated STA n that depends on their transmission rate.

To calculate the area throughput without CSR, we use (4), but for ECSR transmissions, we modify (4). In ECSR, only the sharing AP competes to win the channel, and other APs start their transmissions after receiving the ECSR Trigger frame from the sharing AP. Therefore, the number of contending APs, $M = 1$ and no collision between APs exists, i.e., $p_c = 0$. In addition, in each TXOP, only one STA is connected with its associated AP. Therefore, the value of the associated STAs with AP m, N_m is 1. Now, for (4), $N_b = M_{CR} N_b$, $p_s = \tau$, $p_e = (1-\tau)$, $w_{m,n} = 1$, and $E[T] = p_e T_e + p_s T_{CR}$, where M_{CR} is the number of participating APs in ECSR transmissions and T_{CR} is the total transmission duration of ECSR in each TXOP. Now, T_{CR} can be calculated by

$$\begin{aligned} T_{CR} = T_{RQ} + T_{SF} + T_{RP} + T_{SF} + T_{CF} + T_{SF} + \\ T_{LP} + max(T_D(R_{m,n})) + T_{AK} + T_{SF} + T_{DF}, \end{aligned} \quad (5)$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Channel Bandwidth [MHz]	160
Number of Spatial Streams	1
MCS for Control Frame	0
MCS for Data Frame	0 to 13
OFDM Symbol Duration [μs]	12.8
Guard Interval Duration [μs]	0.8
CW_{min}	15
N_b [Bytes]	1500
T_{LP} [μs]	20
T_{RQ} [μs]	40
T_{RP} [μs]	31
T_{CF} [μs]	38

where T_{RQ}, T_{RP}, T_{CF}, T_{SF}, T_{DF}, T_{AK}, and T_{LP} are the duration of ECSR Setup Request frame, ECSR Setup Response frame, ECSR Trigger frame, Short Interframe Space (SIFS), Distributed Coordinated Function Interframe Space (DIFS), Acknowledgement (ACK), and Legacy Preamble, respectively. The data transmission duration, T_D, depends on $R_{m,n}$, the transmission rate of AP m when it sends data to its associated STA n. The transmission duration of different APs for a fixed payload size may differ due to their different transmission rates, depending on the channel condition. Low transmission rates increase the data transmission duration. Therefore, after calculating the T_D for each AP separately, the sharing AP selects the maximum T_D.

V. PERFORMANCE EVALUATION

In this section, we evaluate our proposed ECSR's performance in both specific and randomly generated scenarios. We use the default path-loss parameters suggested for IEEE 802.11ax enterprise scenarios [16] and a 160 MHz channel bandwidth. For simplicity, we consider only the single input and single output (SISO) system and downlink transmission (from AP to its associated STAs). We designate the traditional CSMA-based access technique, which does not support multiple APs' transmissions, as NCSR. The CSR algorithm, which uses one-way coordination and only optimizes the TX power of shared APs, is defined as CCSR.

In our simulation, we assume that APs employ a single backoff stage. Therefore, according to the model proposed in [17], the transmission probability, $\tau = 2/(CW_{min} + 2)$, where CW_{min} is the minimum contention window size. The simulation parameters considered in this paper are shown in Table I.

A. Fixed Simulation Scenario

We consider a dense WLAN scenario, as mentioned in Fig. 4, where each AP is placed at the center of a $10m \times 10m$ room, and only four APs use the same frequency channel to transmit and receive data. Here, all the four APs are within the transmission range of each other. For simplicity, we assume that each AP has only one associated STA placed at the location shown in Fig. 4. Now, we compute the area throughput for NCSR, CCSR, and ECSR. Fig. 5 shows a comparison between these three protocols.

Insights: The area throughput of the ECSR is about three times higher than the NCSR. In NCSR, when one AP transmits, other APs must wait as they are in the transmission range of each other. In contrast, ECSR allows all APs to transmit simultaneously by setting a proper CR. On the other hand, the throughput of CCSR is the lowest among the three. Two factors are mainly responsible for the poor performance of CCSR. Firstly, in CCSR, only the sharing AP transmits at its maximum power, whereas shared APs optimize their TX power to protect the sharing AP's transmission. Therefore, when multiple APs are close to each other, i.e., in a highly dense WLAN environment, STAs associated with shared APs get low SNR and cannot join the CSR transmission because of interference from the sharing AP. Secondly, the sharing AP does some extra operations to set the transmission parameters of shared APs, which reduces the sharing AP's throughput. Therefore, instead of using a fixed sharing AP, selecting the AP that accesses the channel first as a sharing AP is better.

