DSN: Enabling Lightweight Coordination Between Partially Overlapped Channels in Wireless LANs

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Abstract—**Partially overlapped channels (POCs) have been studied recently to improve network performance. However, the current OFDM-based 802.11 system is designed for co-channel communication, and does not support communication over POCs. Thus the coordination between POCs imposes a new challenge to WLANs. In this paper, we present DSN (Data Symbol Nulling), a novel communication strategy that leverages the pattern of data symbols (null or non-null), rather than the actual data symbol value, to convey lightweight control information (or sequences of binary bits). The receiver whose channel is partially overlapped with the sender, interprets thus-transmitted messages by detecting the energy of received data symbols, the minimum resource units in OFDM. A key principle of DSN is that the newly designed communication strategy does not sacrifice original data throughput. Our extensive results validate communication over POCs, and show that lightweight control information can be delivered with close to 100% accuracy. Further, based on this communication paradigm, we propose DSN-MAC, an efficient coordination scheme between POCs in WLANs. The detailed simulation results show that DSN-MAC can substantially improve overall network throughput.**

I. Introduction

Driven by the explosive increase in the demand of Wireless Local Area Networks (WLANs), the density of Access Points (APs) has increased dramatically. However, the limited 2.4GHz ISM spectrum cannot guarantee non-overlapping between channels used by each co-located WLAN. For example, IEEE 802.11g standard defines 13 available channels, of which only 3 orthogonal channels (i.e., channels 1, 6, and 11) exist [1]. It is difficult to allocate orthogonal channels (shown in Fig.1) to APs in densely populated area. Moreover, the deployments of private APs are spontaneous and unmanaged. Thus, both limited orthogonal channels and chaotic deployments lead to the use of partially overlapped channels (POCs) in modern WLANs, as observed in the measurement studies [2]. In addition, flexible channelization had been proposed in recent works [3], which leads to the coexistence of heterogeneous channels width in a contention domain. The variable-width channelization also makes partially overlapped channels used by different devices unavoidable.

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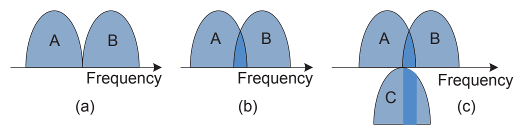

Fig. 1. (a) Non-overlapped (or orthogonal) channels. (b) Two partially overlapped channels. (c) Three partially overlapped channels.

The use of POCs poses a challenge of the coordination between POCs. Since carrier sense works even over POCs, the legacy Medium Access Control (MAC) scheme (i.e., CSMA/CA) defined in 802.11 standards can be used to coordinate transmissions. However, the low efficiency of CSMA/CA had been analyzed in previous studies [4]. In addition, the partial channel blocking and unfairness [3] [5] also have been studied when employing CSMA/CA in POCs. Therefore, the simple carrier sense scheme cannot effectively solve the coordination issue in POCs. Worse, since the current 802.11 system is not design for communication over POCs, direct information exchange between POCs is not possible. Hence, most prior MAC schemes that had been proposed in the literature cannot be used directly in POCs.

The first attempt to take advantages of POCs is presented by Mishra et al. in [1]. The authors show that the interference of POCs is much smaller than the co-channel interference, and improve spatial re-use by POCs assignment algorithm. More studies of POCs had been presented in [6] [7]. However, all of them focus on how to effectively assign POCs in wireless networks. The authors in [5] had shown the feasibility of simultaneous transmissions from POCs is not applicable to OFDM-based WLAN systems such as 802.11g/n. To address collisions between POCs, Li et al. [8] proposed Remap that permutes the bit-to-subcarrier mapping to avoid repeat collisions induced by POCs. The idea of POCs also be utilized to design effective broadcast scheme [9] in multi-channel wireless networks. However, all of the above works do not solve the coordination issue for POCs in wireless networks.

