Coordinated SR and Restricted TWT for Time Sensitive Applications in Wi-Fi 7 Networks

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***Abstract*—The main focus of every new Wi-Fi generation was to increase the overall network throughput capabilities. This paradigm changed somewhat with the introduction of Wi-Fi 6, where new features were introduced that, in addition to throughput increase, dealt with improving the efficiency of resource usage and channel access as well. These features included uplink /downlink orthogonal frequency-division multiple access (UL/DL OFDMA), UL/DL multi-user multiple-input and multiple-output (MU-MIMO), and basic service set (BSS) coloring. With the advent of Wi-Fi 7, also known as IEEE 802.11be, more coordination is foreseen between different access points (APs), bringing the possibility to support time-critical traffic in wireless networks as well. Boosted coordination between APs improves the throughput under dense deployed Wi-Fi networks as well as gives support for prioritized channel access for certain devices and traffic flows. In this paper, we will review coordinated spatial reuse (C-SR) and restricted target wake time (R-TWT) as two features that are going to be introduced in Wi-Fi 7. Further, this paper shows conceptually how the C-SR feature can be implemented in practice. We show the results of a real implementation of both features (C-SR and R-TWT) on top of the openwifi open-source software-defined radio platform.**

***Index Terms*—coordinated spatial reuse (c-SR), R-TWT, openwifi, Wi-Fi 7, IEEE 802.11be**

I. Introduction

Wireless networks are continuously evolving to fulfill the ever-increasing quality of service (QoS) of demanding applications in terms of achieved throughput, reduced latency and jitter, and improved reliability. The main driving force of innovation in the previous Wi-Fi standards (pre Wi-Fi 6) was focused on achieving higher physical data rates to support throughput-hungry applications such as video-conferencing, video-streaming, gaming, and later on virtual reality (VR), eXtended reality (XR). Latency requirement is another relevant parameter for both throughput-hungry applications as well as industrial automation, robotics, and other real-time applications [1]. In addition to meeting demand requirements, wireless networks got deployed denser, posing a high challenge in interference management and efficient spectrum usage.

With the introduction of Wi-Fi 6, new features are supported (uplink /downlink orthogonal frequency-division multiple access (UL/DL OFDMA), UL/DL multi-user multiple-input and multiple-output (MU-MIMO), and basic service set (BSS) coloring) that improve the efficiency of spectrum usage, decrease the channel access overhead and give more coordination inside the BSS to the access point (AP) [2]. To further enhance spectrum efficiency, Wi-Fi 7 (the first draft was released in March 2021, while the final draft is expected by mid-2024) is expected to standardize increased coordination between APs, enabling even time-sensitive applications to benefit. Multi-AP coordination is foreseen for spatial reuse (C-SR), OFDMA (C-OFDMA), and beamforming (C-BF) [3]. While C-OFDMA deals with supporting OFDMA for different overlapping BSS (OBSS) devices at the same time [4], C-BF enables concurrent transmissions from different APs ensuring spatial radiation nulls at the targeted client stations (STAs) [4]. C-SR allows multiple devices (APs or STAs) in the network to transmit in parallel utilizing different transmit power and packet detection thresholds. With more coordination between the APs from different OBSSs, interference due to network densification is managed better, boosting up the overall network throughput.

The target wake time (TWT) was introduced to preserve the battery lifetime of STAs by allowing them to go to sleep for longer periods [5]. In addition, TWT is seen as a way of giving coordinated channel access to specific traffic flows, such as time-critical flows. In Wi-Fi 7, in addition to multi-AP coordination, the restricted TWT (R-TWT) is another feature that will be available to provide dedicated and protected channel access for time-sensitive flows [6].

In this work, we present the low-overhead support of R-TWT by utilizing the time synchronization and scheduling mechanism in openwifi [7]. openwifi is a software-defined radio (SDR) platform that implements the IEEE 802.11 standard, which is widely known by its commercial name Wi-Fi. We describe the concept of region-based C-SR and its implementation in openwifi platform, the first opensource 802.11 baseband SDR platform [8]. We show also the achieved results. In the case of R-TWT, we focus on achieved end-to-end latency as a key performance indicator (KPI) while in the case of C-SR, we focus on overall system throughput increase.