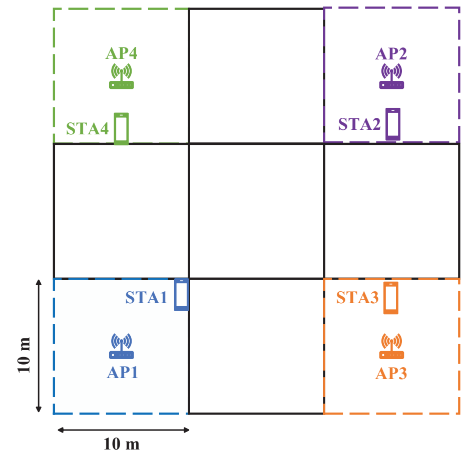

Fig. 4. An dense enterprise WLAN scenario, where four APs using the same frequency channel, and within the transmission range of one another.

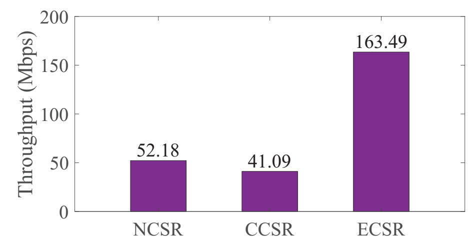

Fig. 5. Area throughput comparison between NCSR, CCSR and ECSR in each TXOP.

B. Randomly Generated Scenarios

We evaluate our algorithm in unknown scenarios by randomly generating the positions of APs and STAs inside their designated rooms. We create 10^5 different deployment settings and measure the area throughput of both ECSR and NCSR for every setting. To check the possibility that STAs associated with shared APs suffer from poor throughput, we also evaluate per-station throughput.

1) Impact of increasing overlapping APs on area throughput: We increase the number of overlapping APs from 2 to 4 and compute the area throughput of both ECSR and NCSR for each case. We create 10^5 different deployment settings for

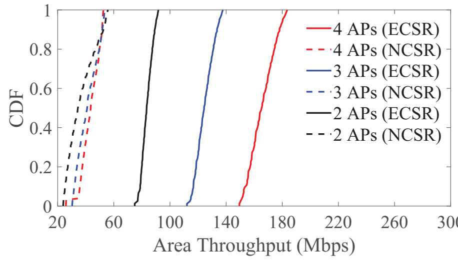

Fig. 6. The impact of increasing the number of overlapping APs on area throughput.

each case by randomly placing APs and STAs. Fig. 6 shows the outcome of our simulation results.

Insights: Fig. 6 shows the Cumulative Distribution Function (CDF) of the area throughput of both ECSR and NCSR. When the number of overlapping APs increases, the area throughput of ECSR also increases as it allows all APs to transmit simultaneously. On the other hand, the area throughput of NCSR is lower than ECSR and follows a similar trend in all the three cases. In NCSR, when the number of overlapping APs increases, it increases the inter-AP contention and co-channel interference, which forces other APs to wait, and only the AP who wins the channel transmits, which reduces the area throughput. Therefore, in dense WLANs where the number of overlapping APs is high, our proposed ECSR performs better than the existing NCSR.

2) Impact of ECSR on station's throughput: We conduct another simulation by placing four different APs at the center of four different rooms and randomly generating the positions of their associated STAs. For simplicity, we consider only one STA connected with each AP. We also assume AP1 is the sharing AP, and STA1 is associated with AP1. In this case, we also create 10^5 different deployment settings and measure the per-station throughput for each setting. Fig. 7 illustrates the throughput of each STA in each different setting.

Insights: The CDF of per-station throughput illustrated in Fig. 7 shows that all STAs follow a similar trend, and there is no significant degradation in STA throughput. The STA's throughput associated with the sharing AP might suffer as the sharing AP does some extra operations to fix the transmission parameters of shared APs. However, our simulation results show that the throughput of STA1 associated with the sharing AP also follows a similar pattern to that of other shared APs. Here, the main contributing factor is the low overhead of ECSR because the sharing AP only uses the RSSI and TX power information collected from shared APs and its own associated STA to set the transmission parameters for all APs.

VI. Conclusion

In this paper, we developed a bidirectional CSR algorithm by selecting an appropriate interference tolerance limit for all APs and stations participating in CSR transmission. Instead of using a predefined interference tolerance limit, the sharing AP collaboratively determines the appropriate limit for all APs and STAs in each TXOP. Then the sharing AP uses this interference limit to calculate CP for all APs. Using an appropriate interference limit instead of optimizing the transmission

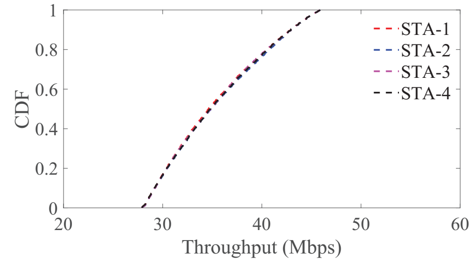

Fig. 7. The throughput of stations participating in ECSR transmission.

range of shared APs increases the number of simultaneous transmissions. We evaluated our proposed algorithm in fixed and randomly generated enterprise scenarios. Our study showed that ECSR performs better than existing CSMA-based channel access techniques and conventional CSR. Finally, using the RSSI and TX power information collected from shared APs to determine the CR and CP will reduce transmission overhead.

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