Exploiting Overlapped Bands for Efficient Broadcast in Multi-channel Wireless Networks

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Abstract—In wireless networks, broadcasting is a fundamental communication primitive for network management and information sharing. However, in multi-channel networks, broadcast efficiency is very poor as devices are distributed across various channels. Thus, a sender tries all channels to broadcast a single message, causing large overhead. In this paper, we propose a novel, drastically different scheme for efficient broadcast in multi-channel networks. Our scheme leverages an overlapped band of adjacent channels, the frequency range that partially overlapped channels share within their channel boundaries. Specifically, a sender advertises a rendezvous channel through the overlapped band of adjacent channels; message sharing is done on the rendezvous channel. Our scheme employs Signaling via Overlapped Band (SOB), which defines a new signal processing mechanism for communication via the overlapped band. SOB is integrated with the following MAC layer mechanisms: 1) Reserve Idle Spectrum Fragment (RISF) to reduce waiting time, 2) Multi-sender Agreement on Rendezvous CHannel (MARCH) to support multi-sender broadcasts, and 3) Reinforce Switch Notification (RSN) to reduce the residing time at a wrong channel. Our scheme can also be integrated with two remarkably simple but efficient mechanisms for improving PDR and reducing delay in a multiple contention domain. We implemented our scheme on the SORA software radio platform. Experimental results validated communication through the overlapped band. Intensive simulation studies showed that our scheme dramatically outperformed a previous approach.

Index Terms—802.11 Wi-Fi, overlapped band, multi-channel wireless network, broadcast

I. INTRODUCTION

Currently, explosive increase in the use of mobile devices (e.g., smartphones, tablet PCs, and laptops) has expanded the demand for Wi-Fi services. To meet this demand, Wi-Fi devices must exploit multiple channels. In a 2.4GHz ISM band, IEEE 802.11g [1] defines 13 channels, of which a maximum of three channels (e.g., 1, 6, and 11 in U.S.A.) are orthogonal. However, it is difficult to fit all Wi-Fi users into only three channels in a densely populated area [2]. Moreover, it is hard to manage the channels of private Access Points (AP) and mobile devices. Thus, despite Adjacent Channel Interference (ACI), using adjacent, non-orthogonal channels (i.e., partially overlapped channel) is inevitable. Previous research has supported the validity of this argument. For example, the authors in [3] showed that APs exploited non-orthogonal channels through measuring AP deployments. In addition, several previous works have indicated that using non-orthogonal channels with careful network settings (e.g., power control and channel assignment) helped improve network performance [4] [5] [6]. The authors in [2] found that Wi-Fi devices were distributed over overlapped channels and proposed a mechanism for alleviating collision between overlapped channels.

In wireless networks, broadcasting is a fundamental communication mechanism for topology maintenance and data dissemination. For example, hello messages are broadcast for topology maintenance; beacons are periodically broadcast for advertising vehicle status in vehicular networks. However, despite its wide applicability, broadcasting in multi-channel networks poses a new technical challenge: a sender and receivers must rendezvous on the same channel.

A naive solution is that a sender tries all channels for broadcasting a single message. However, this approach requires a great number of transmissions, which leads to huge network overhead and power consumption. We quantify the limitation of this approach using QUALNET 6.1 [8]. To be specific, when 100 users in the range of each other periodically broadcast beacon messages every 150ms, its Packet Delivery Ratio (PDR) is only 70% even though a radio interface spends 75% of its time for transmissions and receptions. This means that the broadcast performance is not satisfactory considering the great amount of radio resources put in for broadcast. Thus, we need to reduce the redundant transmissions to increase broadcast efficiency.

Another approach is that a sender and receivers periodically meet at the static Common Control Channel (CCC); and the sender broadcasts a message over the CCC. However, as large demand for broadcast can cause serious congestion at the CCC, the dedicated channel may not be suitable to exchange data (a.k.a. a single point of failure) [12]. Using channel-hopping mechanisms can solve the bottleneck of the static CCC, but they are also limited in that repetitive transmissions are required for broadcasting a single message [12] [13] [14]. This is because a sender cannot identify the channels of its neighbors. Similar to the naive solution, the repetitive transmissions induce large overhead and power consumption.

At this point, we can raise an important question: “Can we broadcast a message using only a few transmissions while avoiding a single point of failure in multi-channel networks?” To answer this question, we propose a novel broadcast scheme that exploits an overlapped band, a range of frequencies that partially overlapped channels (i.e., adjacent channels) share within their own channel boundaries. Previously, the overlapped band has been considered harmful since a signal in the overlapped band causes ACI. However, in our counter-intuitive approach, we leverage the overlapped band for conveying information to other devices in adjacent channels. Specifically, our scheme enables information delivery to multiple adjacent channels with a single transmission through the band that the multiple adjacent channels commonly share. Thus, we can significantly reduce the number of transmissions needed for information delivery to multiple channels. The proposed
scheme consists of two steps: 1) a sender determines a rendezvous channel and advertises it through the overlapped band; receivers jump to the advertised channel (advertisement step), and 2) the sender broadcasts a message at the advertised channel\(^1\) (data transmission step). The proposed scheme (esp. the advertisement step) has similarities with distributed blind rendezvous schemes in terms of 1) goal (establish a common channel for a prompt rendezvous) and 2) operation principles (independent of a fixed CCC and a centralized device). But it has differences from the blind rendezvous schemes in terms of a method for achieving the goal.

However, it is non-trivial to ensure the successful communication of the channel information when a sender and a receiver are in adjacent channels. In most communication systems, to extract a signal only in a specific band, a receiver rejects frequencies outside the band using Low-Pass Filter (LPF). However, if a sender and a receiver are in adjacent channels, the band of transmitted signal and that of LPF are not aligned. Thus, the receiver might reject a fraction of a transmitted signal during filtering process, which distorts the transmitted signal. To address this problem, our scheme adopts a new signal processing mechanism at the physical layer, Signaling via Overlapped Band (SOB). In SOB, a sender divides a channel into multiple sub-channels having an equal bandwidth and loads information on each sub-channel. If the overlapped band between a sender and a receiver encompasses more than one sub-channel, the receiver’s LPF passes all frequencies of the sub-channel. Thus, a receiver can obtain a signal of the carried information without loss.

Even if a receiver gets a signal without loss after filtering, in current channelized network protocols such as IEEE 802.11b/g/n, the receiver cannot decode the signal if using a different channel than the sender. To circumvent this issue, we define a new PHY frame, Rendezvous Signal (RS), and establish a signal processing procedure for en/decoding the RS reliably.

At the MAC layer, we employ three novel mechanisms to further improve broadcast efficiency by addressing the following three problems. First, a sender might have to wait for a long time before accessing a channel in multi-channel networks because a busy medium may come from co-channel interference as well as ACI. To meet this challenge, the proposed scheme employs Reserve Idle Spectrum Fragment (RISF), whereby a sender prevents other devices from occupying any idle spectrum fragments within the sender’s channel. Second, when failing to decode an RS, devices switch to a wrong channel, causing rendezvous failure with a sender. To remedy this problem, our scheme employs Reinforce Switch Notification (RSN), which reduces the residing time in the wrong channel. Third, when multiple senders start their broadcast procedures at a similar time, receivers might fail to rendezvous with some of the senders. To solve this problem, our scheme adopts Multi-sender Agreement on Rendezvous CHannel (MARCH), ensuring that only one rendezvous channel is used by multiple senders at a similar time.