The remaining of the paper is composed as follows: section II gives a tutorial for R-TWT and C-SR features in Wi-Fi, section III presents the concept implementation of both R-TWT and C-SR mechanisms in openwifi platform, section IV describes the test setup and gives results on achieved latency and system throughput, while section V concludes the paper.

II. Wi-Fi Features for time sensitive applications

Supporting time-sensitive applications over wireless networks based on Wi-Fi presents several challenges due to the inherent characteristics of Wi-Fi itself. First of all wireless channel is a shared medium and the opportunistic channel access mechanism in Wi-Fi provides no guarantee of deterministic communication. In addition to this, in case of dense network deployment and congestion, no guarantee can be given for time-sensitive applications.

Some of the new features that are being introduced in Wi-Fi 7 are centralizing the coordination logic towards the APs. As such, in this section, we will give an introduction to the (R)-TWT and (C)-SR mechanisms according to standards and targeted standard proposals. To fully utilize such features for time-sensitive applications in practice some challenges remain: e.g. what will be the C-SR algorithm to select to which devices to transmit, should C-SR mechanism search for all devices of the BSS or this search can be limited to specific regions, how to achieve R-TWT service periods (SPs) organization in BSS, how to achieve coordination between APs etc.

A. Restricted Target Wake Time (R-TWT)

Power-saving mechanisms for Wi-Fi STAs were introduced since the IEEE 802.11 original standard where STAs slept between one or multiples beacon transmissions. The introduction of TWT in IEEE 802.11ah and adoption by IEEE 802.11ax [5] improved the network operation in two directions. On the one hand, it offered a mechanism to reduce power usage for the STAs, while on the other hand, it offered the possibility for the AP to decrease the contention in the network by assigning TWT SPs to a specific STA and traffic flow.

The TWT mechanism is composed of the negotiation phase and the operation phase [9]. During the negotiation phase, the STA negotiates and agrees with the AP regarding the TWT SP. A TWT agreement can be *explicit* (when TWT parameters need to be negotiated before each SP) or *implicit* (when the same set of TWT parameters is used for periodic openings of TWT SP). During the operational phase, for UL communication the TWT SP can be *triggered* or *non-triggered* based. In the case of the former one, the AP will send a trigger at the start of the TWT SP to organize the channel access of each STA during the TWT SP, while in the latter one, all the assigned STAs in the TWT SP transmit data in UL without waiting for the trigger frame.

Even though the TWT can give some channel access prediction, it can not avoid channel busyness from any ongoing transmission that has started before the TWT SP. To account for such cases, IEEE 802.11be is introducing the concept of R-TWT. In the R-TWT case, all the STAs that are not part of the R-TWT SP need to finish their transmission opportunities before the R-TWT SP starts [6].

To protect the R-TWT SP from possible interference from legacy Wi-Fi devices, AP sends a null frame with a duration identifier as long as R-TWT SP will last. As such, all the legacy Wi-Fi devices will declare the channel busy for the period of R-TWT SP.

B. Coordinated Spatial Reuse (C-SR)

The probability of parallel transmissions in different OBSSs is increased in dense network deployment. Depending on the positions of the concurrent transmitters and their respective concurrent receivers such parallel transmissions can be all successful. However, based on the normal Wi-Fi channel access procedure used, many such parallel transmission opportunities can be missed in such scenarios. For example, even though multiple respective concurrent receivers are not interfered by the respective parallel transmissions, the parallel transmission can not start if any of the transmitters has detected the channel busy due to any other transmission.