Motivated by the above observations, we argue that it is preferable to enable explicit information sharing between

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POCs to effectively solve the coordination issue. This paper presents DSN (Data Symbol Nulling), a new strategy of communication between devices using POCs. With DSN, devices can exchange lightweight messages as long as the channel used by the receiver partially overlaps with the channel used by the transmitter, i.e., communication over POCs. More specifically, DSN takes advantages of OFDM-based physical layer techniques to create a lightweight control channel which is built on top of the band that is shared commonly by both the transmitter and receiver. Thus, based on this control channel, effective coordination scheme can be designed for POCs. Note that a key design of DSN is that the lightweight communication between the transmitter and receiver that are using POCs does not harm the original data throughput between the transmitter and receiver that are using co-channels. In other words, DSN allows concurrent transmission of control information and traffic data to non-coherent receivers. Thus the coordination overhead can be avoid.

However, some challenges arise when we design DSN. We address them in the rest of this paper that is organized as follows. Section II presents our observations and proposes our communication strategy. Section III describes the system architecture of DSN in details and addresses practical issues on the physical layer when achieving DSN. Section IV validates communication over POCs and presents extensive results. Finally, this paper is concluded in Section V.

II. DSN DESIGN

The key idea of DSN is to enable simultaneous transmissions of control information and traffic data to non-coherent receivers. For simplicity, the term "receiver" represents the receiver whose channel is partially overlapped with the sender, and the term "intend receiver" represents the receiver whose channel is same with the sender. The proposed DSN imposes two challenges. First, how to ensure the receiver can successfully detect, synchronize, and extract control messages in POCs. Second, how to ensure the transmission of control messages does not harm the normal data throughput between the sender and the intend receiver. We will address these challenges and present DSN in details.

A. Communications over POCs

We use OFDM-based 802.11g to illustrate our detailed design of DSN. A OFDM-based 802.11g channel has a frequency width of 20 MHz including a total of 64 312.5 KHz subcarriers, of which there are 4 pilots, 48 data subcarriers, and 12 guard subcarriers. Each channel consists of 4 subchannels each of which has a bandwidth of 5 MHz. Note that the overlapped channel width between adjacent POCs is in the unit of 5 MHz subchannel. Hence, we can observe that there are only 4 overlapping patterns, i.e., a channel overlaps with $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and full of bandwidth of adjacent channels [5]. Since the minimum band that is shared commonly by multi POCs is 5 MHz (i.e., $\frac{1}{4}$ case), we convey control information over this overlapped subchannel consisting of 9 data subcarriers that are numbered logically from 0 to 8 in our implementation. However, in practice, since one side of the overlapped subchannel is aligned with one edge of the channel of the receiver, 3 data subcarriers on one side of the subband is served as guardband (i.e., 0-2), which leaves 6 data subcarriers for the design of DSN. Our designment will show that the control message rate supported by DSN is is sufficient for various applications. For example, DSN can support a minimum control messages rate of about 29 $Kbps$ when the data rate is 18 $Mbps$. In what follows, we present our proposed novel communication strategy in details.

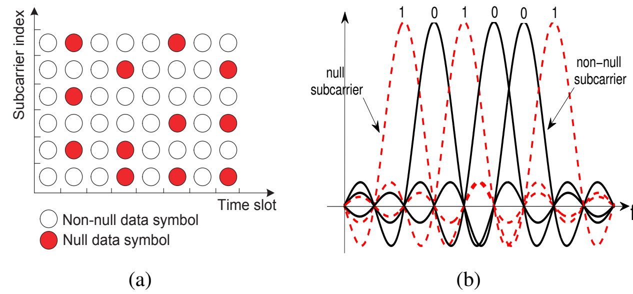


Fig. 2. (a) The message is encoded by varying the pattern of data symbols on OFDM-based PHY. (b) Power allocation of each data symbol in frequency domain for time slot 6.

In OFDM system, the serial data bits are mapped onto OFDM data subcarriers that carry modulated data in parallel. A modulated constellation value corresponds to a data symbol, the smallest resource unit in OFDM (i.e., a two-dimensional time-frequency resource block). The duration of a data symbol (i.e., a time slot) equals to 4 us in 802.11g. DSN maps lightweight control messages into null or non-null data symbols that are used to transmit normal traffic data. A null data symbol is used to express "1" while a non-null (i.e., normal) data symbol is used to express "0". For example, as shown in Fig.2(a), when a sender needs to convey a value of 41 to a receiver, it maps the sequence of binary bits (101001) onto a set of 6 data subcarriers in a time slot (time slot 6). Data symbol nulling can be realized straightforwardly by loading zero power on the corresponding data symbol. Fig.2(b) shows the power distribution of different data symbols in time slot 6. It is easy for a receiver to interpret the modulated control message by energy detection at the granularity of symbols.