In reality, devices are distributed over a large area, thus, some devices might not hear the signals transmitted by others (multiple contention domain). Unfortunately, both PDR and delay of the proposed scheme are unsatisfactory due to the hidden problem in a multiple contention domain. To further improve PDR and reduce delay in a multiple contention domain, we adopt two extremely simple but efficient mechanisms that address the following two problems. First, the devices sometimes fail to notice the start of the data transmission step and postpone their broadcasts in a multiple contention domain. To address this problem, our scheme employs Notification of Data Transmission Step (NTS), ensuring notification of the start of the data transmission step by devices in a rendezvous channel. Second, PDR degradation is mainly attributed to serious collisions in a multiple contention domain. Specifically, all senders attempt to access the channel as soon as the transmission step starts; hidden collisions additionally occur in a multiple contention domain. To meet this challenge, we adopt Decoupling Channel Access time (DCA), which distributes the channel access time of devices throughout the data transmission step.

We have implemented the proposed scheme on the SORA software radio platform [7] and QUALNET simulator [8]. We verify the feasibility of communication via the overlapped band between different channels using the SORA platform; we feed the experimental results into the physical layer model of RS reception in QUALNET. In addition, intensive simulation studies show that the proposed scheme greatly enhances performance over a previous approach [14] - 2.1× (2.6×) in terms of Packet Delivery Ratio (PDR), 92% (81%) reduction in terms of delay, and 87% (95%) reduction in terms of the time that a radio interface spends for broadcasting in a single (multiple) contention domain. Here, a single contention domain refers to a situation when all devices are in the range of each other, thereby being capable to hear signals from others. We also show that our scheme can support vehicular beacon exchanges well in multi-channel networks. Moreover, we observe that devices with our scheme coexist well with current 802.11 devices in multi-channel networks.

In summary, the contributions of this paper are as follows:

- Proposes a novel broadcast scheme requiring a small number of transmissions and avoiding a single point of failure in multi-channel networks.
- Explores the feasibility of information delivery through the band overlapped by partially overlapped channels.
- Proposes three new mechanisms at the MAC layer to fully exploit the advantages of SOB.
- Proposes two simple but efficient mechanisms to improve PDR and reduce delay in a multiple contention domain.
- Implements the proposed scheme on the SORA platform and evaluates the scheme with the implemented testbed.

This paper significantly enhances our earlier work [25] in that we consider practical situations (e.g., multiple contention domain and coexistence with current 802.11 devices) in our design and evaluation. Specifically, our earlier work considered only limited situations (e.g., a single contention domain). On the contrary, in this paper, we find problems of our earlier work in the practical situations, propose simple solutions, and

\(^1\)Even if our design and implementation are based on 802.11g network, this work can be easily extended to other network systems that exploit overlapped channels (e.g., 802.11b and Wi-Fi in Whitespaces [22]).
evaluate the solutions in the practical situations. In particular, we emphasize that our solutions are drastically simple, which is important rationale for practical system designs, and efficient (e.g., an integration with NTS and DCA improves PDR by 15% and reduces delay by 60%). Moreover, this simplicity facilitates integration of the solutions with the schemes proposed in [25]. We summarize enhancements of this paper over our earlier work as follows:

- Proposes remarkably simple but efficient mechanisms for improving the scheme proposed in [25] in a multiple contention domain. (Section VI).
- Investigates several issues including backward compatibility, the size of a sub-channel, and comparison with upcoming OFDMA-based 802.11 standard. (Section VII).
- Provides a complete set of simulation results by considering practical situations, such as working in a multiple contention domain and coexisting with current 802.11 devices (Section VIII).

II. RELATED WORKS

Several works have been proposed for broadcasting in multi-channel networks based on a broadcast schedule [9] [10] [23]. In [9], the authors proposed a scheduling mechanism for broadcasting in multi-channel wireless ad-hoc networks in order to minimize an end-to-end delay. However, the authors in [9] assumed that every device knew the channels of its neighbors, which must be updated frequently via message exchanges in mobile networks. In [10], the authors formulated a multi-channel multi-radio broadcast problem as a minimum spanning problem in simplicial complexes. In [23], a linear programming model was used to formulate a minimum cost broadcast problem in multi-radio and multi-channel wireless networks. To solve this problem, the authors in [23] proposed both centralized and distributed heuristic algorithms. However, the problem formulations and corresponding solutions in [10] [23] were based on an assumption that all devices had multiple radios, which increased the cost.

A number of works have relied on a common channel, on which devices broadcast a message in multi-channel networks [11] [12] [13] [14] [24]. The authors in [11] proposed to establish a common channel via negotiation among devices (i.e., pre-defined sequence). However, message exchanges were required for the negotiation, thereby inducing large network overhead in mobile networks. In [24], a device divided wideband into multiple narrowband channels and exploited only available channels for broadcasting a packet. Specifically, a sender negotiated with each receiver on the channels used for broadcast. However, for negotiation, a sender required information of each receiver (e.g., ID and code), which changed and must be updated frequently in mobile networks, thereby leading to large network overhead. A common channel could be established via channel hopping techniques without the negotiation [12] [13] [14]. Despite no signaling overhead for negotiation, it took some time before making rendezvous; redundant transmissions were required for broadcasting a single message since a sender could not identify the current channels of its neighbors.

We should note that our scheme has some similarities with the distributed blind rendezvous schemes. First, both schemes aim to establish a common channel for a rendezvous. Blind rendezvous schemes build the common channel via channel hopping; devices rendezvous at the same channel in an advertisement step of our scheme. Second, our scheme and blind rendezvous schemes do not rely on a fixed CCC and a centralized device. In blind rendezvous schemes, devices determine their hopping sequences by themselves and the rendezvous channel changes according to a pair of a sender and a receiver. Similarly, a sender determines the rendezvous channel in a distributed manner; thus, the rendezvous channel can change with a sender. Finally, devices do not require informations on their neighbors for establishing a common channel.

It must be noted that there are some differences between the two. First, a pair of devices can periodically rendezvous regardless of having a packet to broadcast (i.e., proactive) in blind rendezvous schemes, whereas a sender triggers a rendezvous procedure only when having a packet to broadcast in our scheme (i.e., reactive). More specifically, in the blind rendezvous schemes, all devices continually switch their radio channels every slot boundary and expect that any pair of devices would rendezvous within a specific time interval. On the contrary, in our scheme, only a sender switches its radio channel and transmits a short RS frame; all devices jump to a rendezvous channel when receiving the RS. Second, a sender must repetitively transmit the same packet to guarantee the packet delivery to all neighbors in the blind rendezvous schemes, whereas only a single transmission is required for the packet delivery in our scheme.

III. OVERVIEW OF PROPOSED SCHEME

To understand our scheme clearly, we start with a single contention domain in describing problems and solutions and then accommodate the solutions to a multiple contention domain throughout this paper. Specifically, we focus on a single contention domain in Section IV-V; we extend the solutions to further improve performances in a multiple contention domain in Section VI.