Wi-Fi channel access mechanism has three indicators to classify a channel as busy [10]:

- **Energy detection**: whenever a device detects a signal with energy higher than -62 dBm, the channel is regarded as busy for the duration of signal transmission
- **Packet detection (PD)**: whenever a device detects a Wi-Fi packet preamble in the channel, the channel is regarded as busy for the duration specified in the preamble. The minimal PD threshold is set at - 82 dBm.
- **Virtual carrier sense**: is achieved by stopping any transmission based on the network allocation vector (NAV) length of any packet that could be decoded correctly. The channel is regarded as busy for the duration of the NAV.

In the IEEE 802.11ax standard, a new feature to distinguish between channel busy events by BSS and OBSS packet transmission is introduced. The so-called *BSS color* is a unique 6-bit ID that is added to the signal field of physical header [5]. As such, each device can determine if the packet originated at its BSS or in another OBSS and can treat channel's busy events differently. Device sets two different PD thresholds. An OBSS-PD threshold higher than the minimal PD threshold (-82 dBm) allows the device to ignore certain OBSS transmissions and continue its back-off procedure or start with the transmission.

The SR mechanism is a distributed mechanism and each device decides when and where to use it. During concurrent transmissions, one of the concurrent transmitters uses the full transmit power while others decrease their transmit power. Such an approach does not offer the best combination possible. During the initial standardization phase of IEEE 802.11be there have been proposals to support the coordination of SR by exchanging data between the OBSS APs.

The description of the C-SR in this paragraph will be based on the proposals during the standardization phase of IEEE 802.11be. In [11] authors propose a C-SR procedure for communication in DL. An AP that has won the transmission opportunity (*sharing AP*), based on the measurements of the interference level on the receiving STA, can decide to share the transmission opportunity with another OBSS AP (*shared AP*). The *sharing AP* will determine the transmission power for the *shared AP* based on the received signal strength indicator (RSSI) known at the receiving STA. This information is shared between the *sharing AP* and *shared AP* with a C-SR trigger frame. In [12] authors propose a UL/DL C-SR procedure, where the *sharing AP* schedules transmission in UL from its STAs, while *shared AP* transmits in DL. Even in this case the transmit power of the *shared AP* is determined by the *sharing AP* and is informed using the C-SR trigger frame. For the UL-DL C-SR and UL-UL C-SR cases, measurements from all devices in the OBSS are required, which complicates the procedure of selection of the concurrent transmitters.

Similar to the R-TWT mechanism, C-SR can be interfered by legacy Wi-Fi devices. Legacy Wi-Fi devices from BSS of *sharing AP* will not transmit as the AP has won the transmission opportunity already. However, for other legacy Wi-Fi devices that reside in the BSS(s) of *shared AP(s)* similar null frame as in the case of R-TWT can be used and needs to be broadcasted by the *shared AP(s)*.

III. C-SR and R-TWT support in openwifi

To support the requirements of a demanding application (high throughput and/or low latency communication), new Wi-Fi features can be employed. While R-TWT can be used to give dedicated channel access for time-sensitive traffic flows, C-SR can be used to improve the overall system throughput in dense scenarios. In this section, we will give the conceptual design for the centralized DL C-SR mechanism and R-TWT support in openwifi.

A. R-TWT service period centralized assignment

To assign dedicated SPs to certain devices and traffic flows, one can use absolute time synchronization between wireless devices. openwifi platform supports accurate time synchronization [7] and scheduling [13] over the air. Synchronization accuracy achieved utilizing the precision time protocol (PTP) over wireless is 1.4 μs [7] enabling shorter guard interval before R-TWT SPs compared to default relative synchronization used in legacy Wi-Fi. Moreover, the PTP overhead is low, with configurable update intervals between 2 and 10 seconds [7].