A lightweight control channel is created by the proposed communication strategy. Note that the control channel is built on top of normal co-channel communications between the sender and the intend receiver. Hence, a key challenge is how to ensure that DSN dose not corrupt normal data frame, i.e., these intentionally inserted null data symbols can be recovered at the intend receiver.

B. Extra Decoding Capacity

In this subsection, we demonstrate the existence of extra decoding capacity in current WLAN systems. Although Cidon et al. [10] had shown similar analysis, but we present more detailed measurement results. The extra decoding capacity can be used to ensure the successful decoding of data frame at

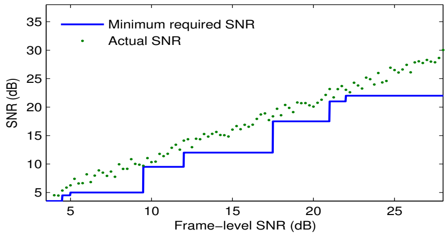


Fig. 3. The SNR gap between the minimum required SNR and the actual channel SNR in our tests using 802.11g.

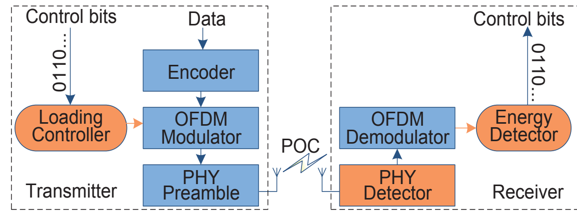


Fig. 4. Architecture of DSN system. The orange blocks are DSN extensions to OFDM-based 802.11g.

the intend receiver by carefully designing the total number of inserted null data symbols.

To maximize throughput, the current commercial 802.11 devices employ rate adaptation based on channel conditions. A lower data rate means higher robustness to channel distortions. The combinations of coding rates and modulation schemes produce various data rates.

However, in practical commodity 802.11 systems, there exists gap between the optimal data rate and the actually adopted data rate, which leads to the fact that the actual decoding capacity at the receiver is always greater than the minimum decoding capacity needed to decode the received frame. This gap comes from the inaccurate estimation of channel status and the stair-case rate adjustment. The current 802.11 devices evaluate channel conditions by the metric of sinal to noise ratio (SNR), of which the signal strength indication (RSSI) is reported by 802.11 NICs and the noise is estimated by the physical preamble. However, the previous measurements [11] have show that the RSSI-based SNR does not reliably reflect the actual channel status due to frequency selective fading. This frame-level SNR metric often leads to the selection of a lower data rate. In addition, a stair-case rate selection is provided by the physical layer while the metric SNR is continuous. Even if the transmitter knows the perfect channel status, the perfect one-to-one matching from channel status to data rate cannot be made [12], which leads to the existence of SNR gap. For example, when the reported SNR is 8 dB at the transmitter, the sender will select the data rate of 12 Mbps whose minimum required SNR is 5 dB, rather than 18 Mbps whose minimum required SNR is 9.5 dB. Hence, this matching gap leads to the under-selection of data rates. Our measurement results are consist with

Based on above analysis, we conduct our experiments and evaluate the total gap between the minimum required SNRs in decoding received frame transmitted by selected data rate and the actual SNRs at the intend receiver. The rate adaptation scheme RBAR [13] is used in our tests. Fig.3 shows the results for measured SNRs, actual SNRs, and minimum required SNRs. We can see that the actual SNR at the intend receiver is significantly above the minimum required SNR to decode data frame. For example, given the measured SNR of 11 dB, the required minimum SNR in decoding of the data frame is 9.5 dB while the actual SNR is 13.2 dB, and this gap value is about 3.7 dB from our tests. This gap suggests that there exits extra decoding capacity to recover more bit errors at the receiver, and we can utilize this residual correcting capability to design the proposed communication strategy.