Fig.1 illustrates the overall procedure for broadcasting a single message (we will call this procedure ‘broadcast procedure’ throughout the paper). In the advertisement step, a sender selects its own channel number for rendezvous (i.e., rendezvous channel) and shares it with neighbors. In our scheme, a sender randomly selects the rendezvous channel
for its simplicity. Despite its simplicity, our scheme with this random selection produces excellent system performance as shown in Section VIII. When receiving the channel number, the neighbors switch their radio channels to the received channel. In the data transmission step, the sender jumps to the rendezvous channel and broadcasts the message.

If using a typical Wi-Fi communication system, a sender needs to try all channels to transmit the rendezvous channel in the advertisement step. Consequently, the number of transmissions grows linearly with the number of channels, which in turn increases network overhead. The proposed scheme meets this challenge by adopting SOB, which is a new signal processing procedure at the physical layer. Specifically, a sender divides its channel into multiple sub-channels with equal bandwidth (e.g., two sub-channels with 10MHz bandwidth in Fig.2) and transmits the rendezvous channel through each sub-channel. If the overlapped band between the sender and its neighbor encompasses at least one sub-channel, the neighbor can receive the rendezvous channel (e.g., devices in channels 1~5 in Fig.2). As several adjacent channels share the same sub-channel in a 2.4GHz ISM band (e.g., channels 1~3 share sub-channel 1 in Fig.2), the sender can deliver its rendezvous channel to the neighbors in several adjacent channels with a single transmission. Therefore, using SOB, we can reduce the number of transmissions for the advertisement.

We will explain the benefit of SOB using a simple example. In this example, we assume that the sub-channel size is 10MHz and a sender needs to advertise its rendezvous channel to devices in 13 channels. First, the sender transmits the rendezvous channel in channel 3 using SOB; neighbors in channels 1~5 can receive the rendezvous channel, as shown in Fig.2. Similarly, the sender transmits the rendezvous channel in channels 8 and 13 using SOB; neighbors on channels 6~10 and channels 11~13 receive the channel number, respectively. Hence, we can reduce the number of transmissions needed for the rendezvous channel advertisement from 13 to 3.

The benefit of SOB can be realized via reliable communications through the overlapped band of adjacent channels, which is not supported in the current 802.11 standard [1]. Thus, we define a new signal processing mechanism in SOB to enable communication through the overlapped band of the adjacent channels. Specifically, we define a special PHY frame, which is referred to as RS, to transmit rendezvous channel information through the overlapped band of adjacent channels. RS is en/decoded with simple on/off keying, which is known to be reliable even in poor channel conditions. The details of signal processing mechanism will be explained in section IV.

Our scheme also employs three mechanisms at the MAC layer to fully exploit the benefit of SOB. First, our scheme employs RISF to reduce the long waiting time caused by ACI. When there are no external interferences, a random selection is efficient because every channel has an equal congestion level at the beginning of a data transmission step. More specifically, when receiving an RS, receivers freeze their radios; thus, all channels have almost equal traffic loads during a data transmission step. In contrast, when considering external interference (e.g., legacy 802.11 traffic), we need to consider the external interference in channel selection due to heterogeneous channel conditions. However, even with legacy 802.11 unicast traffic, our simulation results in Fig.17 shows that our scheme still makes excellent performances.

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A. Frame Format of Rendezvous Signal

Fig.3 illustrates the frame format of Rendezvous Signal. RS consists of four parts: 1) Short Training Signal (STS), 2)
channels can obtain RS within an overlapped via RS reception procedure.

In determining the bandwidth of the sub-channel, we need to firstly select the number of RS transmissions required for advertising the rendezvous channel. More specifically, the bandwidth affects the number of channels where the receiver filter in the radio front-end (i.e., analog filter) can extract an RS without loss. Recall that the loss of an RS signal does not happen when the overlapped band between a sender and a receiver includes more than one sub-channel. The number of channels, in turn, affects the required number of RS transmissions. For example, when using 10MHz sub-channel in IEEE 802.11g, a receiver can extract an RS without loss during filtering process when the channel spacing between a sender and a receiver is no more than two, as shown in Fig.2. In this case, a single RS transmission can reach to five adjacent channels (e.g., channels 1~5 when transmitting an RS on channel 3 in Fig.2); the required number of RS transmissions is three for covering 13 channels in 802.11g.

It is noted that distortion can occur at the edge of the band in an analog filter. Hence, typical Wi-Fi devices allocate 1.875MHz in both edges of a channel as a guard band [17]. Therefore, when fitting an RS frame into a sub-channel, we have to consider these guard bands so that the RS frame in the sub-channel can be transmitted without distortion. For example, when we use 10MHz sub-channel, the band that we can use for carrying an RS is only 6.25MHz (=10-1.875x2), as shown in Fig.5.

C. Procedure for Receiving Rendezvous Signal

A receiver gets a rendezvous channel from an RS according to the three-step procedure, as depicted in Fig.6. In the first step, a receiver performs low-pass filtering in the radio front-end (i.e., filtering with an analog filter) and checks whether the channel is busy or not. If detecting busy channel, the receiver includes more than one sub-channel. The intuition behind this generation procedure is that we have to propose a reliable method for delivering an RS via an overlapped band of adjacent channels. To achieve this reliable delivery, we exploit a simple on/off keying based on an amplitude of each signal: the amplitude larger than a threshold represents one and the amplitude smaller than the threshold represents zero. The intuition behind this frame format is that we have to propose a reliable method for delivering an RS via an overlapped band of adjacent channels. To achieve this reliable delivery, we exploit a simple on/off keying based on an amplitude of each signal: the amplitude larger than a threshold represents one and the amplitude smaller than the threshold represents zero. The proposed frame format facilitates this on/off keying: two TSs precede four DSs in the RS frame; we determine a threshold by averaging amplitudes of two TSs and we use the threshold for decoding each DS.

B. Procedure for Generating Rendezvous Signal

Fig.4 illustrates an RS generation procedure. First, a sender makes an RS frame according to the format in Fig.3. Second, the sender determines the bandwidth of a sub-channel and fits the bandwidth of the frame into the bandwidth of the sub-channel. Third, the sender relocates the RS frame into each sub-channel. The intuition behind this generation procedure is that a sender must be able to deliver a RS to devices in multiple adjacent channels with a single transmission. To achieve this, a RS must be placed in more than one sub-channels because devices in multiple adjacent channels must be able to extract the RS. Specifically, we place an RS information in every sub-channel of the channel as shown in Fig.4; receivers in adjacent sub-channels in multiple adjacent channels must be able to extract the RS. Therefore, when we use 6.25MHz band for data bandwidth, the delay for transmitting an RS is only 205us even with the most reliable modulation (i.e., lowest rate).

A receiver should also be able to receive typical Wi-Fi signal with full-channel bandwidth. For this purpose, before moving on to step 2, a receiver feeds a signal into the reception procedure of typical 802.11 communication system. If passing CRC, a receiver recognizes that the busy medium comes from the typical Wi-Fi signal and does not go to step 2. Otherwise, a receiver goes to step 2.

4Our scheme exploits the analog filter without modification. We only modify the digital part, which is more flexible in modification. (e.g., software defined radio).