A centralized network controller assigns R-TWT SPs for respective STAs/traffic flows based on the application requirements. In openwifi there is no need for quiet intervals or management of transmission opportunities for each STA by the AP, as all the STAs are accurately time synchronized, and their transmissions are fully scheduled. R-TWT SPs can be used by STAs for time-critical traffic to support deterministic communication latency. In such a case the maximum communication latency will depend on the repetition period of the SPs, given that the generation time of the packet is not synchronized with the SP and can happen at any time. Currently, only periodic R-TWT SPs are supported by the implemented scheduler, when latency requirements are multiple of each other. It is clear that if the latency requirements are not multiple of each other there will be R-TWT SPs when transmissions from different STAs will overlap. To avoid packet collision in such case a solution is to determine the period at which such overlap will happen and then shift one time slot compared to the other. Such a shift can be done based on STA priority or dynamically based on the generation time of the packets that are ahead of the queue. Another possibility is the Earliest Deadline First (EDF) scheduling similar to scheduling applied in time-sensitive networking [14].

B. Centralized C-SR algorithm

In this subsection we will describe the centralized C-SR algorithm implemented in network controller. The first phase of the centralized DL C-SR algorithm is the collection of the RSSIs at each STA. Each STA monitors all the beacons from each overhearing OBSS AP and creates a table with averaged RSSIs of the beacons received in the last 2 seconds from each AP. This information is shared using the in-band network telemetry (INT) [15] with the central controller. The overhead is limited to additional bytes to data packets: 8 bytes of INT [15] header and 1 byte per RSSI.

In the second phase, the centralized DL C-SR algorithm determines the transmit power of the concurrent transmitters in DL and the MCS indexes used for each concurrent transmission. The transmit power of all the *shared APs* is defined based on the interference levels that those APs cause on the receiver (*main receiver*) of the *sharing AP*. By reducing the transmit power of *shared APs*, the algorithm makes sure to have an interfering level smaller than the PD threshold (-82 dBm) in the *main receiver*. As such, the *main receiver* does not get locked on transmissions from OBSS APs. Simultaneously, the *main receiver* uses the highest possible MCS index based on its signal-to-interference and noise ratio (SINR) level, determined as the difference between the RSSI from the *sharing AP* and the PD threshold.

For any parallel transmissions from *shared AP* towards its respective chosen STA (*concurrent receiver*) the SINR is calculated as the difference between the measured RSSI from the *shared AP*, corrected for the transmit power reduction in *shared AP*, and the measured RSSI from the *sharing AP*:

$$\begin{aligned} SINR_{concurrent-receiver} &= \\ = (RSSI_{shared-AP} - R_{Tx}) &- RSSI_{sharing-AP} \end{aligned} \tag{1}$$

where R_{Tx} is the transmit power reduction in shared AP.

In case when there are multiple *shared APs*, if in specific *concurrent receiver* the RSSI difference from another *shared AP* is higher than from the *sharing AP*, the SINR is calculated as follows:

$$\begin{aligned} SINR_{concurrent-receiver} &= \\ = (RSSI_{shared-AP} - R_{Tx}) &- \\ -max(RSSI_{sharing-AP}, RSSI_{shared-AP}) \end{aligned} \tag{2}$$

where $max()$ is the maximum of all RSSI from the other *shared APs* and *sharing AP* during the same time period.

For each pair of *main receiver* and *concurrent receiver*, the SINR can be calculated and thus the MCS index can be determined. *Concurrent receivers* can be selected only if the SINR is higher than 0 for given *main receiver*.

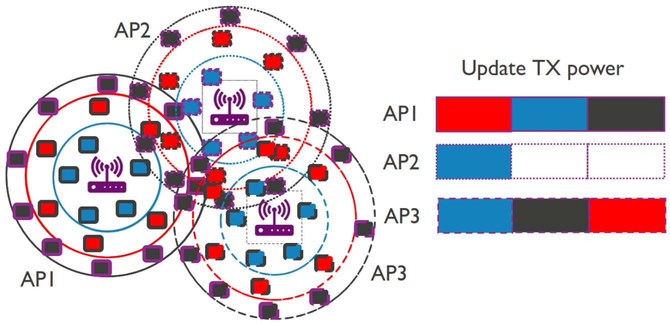


Fig. 1: Region based C-SR. STA color determines the region while its contour determines serving AP.