III. IMPLEMENTATION

This section presents detailed implementation of DSN. In the following subsections, we first present the overall architecture of the proposed DSN, followed by detailed design of newly added modules.

A. Overall System Architecture

Based on current OFDM-based 802.11g physical layer, DSN adds and modifies some components including frame detection and synchronization, modulation/demodulation, rate selection of control messages. As illustrated in Fig.4, DSN works as follows. The transmitter encodes control messages by the loading controller module, and both traffic data and control information are sent to the channel simultaneously. At the receiver side, the incoming data frame will first be detected and synchronized by the PHY detector module. After performing Fast Fourier Transform (FFT), the energy detector module decodes and interprets the received control messages. Hence, extracting control messages is achieved on the physical layer without traditional decode procedure. Note that the intend receiver whose channel is the same with the sender works the same as traditional to receive normal traffic data.

B. Frame Detection and Synchronization

Since the channel of a receiver partially overlaps with the channel of a transmitter, it is a challenge for the receiver to detect and synchronize the incoming data frame. In typical co-channel communications, detecting and synchronizing are achieved by the physical preamble that is a set of predefined sequences [14]. In IEEE 802.11g standard, the preamble structure consists of ten Short Training Symbols (STS) and two Long Training Symbols (LTS) that are transmitted by all 64 subcarriers in frequency domain [15]. Based on the periodic characteristic and strong correlation property of physical preamble, frame detection and synchronization can be achieved by searching the known pattern s of length L in the incoming signal y (or samples). The correlation algorithm is given by

$$C = \sum_{k=0}^{L-1} s^*[k] y[k], \tag{1}$$

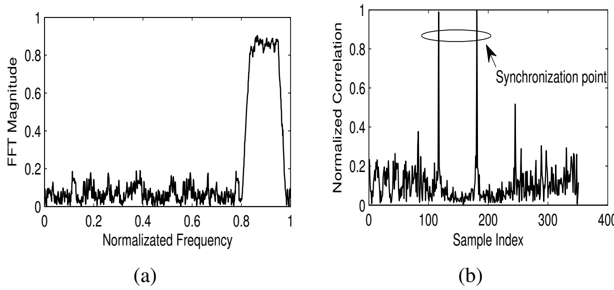


Fig. 5. A $\frac{1}{4}$ overlapping case. (a) Channel overlapping pattern detection by energy detection in frequency domain. (b) Correlation detection to mark precise symbol alignment.

where C denotes the correlation coefficient, and the $s^*[k]$ is the complex conjugate of $s[k]$. A peak correlation value appears if and only if $y[k]$ aligns well with the known pattern s, and the peak value position is used to synchronize the start of the incoming data frame and mark precise symbol alignment.

However, when communicating over POCs, only a fraction of all subcarriers are available to the receiver. Since time domain OFDM signal changes with change in frequency domain, the suppression of subcarriers used to transmit physical preamble will change the structure of preamble in time domain, which leads to failed correlation with predefined preamble. A simple idea to address this challenge is redesign the preamble structure. However, this method poses a obstacle to be compatible with legacy 802.11 preamble. In our design, we restore the correlation properties of physical preamble at the receiver. We modify the original correlation algorithm to cope with truncated preamble as follows.

First, the receiver senses the channel-overlapping patterns by detecting energy distribution of subcarriers in frequency domain, which is achieved through taking the FFT of incoming signal samples. Since the front-end at the receiver filters out a subset of subcarriers that are not present in the overlapping band, it is easy to identify the overlapping cases ($\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and full) by subcarrier-level energy detection. For example, Fig.5(a) shows the energy detection under the $\frac{1}{4}$ overlap case.