5The transmission rate is proportional to the data bandwidth, thus, the delay for RS transmission grows. However, as the size of an RS frame is very small, the increased delay is also short. For example, when we use 6.25MHz band for data bandwidth, the delay for transmitting an RS is only 205us even with the most reliable modulation (i.e., lowest rate).

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step, the receiver finds an RS using ‘RS detection algorithm’ within the signal. Similar to the first step, the receiver goes to the next step only if finding an RS. In the third step, the receiver decodes the rendezvous channel from an RS according to ‘RS decoding algorithm’. It is noted that a receiver conducts a test in each step as depicted in Fig.6. Intuitively, each test works like a valve: each signal can go to the next step only if finding an RS. In the third step, the receiver finds an RS using ‘RS decoding algorithm’. It is noted that a receiver conducts a test in each step as depicted in Fig.6.

The **RS detection algorithm** consists of two phases: 1) a digital filtering phase and 2) a detection test phase. In the digital filtering phase, a receiver filters the sub-channel of an RS from the analog filter output via D-BPF. However, the receiver cannot identify the center frequency of the sub-channel since the center frequency changes according to the channel of an RS sender, which the receiver does not know. To meet this challenge, the receiver must conduct filtering several times by changing the configuration of D-BPF, assuming that an RS is sent on one of adjacent channels. For example, when residing in channel 3 and using 10MHz as the sub-channel size, a receiver can receive an RS only if a sender transmits the RS in one of five channels (channels 1–5). Thus, the receiver conducts filtering assuming that an RS is sent on one of the five channels. As a result, the receiver performs filtering three times by configuring the center frequency of the D-BPF with 2412MHz, 2407MHz, and 2017MHz for each filtering.

In the detection test phase, a receiver checks whether the RS is detected or not in each filter output of the digital filtering phase. As illustrated in Fig.7, a receiver performs two RS detection tests and declares that an RS is detected if passing both tests. The first test is conducted at STS and consists of three sub-tests: 1) energy detection test, 2) auto-correlation test, and 3) cross-correlation test. More specifically, the three sub-tests are conducted during the first four symbols of STS because this detection mechanism works like a valve: if detecting a frame, a device continues to receive remaining parts of the frame; otherwise, the device discards the signal. In each sub test, the receiver calculates energy, auto-correlation, and cross-correlation with known sequence, respectively. If the calculated value is larger than the pre-defined threshold, the receiver declares pass in each sub-test. When passing three sub-tests, the receiver declares the pass in the first test. The receiver performs the second test after receiving DS. Specifically, the receiver checks whether the channel is busy or not during DIFS. The second test is for screening normal Wi-Fi signals that falsely pass the first test. Thus, as the length of normal Wi-Fi signal is longer than an RS, we make the receiver declares pass in the second test if the channel is idle during DIFS.

Through the second test, we can reduce false positive detection error leading to rendezvous error. More specifically, through the second test (checking medium after DS), we can reduce false positive detection error caused by legacy 802.11 signal. As a tradeoff, the overhead (DIFS waiting after DS) might induce negative effect on system performance, but the effect is negligible. Specifically, it is obvious that PDR can be improved; the increase in broadcast delay is very small (around 400us in 802.11g).

The **RS decoding algorithm** consists of two steps. In the first step, a receiver calculates a threshold by averaging the energy of two symbols in TS. This is because the first and the second symbol in TS represents high and low energy, respectively. In the second step, the receiver decodes each symbol in DS by comparing the symbol energy with the calculated threshold. If the symbol energy is larger than the threshold, the corresponding symbol represents one, and vice versa, for representing zero. If the energy is equal to the threshold, the symbol is randomly declared to one or zero with equal probability.

**V. Mechanisms at the MAC Layer**

In this section, we introduce three novel mechanisms at the MAC layer: RISF, RSN, and MARCH, which are integrated with SOB to fully exploit the benefit of SOB.

**A. Reserve Idle Spectrum Fragment**

In Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA), devices must wait when the medium is sensed to busy. In multi-channel networks, the medium can become busy due to interferences in the same channel as well as the adjacent channels. Thus, the device might wait for a long time for accessing the medium in the multi-channel networks.

To meet this challenge, we propose RISF to reduce such long waiting time by reserving idle spectrum within a channel.

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\*\*\* We have reserved 6 other STS symbols for future use such as Automatic Gain Control (AGC), which we did not implement due to hardware limitations.

\*\*\* We use threshold values similar to those of normal Wi-Fi transceiver [15], but need to customize the values according to the bandwidth of an RS frame.

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\*\*\* This is because the first test is very similar to the normal 802.11 preamble test. Thus, even if the band of normal Wi-Fi signal and an RS is not aligned, receivers may falsely declare RS detection, which we have observed during our measurement with SORA.
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Fig. 8: Reserve Idle Spectrum Fragment

until transmitting a message. When generating the message, a device checks whether the current channel is busy or not. If the medium is idle, the device follows a normal CSMA/CA mechanism. Otherwise, the device starts RISF and ends only after they find that all spectrum fragments become idle.

As shown in Fig.8, RISF consists of two phases: 1) a monitoring phase, 2) a reservation phase. In the monitoring phase, a device checks which spectrum fragments are idle in its current channel\(^{11}\). In the reservation phase, the device transmits a jamming signal in idle fragments for reservation (e.g., 3\(^{rd}\) and 4\(^{th}\) fragments in the reservation phase of Fig.8). Here, the jamming signal is simple repetition of Pseudo Number (PN) sequence, which is encoded with on-off keying and detected with an energy detection. Then, when detecting the busy medium on those fragments, other devices cannot access the channel that shares the fragments (e.g., Dev 2 in Fig.8).

During the reservation phase, a busy spectrum fragment becomes idle due to the transmission end in adjacent channels. In this case, a device must also reserve the fragment as well as previous idle fragments by sending jamming signals in those fragments. The device keeps transmitting the jamming signal until all fragments become idle within its channel. When finding all fragments are idle, the device sends its message without random backoff.

To maintain the reservation, a device must monitor its channel, while keep transmitting a jamming signal. However, current mobile devices exploit the half-duplex antenna, thereby not being able to transmit a signal and listen to the channel simultaneously. To meet this challenge, a device flips between RX and TX mode frequently. In other words, the device must keep switching between the monitoring phase and reservation phase frequently. For maintaining the reservation, the length of RX mode must not be larger than minimum waiting time for accessing the channel (e.g., DIFS in 802.11g). Thus, we set the flipping interval to the value that is slightly shorter than the minimum waiting time.

B. Reinforce Switch Notification

Sometimes, a receiver might jump to the wrong channel if RS decoding error or false RS detection (i.e., false alarm) happens. When jumping to the wrong channel, the receiver cannot receive a message that a sender broadcasts. Moreover, the receiver unnecessarily changes its radio channel when the false alarm happens, which leads to missing the opportunity to receive data messages in the current channel.

\(^{11}\) For spectrum analysis and reservation in RISF, we divide a channel into multiple spectrum fragments and set the bandwidth of the fragment to be the minimum sharing bandwidth between adjacent channels.