C. Region based C-SR

In cases when STAs and APs do not use multiple antennas and do not support beamforming, one has to take care of proper scheduling of concurrent transmissions between different APs. To overcome scanning for all the possible concurrent STAs and simplify packet queuing in such cases, we separated BSS coverage into regions. In a typical C-SR scenario, the *shared AP* must scan its entire set of STAs to identify the STA that would optimize the overall throughput. Some STAs can be excluded from this search if they are known to experience high interference from the *sharing AP*. To streamline this process and reduce the number of STAs that need to be examined, we define distinct regions within the BSS that can be addressed during specific C-SR opportunities. The STA's region is determined based on the RSSI reports and does not need to be known by STA itself. Network controller will determine the RSSI thresholds for each region based on the interference levels from other APs as well.

This approach aids in organizing packet queues within the AP based on the region of the STA to which the packet is intended. Thus, the number of regions per AP should not exceed the number of hardware queues that platform supports. Given the fact that the *main receiver* is located in a certain region of the *sharing AP*, we can select *concurrent receiver(s)* only from certain regions of the *shared AP(s)* that match the concurrency transmission. This can be seen as scheduling problem, where certain queues can or can not be served at the same time at different APs. As shown in Figure 1 when the *main receiver* is from the red region in BSS 1, then the *concurrent receivers* can be chosen only from the blue region of BSS 2 and 3. The blue region in BSS 2 and 3 will not be interfered by the transmission from BSS 1. Also the transmission of BSS 2 and 3 to the blue region should have reduced power to not interfere with the red region of BSS 1. Thus the red region of BSS 1 and the blue regions of BSS 2 and 3 are served at the same SP in the communication schedule. The communication schedule shown in Figure 1 is not exhaustive but just a possible combination.

Once each STA is assigned to one of the regions, we can do C-SR scheduling based on regions where each region is assigned a single queue in the APs. Then multiple queues from different APs can be served concurrently based on the C-SR parameters determined for the chosen *concurrent receiver* as shown in the schedule in Figure 1.

D. Implementation

Both mechanisms in openwifi are used to support each other. R-TWT SP scheduling is used also for aligning concurrent transmissions once the C-SR mechanism is enabled.

R-TWT scheduling is implemented as cyclical scheduling of SPs for specific queues in specific STAs. R-TWT SPs are organized in a repetition period between 512 μs and 65536 μs, while the smallest R-TWT SP can be 128 μs. All the nodes share the same repetition period for R-TWT SPs, while R-TWT SPs can be dedicated or shared. The R-TWT SP interleaving offsets inside the schedule are calculated based on latency requirements of each application.

The network controller determines also the C-SR concurrent receivers given a specific main receiver. Once the pairs of main receiver and concurrent receiver(s) are determined, the communication times in DL are scheduled in the same SP from all APs. In addition to this, for each SP the transmit power is determined as well as the MCS index to be used during that SP. Such information is disseminated to all APs and openwifi physical layer is instructed to update the transmit power and MCS index on an SP basis.

IV. Experimental Setup and Results

To validate the benefits of using R-TWT SPs for time-critical traffic and C-SR for improved system throughput we conducted several tests in IDLab Industrial IoT testbed. All the wireless devices were openwifi nodes supporting R-TWT scheduling and C-SR. In the case of R-TWT measurements, the network topology consisted of one AP, 4 STAs, the network controller, and one wired node. STAs were distributed around the AP between 2 to 3 meters, as the transmit power of the development platform was only -17 dBm (very low). In the case of C-SR measurements, the network topology consisted of three APs and two STAs per each AP located in different regions (near the main AP and in the zone between APs). In the C-SR case, APs were located at the same height and were distributed on corners of an equilateral triangle with a distance between them $\sim$ 7m. For AP we used Zynq ZCU 102 boards, while for STAs we used Zedboard to run openwifi. For each case, we describe the traffic flows present in the network and show the achieved performance in terms of end-to-end latency and overall system throughput, respectively.