Second, based on the detected channel-overlapping pattern, the receiver needs to regenerate corresponding time-domain preamble. For example, when a data frame occupying $\frac{1}{4}$ channel width is detected, only the overlapped subcarriers are used to regenerate preamble in frequency domain while nulling the other subcarriers, and the frequency-domain preamble is transformed to time domain by taking Inverse FFT (IFFT). Then the receiver uses the regenerated preamble pattern to detect and synchronize the incoming frame by correlation algorithm. Fig.5(b) presents the correlation result in the $\frac{1}{4}$ overlap case. In practical implementation, four different preamble patterns are pre-calculated and are stored locally at the receiver.

C. Modulation/Demodulation of Control Messages

Based on the control message (sequence of binary bits) and the set of subcarriers used to be served as control channel, the loading controller is used to control power allocation at data symbol level. By taking N-points IFFT, an OFDM signal in time domain can be obtained by

$$x[n] = \sum_{k=0}^{N-1} X[k] e^{j2\pi \frac{kn}{N}}, \quad n = 0, 1, ..., N-1 \tag{2}$$

where $x[n]$ is the time domain OFDM signal at sample time n, N is the number of OFDM subcarriers, and $X[k]$ is a data symbol on subcarrier k. In normal data transmissions, the modulated symbol values are non-zero. For example, the modulated symbols are $1 + 0i$ and $-1 + 0i$ in BPSK. To implement null symbols, the transmitter can simply feed 0 instead of modulated data symbols to the subcarriers, leading to zero power on the corresponding positions of symbols. Therefore, the control bits '1' and '0' are presented by null symbols and normal symbols, respectively.

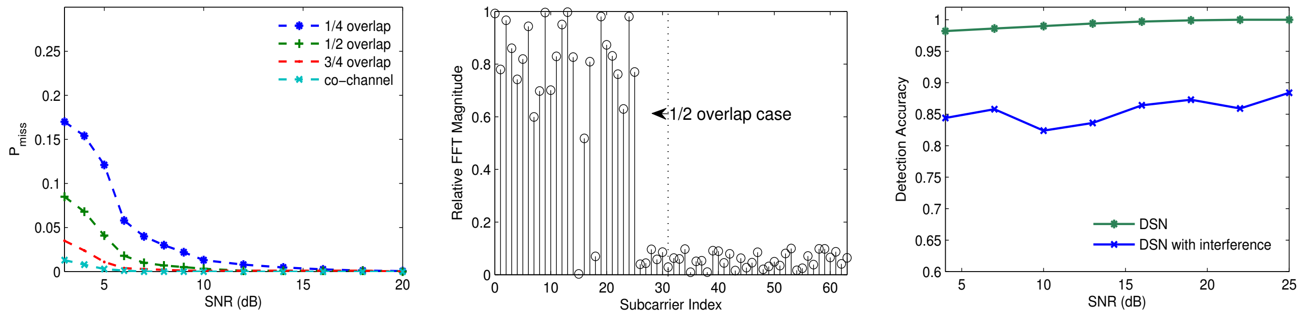
At the receiver side, once the frame detection and synchronization are achieved successfully, the receiver can obtain data symbol level energy detection by taking FFT of incoming signal that is a composite waveform consisting of subcarriers. We emphasize that accurate frame detection and synchronization are important to correctly take FFT that needs right alignment for OFDM symbol boundary. Let $y[n]$ be the signal sample at time n, we get data symbol on subcarrier k by

$$Y[k] = \frac{1}{N} \sum_{n=0}^{N-1} y[n] e^{-j2\pi \frac{kn}{N}}. \tag{3}$$

Based on the FFT result, the energy detector module detects energy of per subcarrier data symbol and interprets transmitted control messages. Note that the energy of those subcarriers where zero power is allocated may not be zero in practical system due to the existence of noise. Fortunately, the noise energy is distributed evenly across all subcarriers. Our test results show that the energy difference between noise subcarrier and signal subcarrier is very apparent. We emphasize that extracting control messages does not need traditional decoding procedure that requires strict channel condition.