To address this problem, we propose RSN that reduces the residing time in the wrong channel. Specifically, after transmitting an RS, a sender temporarily jumps to the rendezvous channel and transmits Notification Signal (NS). Then, the sender jumps to the next RS transmission channel or the rendezvous channel according to the current step in its broadcast procedure. Here, NS is the repetition of PN sequence, which is en/decoded with simple on-off keying and detected with correlation with a known sequence. If detecting the NS within a predefined time\(^{12}\), the receiver validates the current switch. Otherwise, the receiver goes back to its original channel.

C. Multi-sender Agreement on Rendezvous Channel

Until now, we focus on the design when a single device broadcasts a message. However, in practical situations, multiple devices try to broadcast their messages at a similar time. In this case, one device (e.g., dev 2 in Fig.9) may start its broadcast procedure before completing the broadcast procedure of the other device (e.g., dev 1 in Fig.9). This situation can cause a rendezvous failure between a receiver and a sender (e.g., dev 3 fails to rendezvous with dev 2 at the data transmission step in Fig.9). This is because multiple senders determine their rendezvous channels independently (e.g., dev1 (dev2) selects channel 5 (10) in Fig.9); but receivers must follow only one of the rendezvous channels.

A solution to this problem is the agreement on the rendezvous channel among multiple devices that start broadcast procedures at a similar time. The devices can achieve the agreement by following the command of an RS when receiving the RS from the other device (‘RS initiator’). Specifically, when receiving the RS, other senders (‘RS followers’) suppress their RS transmissions and jump to the received rendezvous channel. Then, the RS followers broadcast their messages when all receivers are gathered in the channel.

We make only an RS initiator notify the start time of the data transmission step (i.e., time when all receivers are gathered) because only an RS initiator is able to know accurate time when the advertisement step has ended. In contrast, RS

\(^{12}\) As a sender transmits NS after switching channel and performing RISF, the pre-defined time can be calculated as the sum of channel switching delay and the waiting time in RISF. The upper bound of the waiting time is equal to the maximum occupation time of a spectrum fragment, which is equal to the transmission delay of the longest MAC frame.
followers cannot estimate the ending time accurately because they do not know how long an RS initiator has to wait (i.e., random backoff) for transmitting an RS in an advertisement step. As having a message to broadcast, an RS initiator can notify the start of the data transmission step as follows. First, an RS initiator jumps to the rendezvous channel when it completes advertising rendezvous channel information. Second, the initiator broadcasts its message in the rendezvous channel, and RS followers recognize the start of the data transmission step by receiving the message.

It is noted that devices might receive multiple RSs from different senders. Specifically, in the received rendezvous channel, the devices might receive an RS from others that do not suppress their RS transmissions yet. Thus, the devices may be confused which channel they must jump into. To avoid the confusion, the devices jump into the rendezvous channel only when receiving an RS firstly, and does not react to other RSs until completing the current broadcast procedure.

One may insist that packet collisions might occur if RS followers broadcast their messages during a data transmission by a RS initiator. However, if not combined with NTS in a single contention domain, these packet collisions rarely happen. This is because the RS followers start their transmissions only after recognizing data transmission by a RS initiator if not combined with NTS. On the contrary, if our scheme is integrated with NTS to further improve performances in a multiple contention domain, packet collisions could happen among a RS initiator and RS followers. However, we can reduce the probability of collisions by employing DCA because DCA distributes time to transmit messages by devices throughout data transmission step, as depicted in Fig.12. We will explain the details of NTS and DCA in Section VI.

VI. TOWARDS IMPROVEMENT IN MULTIPLE CONTENTION DOMAIN

Until now, we have focused on the design only when all devices can hear a signal transmitted by other devices, i.e., a single contention domain. However, in reality, some devices might not hear a signal if the sender of the signal is distant from them, i.e., a multiple contention domain. In a multiple contention domain, we notice that both PDR and delay of our scheme (i.e., integration of SOB and three MAC layer mechanisms) are unsatisfactory. (see line tagged with “Proposed scheme” in Fig.19). This is because we did not consider hidden problems (i.e., problems caused by hidden devices), which occur frequently in a multiple contention domain, when devising SOB and MAC layer mechanisms in Section IV and V. To meet this challenge, we propose remarkably simple but efficient mechanisms: 1) NTS and 2) DCA. From now on, we refer to our scheme integrated with two mechanisms as “integration mode” and the scheme without integration as “basic mode”.

A. Notification of data Transmission Step

Fig.10 illustrates the reason for a long delay when we configure our scheme in basic mode in a multiple contention domain. In basic mode, if not receiving a data message from an RS initiator after jumping to a rendezvous channel, an RS follower fails to notice the start of a data transmission step and postpones broadcasting its data message until receiving messages from others or a current data transmission step has ended. This undesirable situation happens when an RS follower is located within RS reception coverage but outside data reception coverage, as shown in Fig.10. RS reception coverage (e.g., dotted circle of the left hand side figure in Fig.10) is normally larger than data reception coverage (e.g., dotted circle of the right hand side figure in Fig.10) because encoding/decoding scheme for an RS (i.e., SOB) is more reliable than encoding/decoding scheme for a data message (i.e., typical 802.11 communication system). To meet this challenge, we propose NTS that enables all devices in the rendezvous channel to recognize the start of the data transmission step. For this purpose, NTS improves coverage of notification of the start as follows. Before broadcasting a data message, an RS initiator disseminates Notification Control Signal (NCS) with the SOB encoding method in the rendezvous channel. Then, devices in the rendezvous channel recognize the start of the data transmission step by receiving NCS using the SOB decoding method. This simple mechanism enables most devices in the rendezvous channel (i.e., devices that have received an RS) to recognize the start of the transmission step because RS reception coverage is comparable to NCS reception coverage. Consequently, RS followers can broadcast their data messages as soon as entering the data transmission step, thereby reducing delay.

B. Decoupling Channel Access time

Fig.11 illustrates a problem with our scheme configured in basic mode when a number of devices generate data messages at nearly the same time. Specifically, in basic mode, devices with data messages (e.g., dev 1–3 in Fig.11(a)) start a collision resolution mechanism (CSMA/CA) at nearly the same time (i.e., as soon as a data transmission step starts). Thus, network becomes quite congested, which leads to packet collisions.

An RS initiator determines the ending time of a data transmission step and piggybacks this time into several messages: 1) RS, 2) notification control signal (NCS), and 3) data message. Thus, when receiving one of the above-mentioned messages, a device can obtain the ending time of data transmission step.

Fig.14 demonstrates that the probability of decoding error of an RS is around 10% with 10MHz spacing (worst case) and the probability is less than 5% with smaller spacing (5MHz or 0MHz spacing) when SNR is 6dB. In contrast, even with the most reliable transmission rate (6Mbps), the probability of decoding error in 802.11g is around 30% when SNR is 6dB with a 512byte message [28].
The problem becomes exacerbated in a multiple contention domain because CSMA/CA is poor at avoiding collisions by hidden devices. Specifically, hidden devices (e.g., dev 2 and dev 3 in Fig.11(b)) cannot detect a signal by a sender (e.g., dev 1 in Fig.11(b)), so they do not backoff their transmissions. For this reason, to avoid collisions by hidden devices, the difference between the transmission starting time of one device (e.g., dev 1 in Fig.11(b)) and that of a hidden device (e.g., dev 2 or dev 3 in Fig.11(b)) must be longer than the duration of a data transmission. However, as shown in Fig.11(b), contention window size is not long enough to make the difference longer than the duration of the transmission. Thus, in a multiple contention domain, collisions by hidden devices frequently happen, which significantly degrades PDR.