A. R-TWT Results

For R-TWT SP scheduling we had a mixed UL/DL scenario consisting of industrial traffic flows: one programmable logic controller (PLC) traffic flow in the UL, and three unidirectional voice traffic flows in the DL. This measurement test aimed to show that the end-to-end latency requirements for each traffic flow can be maintained using separate R-TWT SPs scheduling.

The PLC traffic flow generated one 200-byte packet every 16 ms, resulting in a 100 Kbps data rate. The voice traffic

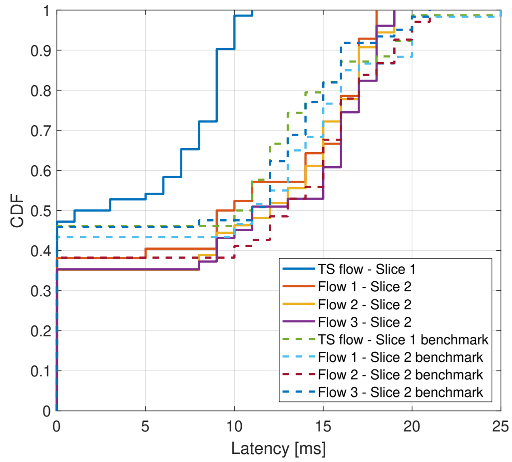


Fig. 2: End-to-end latency CDF for each traffic flow (dashed lines show the benchmarking case for each traffic flow)

flows were emulated using IPERF with 2 Mbps data rate each and a packet size of 500 bytes. The end-to-end latency for PLC and voice traffic flows is required to be smaller than 10 ms, and 20 ms, respectively. The physical data rate was fixed for both AP and STAs at 26 Mbps.

A cyclical schedule for SPs was assigned to the AP and the STAs. Part of the air time was used for control traffic and for PTP traffic. A dedicated R-TWT SP of 128 μs every 8 ms was assigned for PLC traffic flow (slice 1), and a shared R-TWT SP of 7680 μs every 16 ms was assigned to AP for all the three voice traffic flows (slice 2). To benchmark the results when no R-TWT SPs are used all the traffic flows (PLC and voice traffic flows) are scheduled at a shared SP of 7936 μs every 16 ms, competing with each other for channel access. This ensures that channel capacity assigned to all the traffic flows is 49% in both cases. By assigning all the traffic flows in a shared SP it is the same as there will be no TWT case. Moreover, this ensures the fairness in capacity allocation in both cases and ensures that PTP traffic is not mixed with traffic under test, keeping the same synchronization accuracy.

Figure 2 shows the cumulative distribution function (CDF) of the latency for each flow for both cases. When R-TWT SPs are used, all the latency requirements can be met for each of the flows. As shown in Figure 2, in 99% of the cases the latency for PLC traffic is smaller than 10 ms (time-sensitive flow with solid line), and in 100% of the cases, the latency for voice traffic flows is smaller than 20 ms (flow 1 to 3 with solid lines). On the other hand, when R-TWT SP is not used and all the traffic flows share the same SP, this fulfillment drops to 48% for PLC traffic flow (time-sensitive flow with dashed line), and to 93% for voice traffic flows (with some flows even below 90%), as shown by dashed lines for flow 1 to 3 in benchmark case in Figure 2.