D. A Case for DSN-based Applications

Based on the lightweight communication over POCs provided by DSN, we proposed an efficient MAC layer coordination scheme DSN-MAC. The Distributed Coordination Function (DCF) is a contention-based MAC scheme proposed in 802.11 standards. To avoid collisions, nodes execute backoff procedure with backoff counters that are selected randomly. However, this random nature of backoff procedure leads to low coordination efficiency [4]. Here, we will show how to take advantages of DSN to design DSN-MAC that can be worked both in co-channel and partially overlapped channel scenarios. In DSN-MAC, when the sender transmits data frames, the next backoff counter [4] is embedded into the control messages. Hence, both the intend receivers and the receivers can obtain this reservation information, and they perform backoff procedure without selecting this backoff counter. By this way, the number of collisions will decrease. The detailed evaluations of DSN-MAC are given in next section.



(a) (b) (c)

Fig. 6. (a) Miss detection probability for frames from partially overlapped channels. (b) FFT Magnitude. (c) Accuracy of detecting control messages.

IV. Evaluation

This section first validates the feasibility of communication over POCs. Next, we test appropriate rates of control messages. Finally, our simulation results are presented to study the performance of DSN-MAC. Our implementation of DSN is based on standard 802.11g physical layer, and our simulations are written in C++ and Matlab.

A. Feasibility of Communication over POCs

The accuracy of frame detection and synchronization is evaluated by the miss detection probability P_{miss} under a large SNR region. P_{miss} is calculated by the fraction of transmissions that are expected to detect but fails to be detected. Four channel overlapping patterns are used in our testes. As shown in Fig.6(a), the P_{miss} depends on both the channel overlapping patterns and the SNRs. Under the $\frac{1}{4}$ overlap case, when SNR increases, the corresponding P_{miss} decreases sharply. Although the $\frac{1}{4}$ overlap case shows a higher miss detection probability at low SNR (below 6.5 dB), but the actual wireless networks work in a high SNR region (above 7 dB) that is sufficient for DSN to achieve a close-to-zero P_{miss}. For other overlap cases, the P_{miss} is very low for all SNRs. This implies that when only a small fraction of the channel is used to transmit preamble, the correlation detection becomes vulnerable to noise.

Once the frame detection and synchronization are achieved, the receiver can extract control information by taking FFT of incoming samples. The $\frac{1}{2}$ overlap case is used in this experiment. Fig.6(b) shows the magnitude of 64 points FFT. All 64 subcarriers are numbered logically from 0 to 63, of which the subcarriers [13, 14, ..., 18] are used to convey control bits. Based on energy detection on individual subcarriers, the conveyed value is interpreted as "110110". We perform this experiment with 2000 packets to evaluate the detection accuracy under various SNRs. As shown in Fig.6(c), we can observe that the detection accuracy is above 98% even at low SNRs, and it is close to 100% when the SNR is above 17 dB. However, the detection accuracy is below 89% when there is interference, and the increase of SNR has little effect on detection accuracy under interference case. This is because interference may fall onto those intentionally inserted null data symbols so that these null data symbols are falsely detected to be interpreted as '0'. In our experiments, we do not consider interference that can be avoid by MAC coordination scheme, and how to solve interference issue will be our further works.

TABLE I
MAXIMUM NUMBER OF INSERTED NULL DATA SYMBOLS PER SECOND AT VARIOUS CHANNEL SNRS.

QPSK 1/2		QPSK 3/4		16QAM 1/2		16QAM 3/4	
SNR	R_m	SNR	R_m	SNR	R_m	SNR	R_m
5.2dB	18000	9.6dB	14500	12.3dB	11200	17.7dB	9800
5.8dB	39000	10.1dB	21000	13.0dB	23500	18.1dB	11700
6.7dB	82000	10.7dB	43000	13.8dB	53000	18.8dB	24000
7.5dB	113000	11.0dB	71000	15.2dB	78500	19.6dB	51000
8.7dB	113000	11.5dB	93000	16.7dB	78500	20.2dB	64000
9.2dB	113000	11.8dB	93000	17.2dB	78500	20.8dB	64000

B. Rate of Control Messages

The key principle of designing DSN is to ensure the total number of intentionally inserted null data symbols does not destroy the normal data communications, i.e., these null data symbols can be recovered successfully by extra decoding capacity. Let R_m denote the maximum number of inserted null data symbols per second. On various channel conditions, we obtain the corresponding R_m by extensive simulations. In our implementation, the number of control subcarriers is fixed and equals to 6, and we change the rate of inserted null data symbols to obtain acceptable packet reception rate (PRR) at the intend receiver. Note that half of the transmitted control bits are "1", so the average rate of control messages is twice the value of R_m. The SNR-based adaptation scheme is used to adjust the data rate that is a combination of modulation scheme and code rate, and four data rates are tested. (QPSK,1/2), (QPSK,3/4), (16QAM,1/2), and (16QAM,3/4) correspond to data rates of 12 Mbps, 18 Mbps, 24 Mbps, and 36 Mbps, respectively.