To address this problem, we devise DCA that distributes time for accessing a channel throughout the data transmission step. More specifically, instead of starting CSMA/CA immediately after the data transmission step begins, each device starts CSMA/CA at the time that has been distributed throughout the data transmission step, as illustrated in Fig.12. DCA improves PDR for the following reasons. First, the number of contenders decreases, thereby reducing collision probability. Second, hidden collisions can be avoided because the difference in channel access time between devices could be larger than the transmission duration, as shown in Fig.12.

\[\text{For broadcasting, minimum contention window size is used, which is comparable to 135us in IEEE 802.11g [1].}\]

VII. DISCUSSION

In this section, we briefly describe a few additional points for consideration but leave their solutions as future work.

A. Backward compatibility

Devices with our scheme coexist well with current 802.11 devices. This is because channel access in our scheme is based on CSMA/CA; thus, devices with our scheme defer their channel access when detecting busy channels caused by current 802.11 devices. However, as shown in Fig.11(b), (e.g., dev 1 in Fig.11(b)) and that of a hidden device (e.g., dev 3 in Fig.11(b)), so they do not backoff their transmissions. For this reason, to avoid collisions by hidden devices, the difference between the transmission starting time of one device (e.g., dev 1 in Fig.11(b)) and that of a hidden device (e.g., dev 2 or dev 3 in Fig.11(b)) must be longer than the duration of a data transmission. However, as shown in Fig.11(b), contention window size is not long enough to make the difference longer than the duration of the transmission. Thus, in a multiple contention domain, collisions by hidden devices frequently happen, which significantly degrades PDR.

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\[\text{For example, an RS transmission delay with 10MHz setting is only 205us with the lowest rate, while the delay is 1.025ms with 5MHz setting. Considering the number of transmissions and channel switching delay (e.g., 80us [12]), the total delay for advertisement is 775us with 10MHz setting, while the delay is 2.1ms with 5MHz setting.}\]
Second, reliability for detecting and decoding an RS increases with the bandwidth of a sub-channel. Specifically, detecting and decoding an RS via the band overlapping the sender’s and the receiver’s channels becomes more reliable as the center frequency spacing between two channels becomes smaller, as shown in Fig.14. This is because signal distortion during low-pass filtering at the RF front-end increases along with the center frequency spacing due to the imperfect frequency response of an analog filter, as explained in Section VIII-A. Obviously, as the bandwidth of a sub-channel becomes smaller, it is more probable that the spacing between a sender’s channel and a receiver’s channel becomes large. We explain this with a simple example, assuming that receivers are equally distributed over 13 channels. With a 10MHz setting, a sender broadcasts an RS over channels 3, 8, and 13. Then, the spacing averaged over all receivers’ channels (channels 1~13) is 5.76MHz. On the contrary, with a 5MHz setting, a sender broadcasts an RS over channels 4 and 11. In this case, the average spacing is 8.07MHz.

C. Comparison with Upcoming 802.11 standard

The upcoming standard IEEE 802.11ax [27] adopts Orthogonal Frequency Division Multiple Access (OFDMA) for coordinating channel accesses by multiple users. Using OFDMA, a sender can broadcast its data message over all channels via only a single transmission. Thus, at first glance, OFDMA seems to be more attractive than our scheme for broadcasting in multi-channel networks. However, OFDMA is not suitable in a distributed and mobile network system. This is because the OFDMA requires tight time synchronization, which is difficult to achieve in network systems without a centralized device (distributed system). Moreover, overhead for resource scheduling could be very large in distributed and mobile environments. Several applications for multi-channel broadcast operates in mobile and distributed environments (e.g., hello messages in a mobile ad-hoc network, beacon messages in a vehicular network).

D. Comparison with 802.11 having Small Channel Size

The IEEE 802.11 standard supports multiple channel sizes [1]. If we use a 5MHz channel size in a 2.4GHz band, the channelization method changes from partially overlapped channels into orthogonal channels with small bandwidth. This case is equivalent to the case when we divide all the channels with typical size (i.e., 20MHz) into subbands with 5MHz and regard each subband as a separate channel. In this case, defining a problem remains the same even if the channelization method changes. Specifically, the problem is still “making a rendezvous at the same channel” because devices are distributed over different channels. However, the solution must be modified; i.e., only part of our solution can be used in this situation. Our scheme exploits overlapped bands of adjacent channels to reduce the number of transmissions required for a rendezvous; thus, the mechanism that leverages the overlapped bands cannot be used. Specifically, we cannot use SOB because SOB exploits the overlapped band to advertise the rendezvous channel; thus, the number of transmissions required for advertisement increases. However, we can use mechanisms that do not exploit overlapped bands, such as the MAC layer mechanisms (e.g., RSN, MARCH) or the two mechanisms for improving performances in a multiple contention domain (e.g., NTS, DCA).

E. Effect of Advertisement Channels

The selection of advertisement channels (i.e., channels to transmit an RS in an advertisement step) as well as their sequence that a sender follows in an advertisement step influences system performances, particularly when multiple senders attempt to broadcast their RSs at a similar time. We explain this argument with a simple example of two senders starting their advertisement steps at nearly the same time. Let’s suppose one sender attempts to transmit its RS with a sequence (3, 8, 13) and the other sender tries to broadcast an RS with a sequence (8, 13, 3). In this situation, as the channels in the two sequences are orthogonal with each other, both senders can transmit their RSs concurrently, thereby reducing delay in transmitting their RSs.

The selection of advertisement channels and their sequence also affect making a rendezvous among devices when many senders attempt to transmit their RSs at a similar time. To understand this argument clearly, we consider two cases and compare rendezvous error in one case with that in the other case: 1) two senders choose the same channels (3, 8, 13) and 2) one sender (sender 1) chooses channels (3, 8, 13) and the other sender (sender 2) chooses channels (13, 3, 8). In the first case, rendezvous error is unlikely to occur if we adopt MARCH, as illustrated in Fig.13(a). Specifically, sender 2 and a receiver can receive a RS from sender 1 when the sender 1 transmits an RS in channels 3 and 8, respectively. Thus, all devices can be united in channel 5 in a data transmission step. On the contrary, in the second case, rendezvous error happens even with MARCH as depicted in Fig.13(b). Specifically, sender 2 cannot receive an RS from sender 1 because their channels are orthogonal with each other throughout the advertisement step. Thus, a receiver fails to rendezvous with sender 2 even with MARCH.

VIII. PERFORMANCE EVALUATION

In this section, we implement and evaluate a signal processing procedure for RS generation/reception on the SORA platform [7] to validate the communication via an overlapped band of adjacent channels. Next, we evaluate the proposed scheme in various network conditions and compare the scheme with previous work using QUALNET 6.1 [8]. In QUALNET, we feed the SORA experiment results into a physical layer

17For example, in the IEEE 802.11g, the number is two with a 5MHz sub-channel size when channels are partially overlapped and their bandwidths are 20MHz (w/SOB). However, the number is 13 when all channels are orthogonal and their bandwidth are 5MHz and we adopt a naive approach (w/o SOB).