B. C-SR Results

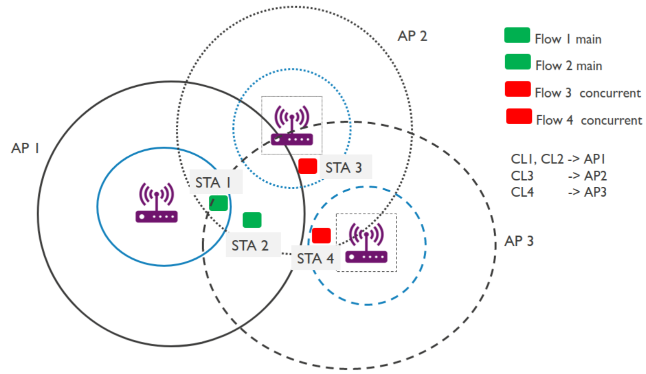
In the case of C-SR measurements, we focused on the overall achieved system throughput as the main KPI. The network topology of the two tests we did is shown in Figure 3, where concurrent receivers (STA 3 and STA 4, respectively) are placed in the inner zone between APs (Figure 3a) and in the outer zone of the APs (further away from AP1, Figure 3b). Each AP in the setup classified STAs in two main regions: the nearby region ($RSSI > -50dBm$) and the faraway region ($-82dBm \leq RSSI \leq -50$). STAs 1 and 2, located in the nearby region and the faraway region, respectively, were selected as the main receivers. This means that AP 2 and AP 3 will adapt transmit power during the parallel transmission.

R-TWT SP scheduling mechanism was used to schedule concurrent transmissions from each AP. As such, we gave a 5.120 ms SP for each traffic flow 1 and 2, going from AP 1 to STA 1 and STA 2, respectively. These SPs were scheduled every 16.384 ms. The rest of the air time was used for PTP and control traffic. At the same absolute time as the SPs assigned for traffic flow 1 and 2, we assigned 2 SPs of 5.120 ms, for traffic flow 3 and 4, going from AP 2 and 3 to STAs 3 and 4, respectively. All the traffic flows were generated using IPERF UDP and TCP traffic flows, respectively. We always asked for the highest application layer data rate based on the selected MCS by the C-SR algorithm and the share of the air time given to specific traffic flow. As such, the system was tested under stress conditions near the capacity maximum.

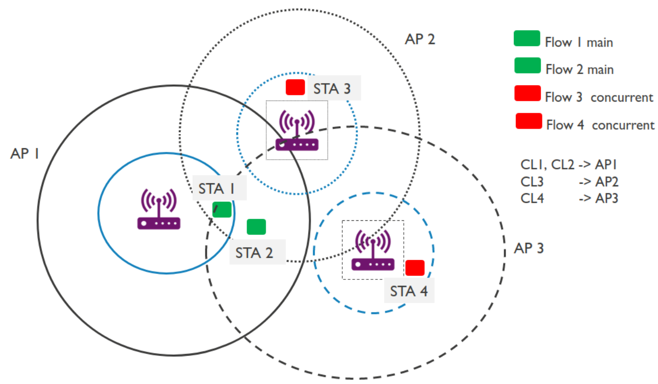
To benchmark the results taken with the C-SR algorithm, for the same network topology we disable the C-SR mechanism, while all the 4 traffic flows were transmitted during the same SPs. For the MCS index selection, we tested several cases: the MCS index for each flow was fixed to the highest one possible as if traffic flows were sent alone, the MCS index was left to be adapted dynamically by the minstrel algorithm and the MCS index was fixed to the lowest one. We also did measurements for UDP traffic flow and TCP traffic flow.

Results for achieved overall system goodput with C-SR and the benchmark cases without C-SR are shown in Figure 4. When considering the overall system goodput, C-SR demonstrates superior performance compared to all other scenarios. Specifically, for UDP and TCP traffic, it achieves a 20% and 800% increase, respectively, in goodput when compared to the case where a fixed highest MCS is utilized. Additionally, in comparison to the scenario employing dynamic MCS, C-SR results in a 33% increase for UDP traffic and a 850% increase for TCP traffic in terms of goodput. This is for the case when the concurrent receivers are placed in the inner zone of the APs. If the concurrent receivers are located in the outer zone, the improvement is even higher.