As illustrated in Table. I, the values of R_m are given on various channel SNRs. For example, when the channel SNR is 10.7dB, $R_m = 43,000$ and the corresponding average rate of control messages is 86 $Kbps$. Given a data rate, the value of R_m increases faster as the increase of channel SNR. The upper bound of R_m is limited by the capability of channel code. When data rate is 18Mbps, a maximum R_m is 93,000

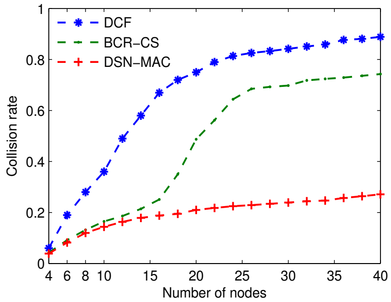


Fig. 7. Collision rate versus number of nodes when POCs exist in network.

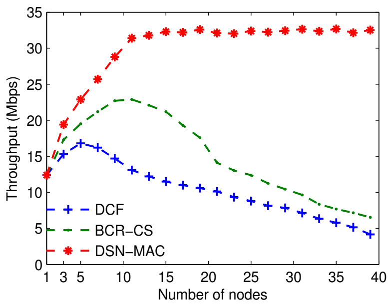


Fig. 8. Throughput versus number of nodes when POCs exist in network.

and a minimum R_m is 14500. However, a limitation of DSN is the capacity of control messages with in a single frame transmission is small. Since the frame aggregation technique is widely used in modern WLANs, more control bits can be transmitted within a transmission chance.

C. Performance of DSN-MAC

In this subsection, we evaluate the performance of DSN-MAC in details. Two types of nodes are included in this simulation where type A nodes operate in channel A while type B nodes operate in channel B. Channel A overlaps with $\frac{1}{4}$ of channel B. All nodes are in the same contention domain, and the number of type A nodes equals to the number of type B nodes. Both 802.11 DCF scheme and the BCR-CS [4] scheme are used to be compared with DSN-MAC.

Fig.7 shows the result of collision rate for DCF, BCR-CS, and DSN-MAC as the number of static nodes increases from 4 to 40. We can observe that the collision rate of both BCR-CS and DSN-MAC are smaller than DCF. This is because both of these two scheme adopt backoff counter reservation to reduce collisions. However, the collision rate of DCF becomes more serious than DSN-MAC when the number of nodes increases. Since type A nodes can not directly communicate with type B nodes, type A nodes can not overhear the reserved backoff counters from type B nodes so that the reservation is not fully utilized for BCR-CS in partially overlapped channels scenario. The overall throughput is shown in Fig.8. Note that when more nodes are in the network, the BCR-CS scheme is slightly superior to DCF method. However, DSN-MAC still maintains a high throughput. The reason is that information exchange works even for POCs in DSN-MAC. For example, when the total number of nodes is 20, DSN-MAC exhibits 120.6% higher throughput than BCR-CS.

V. Conclusion

Different from previous works that focus on coordination in co-channels, this paper considers coordination between partially overlapped channels, and presents DSN, a novel cross-layer design that aims to enable lightweight communication between partially overlapped channels. The key concept of DSN is that the control message is embedded into the data symbol pattern (null or non-null), rather than the actual data symbol value. We address practical challenges in designing DSN, and our extensive results validate the feasibility of DSN in a large SNR range. We believe the applications of DSN include, but not limited to, coordination. Other applications such as throughput aggregation, resource allocation, and energy management will be explored in our future work.

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