18This argument is valid when only one sender tries to transmit its RS in an advertisement step. To reduce the delay, a sender must place an idle channel earlier than a busy channel in its sequence. This is because we can avoid backoff waiting time caused by the busy medium. Specifically, we can avoid waiting time when transmitting an RS in idle channels; the busy channel is likely to become idle when switching to the channel.
model for RS reception. Throughout this section, we set the bandwidth of the sub-channel to 10MHz, the bandwidth of each channel to 20MHz, the number of channels to 13. Thus, a pair of devices can communicate with each other through overlapped band when center frequency spacing is equal to or less than 10MHz.

A. Validation of Communication between Adjacent Channels

To validate the communication between two adjacent channels, we prototype a new signal processing procedure, i.e., SOB, on the SORA platform. SORA is a software-defined radio platform in which we can implement a digital signal processing mechanism using C programming language. SORA can convert digital signals into analog waveforms for transmitting the signals. Also, it can receive analog waveforms via RF front-end device, convert the waveforms into digital signals, and conduct digital signal processing for decoding the signals. Our implementation includes the entire baseband signal processing mechanisms of SOB based on brick library provided in SORA SDK 2.0. More specifically, we implement 1) a procedure for generating an RS and 2) a procedure for receiving an RS (e.g., detecting and decoding an RS).

In the experiment, we exploit two SORA devices: one as a sender and the other as a receiver. For validation, we derive three performance metrics under different SNR (SNR) levels and center frequency spacing between a sender and a receiver: 1) false alarm probability ($p_{fa}$), 2) probability of mis-detection ($p_m$), and 3) probability of decoding error ($p_e$). $p_{fa}$ is defined as a fraction of RS detections among all detection tests even if a sender does not transmit an RS. $p_m$ is defined as a fraction of RSs that a receiver expects to detect but fails in detection. $p_e$ is derived as a fraction of RSs that fail to decode the rendezvous channel among all detected RSs.

In Fig.14(a), we observe that $p_{fa}$ is almost close to zero. This is because a receiver must pass two tests for declaring a detection success: 1) preamble detection at STS and 2) energy detection after receiving the RS. The first test is similar to the preamble detection of IEEE 802.11 standard [15], except that we perform the test with signal of an overlapped band. The second test is for avoiding false alarm that comes from normal Wi-Fi signal. As our system needs one more step for detecting a signal than a normal 802.11 preamble detection, $p_{fa}$ in our experiment are less than those of 802.11 detection (e.g., $p_{fa}$ is 0.005 when SNR is around 3dB and zero when SNR is larger than 4dB [18]).

In Fig.14(b), we notice that the $p_m$ is less than 5% in all experiment settings. Moreover, in the practical SNR range ($\geq$ 10dB) [18], the detection error is less than 2% for all center frequency spacing settings. In Fig.14(c), we observe that $p_e$ is relatively high when SNR is 3dB, but $p_e$ is close to zero in practical SNR range. From these observations on $p_{fa}$, $p_m$, and $p_e$, we can verify the feasibility of communications via overlapped band between adjacent channels.

It is noted that $p_{fa}$, $p_m$, and $p_e$ increase as the center frequency spacing between a sender’s channel and a receiver’s channel rises. This is because the filter in the RF front-end (e.g., XCVR2450 in our experiment) is not an ideal filter. Specifically, the frequency response of the realistic filter is not a perfect rectangular shape: the gain decreases as the frequency is getting away from the center frequency, and decreases rapidly around the cut-off frequency [19]. However, as the frequency spacing increases, frequency corresponding to an overlapped band is getting far from the filter’s center frequency. Thus, signal distortion increases as the spacing rises, which leads to higher $p_{fa}$, $p_m$, and $p_e$.

B. Improvement over Previous Work

We evaluate the proposed scheme in various network conditions through QUALNET 6.1. We use two-ray ground model as a propagation model. In the PHY layer settings, we use IEEE 802.11g physical layer for transmitting and receiving data messages through 20MHz channel. Moreover, we use the SORA experiment results for the physical layer model for RS reception that exploits 10MHz sub-channel[19]. In the MAC layer settings, we use default values that are defined in IEEE 802.11g (e.g., CW, SIFS, and slot size). Devices are distributed across various channels, which are selected uniformly at random among 13 channels. We compare our scheme with BRACER [14], which outperforms the other previous works for broadcasting with a single radio interface in multi-channel networks. In [14], each device establishes its own hopping sequence independently, which makes BRACER a fully distributed system. As a sender does not know receivers’ hopping sequences, the sender broadcasts a single

\[\text{To get } p_{fa}, p_m, \text{ and } p_e \text{ outside the tested SNR range, we use interpolation and extrapolation techniques.}\]

\[\text{Even if there are a lot of previous works on broadcast in a multi-channel network, most works are based on multiple-radios; thus comparison with them is not fair.}\]
packet several times to ensure packet delivery to receivers. Each simulation is iterated with 20 random deployments in a 0.5km x 0.5km region (a single contention domain); we get 95% confidential interval from the iterations.

We get three performance metrics in the simulation: 1) PDR, 2) delay, and 3) busy radio ratio. We define PDR as a fraction of the devices that successfully receive a broadcast message. Delay is referred to as an interval between a message generation and a message reception. The busy radio ratio is defined as a fraction of time in which a radio interface is in the busy state (i.e., reception, transmission, or busy channel detection states). From the busy radio ratio, we can infer three important points. First, we can infer the device energy consumption since radio in busy state consumes much more power than in idle state. Second, when there are only broadcast traffic, we can infer how much channel resources are used for the broadcast. Finally, from the simple calculation, ‘1 - busy radio ratio’, we can infer how much time the radio can be used for other purpose, such as unicast data transmission.

The three metrics are derived according to three independent
variables: 1) the number of users, 2) the source rate, and 3) the unicast traffic that coexists with the broadcast traffic. The typical settings on the variables are 40 users, 7.5 (pkt/sec), and no unicast traffic. To isolate the effect of each variable, we change the variable while fixing others to the typical settings.

1) The number of users: When more than two senders start their broadcast procedures at a similar time, receivers cannot make rendezvous with all senders since the senders determine the rendezvous channel independently. To mitigate the rendezvous failures, we propose a solution, MARCH (see section V-C for detail), while the BRACER does not.

The adoption of MARCH leads to improvement over BRACER. Specifically, as depicted in Fig.15(a), the proposed scheme outperforms BRACER by up to 108%. Moreover, Fig.15(b) shows that delays of the proposed scheme keeps less than 2ms, which is 7~10 times shorter than those of BRACER.

Fig.15(c) illustrates that the busy radio ratio of the proposed scheme is 4~5 times less than those of BRACER. This is because of the following reasons. First, as we reduce the number of transmissions for the advertisement using overlapped band, the proposed scheme needs a small number of transmissions for broadcasting a single message. Second, in MARCH, some senders skip their RS transmissions, which reduce the number of transmissions further. On the other hand, the sender in BRACER must transmit a message with the predefined number of times, to ensure the successful reception by all receivers in various channels. Thus, the ratio in BRACER increases linearly with the number of users.