In Figure 4b, it is evident that C-SR surpasses all other scenarios. Specifically, for UDP traffic flows, it exhibits a 50% improvement compared to the cases involving a fixed highest MCS index or dynamic MCS index. When dealing with TCP traffic flows, the performance boost is even more remarkable, with C-SR achieving an 850% increase compared to the scenario with a fixed highest MCS index and a 960% improvement compared to the scenario with a dynamic MCS index. The significant increase in the case of TCP is attributed to the behavior of the congestion control mechanism. Because



(a) Concurrent receivers placed in the inner zone



(b) Concurrent receivers placed in the outer zone

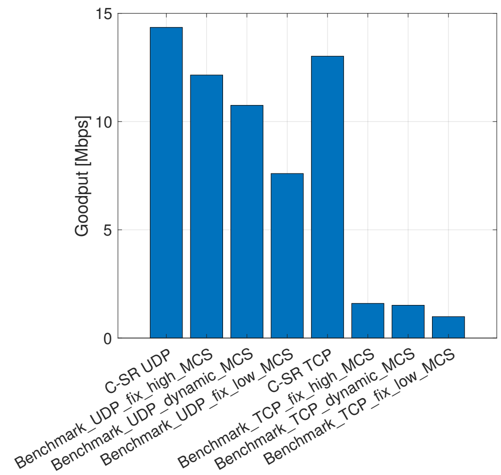
Fig. 3: C-SR measurement network topology setup

of this mechanism, as the packet loss ratio rises due to absence of C-SR, TCP's congestion control logic will decelerate the transmission of packets, leading to an overall reduction in the system throughput.

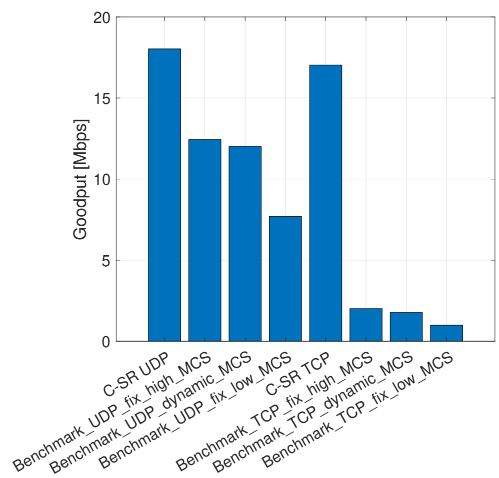
V. Conclusions

With the new features being introduced in upcoming IEEE 802.11be, like R-TWT and C-SR, the efficiency of resource usage as well as channel access efficiency is increased. In addition to the power-saving mechanism for end stations, the R-TWT mechanism can be used to support dedicated and protected channel access for time-critical traffic flows. Next to this, the C-SR mechanism will improve spectrum usage efficiency increasing the overall system throughput, by employing multiple parallel transmissions with optimized MCS index and transmit power.

In this paper, we gave a short tutorial on R-TWT and C-SR and how they are considered to be included in the standard. Next to this, we showed the design concept of such features in openwifi platform making use of accurate time synchronization and scheduling for R-TWT and on-time-base transmit power and MCS index adjustment for C-SR. The coordination of such features is not straight forward. We have achieved this by employing accurate time synchronization between devices and scheduling of SPs from a central network controller. We showed the initial results regarding the ability



(a) Concurrent receivers placed in the inner zone



(b) Concurrent receivers placed in the outer zone

Fig. 4: Overall system goodput for C-SR and benchamrking case

of latency requirement fulfillment when R-TWT scheduling was employed for time-critical traffic flows as well as overall goodput increase (between 20% and 50%) in the case of C-SR usage when UDP traffic flows were used. In case of TCP traffic flows the increase in overall goodput was between 800% and 960%, due to negative impact of congestion control mechanism under congested wireless links. Nevertheless, there are still open questions about how such features can be brought into real deployment. C-SR case scheduling for each STA might not be feasible, thus we showed a region-based approach. However, the granularity of concurrent STA choices decreases with the number of regions. In addition to this, sectorial-based scheduling might further improve the overall performance as was shown by changing the position of the STAs in the same region but different sectors. For R-TWT scheduling time synchronization between the devices as well as the ability to maintain a schedule for a longer time is a crucial challenge, to decrease the overall scheduling overhead.

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