2) Source rates: Similar to Fig.15(a)~Fig.15(c), we observe that the proposed scheme outperforms BRACER due to the adoption of a solution for mitigating the rendezvous failures (i.e., MARCH). To be specific, in Fig.16(a), we observe that PDR of the proposed scheme is larger than that of BRACER by up to 68%. In Fig.16(b), the delays of the proposed scheme is 10~12 times shorter than those of BRACER.

From the result in Fig.16(c), we can infer that the proposed scheme uses 5~7 times less channel resources that BRACER. This is because the proposed scheme reduces the number of transmissions by using overlapped channel for the advertisement (i.e., SOB). Moreover, the adoption of MARCH further reduces the number of transmissions as mentioned before. Thus, the slope in the proposed scheme is smaller than those of BRACER.

3) Coexistence with unicast traffic: In practical situations, broadcast traffic may coexist with unicast traffic. Thus, we evaluate the proposed scheme and compare it with BRACER in the coexistence scenario. Every user generates broadcast traffic periodically. For generating unicast traffic, we use UDP packets with 100kbps generation rate and 512byte packet size. Then, we vary the amount of traffic by changing the number of unicast senders.

Fig.17(a) shows that as unicast traffic increases, PDR of the proposed scheme rarely decreases, while that of BRACER almost linearly decreases. This is because the proposed scheme exploits small amount of channel resource for broadcast, as depicted in Fig.15(c) and Fig.16(c). Hence, in the proposed scheme, there are much more room for the unicast traffic transmission than in BRACER. As a result, the PDR of the proposed scheme is larger than that of BRACER up to by 60%.

In Fig.17(b), the delay of the proposed scheme rarely changes according to unicast traffic. However, the delay of BRACER increases as the traffic rises. This is because the proposed scheme employs RISF, ensuring that a sender can access the channel reliably even if the unicast traffic coexist. Moreover, the proposed scheme exploits much less channel resource for broadcasting, thereby, having more room for transmitting unicast traffic than BRACER. Therefore, in the coexistence scenario, network congestion of the proposed scheme is not so large. As a result, the delay of the proposed scheme is 9~15 times shorter than that of BRACER.  

4) Coexistence with current 802.11 devices: In practical situations, devices with our scheme may coexist with current 802.11 devices [1]. To evaluate coexistence, we follow a methodology suggested by the specification about Wi-Fi and LTE coexistence [26]. To be specific, we measure PDRs and delays in three cases: 1) when only 802.11 devices exist, 2) when only devices with our scheme exist, and 3) when two types of devices coexist and the number of 802.11 devices is same with that of our scheme. First, to investigate the effect of the coexistence on the performances of current 802.11, we compare PDRs and delays of current 802.11 in case 1 with those in case 3. Second, to show the effect of coexistence on the performances of our scheme, we compare PDRs and
delays of our scheme in case 2 with those in case 3. To quantify the degradation induced by coexistence, we derive two performance measures: 1) a decrease in PDR normalized with PDR in a non-coexistence case and 2) an increase in delay normalized with delay in a non-coexistence case (e.g., case 1 or case 2). For example, the normalized decrease in PDR for current 802.11 (see black line in Fig.18(a)) can be calculated by $\frac{PDR_{802.11} - PDR_{n,802.11}}{PDR_{802.11}}$, where $PDR_{n,802.11}$ is PDR of current 802.11 in case n. Both types of devices periodically broadcast data messages. Moreover, current 802.11 devices do not change their channels, after being selected uniformly at random among 13 channels. We can frequently find this situation in reality - private APs select their channels independently and broadcast data messages in their own channels; devices receive only messages from APs in the same channel.

In Fig.18, we observe that degradations of current 802.11 caused by coexistence with our scheme are very small (≤2% for PDR and ≤5% for delay). Moreover, we notice that PDR degradations of our scheme originated by coexistence are negligible (≤2%) and delay degradations of our scheme are reasonable. Consequently, we conclude that our scheme coexists well with current 802.11.

5) Multiple contention domain: For evaluating network performance in a multiple contention domain, we generate 20 random deployments in a 1.2km×1.2km region. In a multiple contention domain, we expect that reception failure caused by hidden devices degrades network performances, which can be overcome by two mechanisms proposed in section VI (NTS and DCA). To confirm our hypothesis, we use two different modes in our scheme: the scheme without NTS and DCA (“Proposed scheme” in Fig.19) and the scheme with NTS and DCA (“Proposed scheme with NTS+DCA” in Fig.19) and compare them with each other. Moreover, we compare them with BRACER [14].

In Fig.19, we observe that our scheme significantly outperforms BRACER in a multiple contention domain. More specifically, PDRs of our scheme are higher than those of BRACER by up to 160% (Fig.19(a)); delays of our scheme are 4~5 times shorter than those of BRACER (Fig.19(b)); and the ratios of busy radio are 5~20 times less than those of BRACER (Fig.19(c)).

Fig.19(a) illustrates that integration with NTS and DCA improves PDRs by up to 15%. In Fig.19(b), we notice that the integration reduces delay by up to 40~60%. The beauty of NTS and DCA is that these mechanisms are efficient, but extremely simple and easily integrated with our scheme. However, the integration with NTS and DCA slightly increases the ratio of busy radio, as depicted in Fig.19(c). This is because an additional control signal (i.e., NCS) is transmitted in NTS.

6) Application to Vehicular Communication: We can apply the proposed scheme to several applications, such as beacon exchange in vehicular networks and hello message exchanges in mobile ad-hoc networks. In this subsection, we investigate how well the proposed scheme can support beacon exchanges in vehicular networks. In the simulation, every vehicle broadcasts its beacon every 150ms in 2 mile highway area. In Fig.20, we observe that PDR of the proposed scheme with NTS and DCA is above 85% and delay is below 5ms, which is acceptable in several vehicular safety applications [21]. Moreover, the proposed scheme significantly outperforms BRACER in terms of PDR and delay; we notice that the integration with NTS and DCA improves PDR and delay.

22In 100 users, we notice that delay degradation is around 10%, which is a little bit larger than measurements in other settings. However, we must note that delays are still short, e.g., less than 3ms.

23For realizing safety applications, each vehicle must have accurate knowledge on surrounding situations (i.e., neighbor’s position). [20] verified that errors in estimating neighbor’s position is negligible with 150ms beacon interval when vehicle speed is equal to the speed limit in most U.S. highway.
IX. CONCLUSION

In this paper, we introduced a counter-intuitive approach that overlapped band of adjacent channels was exploited for an efficient broadcast in multi-channel networks. Specifically, a sender advertised the channel for rendezvous through the overlapped band of adjacent channels; the sender broadcast its message on the rendezvous channel. To enable communication through the overlapped band, we proposed a new signal processing mechanism at the physical layer. We have also proposed three MAC layer mechanisms to further improve the broadcast efficiency. We proposed two simple but efficient mechanisms to improve PDR and reduce delay in a multiple contention domain. We implemented the proposed scheme in the SORA platform and validated communication via overlapped band of adjacent channels. Using QUANLET simulation, we showed that the proposed scheme accomplished huge improvement over a previous work.

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