# Design of Non-orthogonal Multi-channel Sensor Networks

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Abstract—A critical issue in wireless sensor networks (WSNs) is represented by the network throughput. To meet the throughput requirement, researchers propose multi-channel design in 802.15.4 networks to better utilize the wireless medium and avoid the co-channel interference. However, traditional orthogonal channel design restricts the number of channels and limits the throughput performance. We argue that the orthogonality is not necessary for multi-channel design in WSNs.

In this paper, we investigate the feasibility of non-orthogonal channel design. In our experiment, we observe that with nonorthogonal transmission, the effect of interference comes from co-channel and inter-channel is different. More specifically, the inter-channel interference is tolerable with certain channel center frequency distance (CFD). According to that, we propose a novel scheme DCN (Dynamic CCA-threshold for Non-orthogonal transmission) which adjusts the CCA-threshold to enable the concurrent transmissions on adjacent non-orthogonal channels and thus improve the overall network throughput performance. Through comprehensive experiments on our testbed, we verify that our DCN achieves about  $38.4\% \sim 55.7\%$  throughput improvement in general network configurations comparing to the default ZigBee design.

*Index Terms*—Multi-channel, orthogonal channel, interference, CCA-threshold, wireless sensor networks.

## I. INTRODUCTION

As an emerging technology, wireless sensor networks (WSNs) have been designed to support a wide range of potential applications, including environment monitoring, event detection as well as information collection [1][2][14]. In these applications, large number of sensors are deployed in the interested region, communicate with each other using wireless medium. Due to the shared nature of wireless medium, the interference among multiple transmissions that use the same channel becomes a fundamental issue [3]. Existing works [20] show that concurrent transmissions in the same channel is a great menace to the communication, since it will lead to collision where the collided packets would not be decoded successfully. It is well known that the current WSN hardware, such as Micaz and Telos that use the CC2420 radio, already provide multiple frequencies. Therefore, designing multi-channel based communication protocols in WSNs to improve network throughput and provide high performance communication services is then a nature way [18].

For multi-channel based communication protocol design in WSNs, one of the most important parameters is the number of channels which can actually be used. The CC2420 radio

chip that follows ZigBee standard [10] provides 16 channels, with 5MHz as the center frequency distance (CFD) between neighboring channels. However, as Wu et al. pointed out [18], not all channels can be used in a single sensor network to provide parallel transmissions because of close channel interferences and interferences caused by other wireless networks. To address the channel scarcity issue, several studies [7][15] have been proposed to utilize overlapping channels, which were targeted for 802.11 networks only. Similar studies in 802.15.4 networks are limited. Through our experiment, we find that 802.15.4 networks show unique interference characteristics which cannot be captured by existing 802.11 models. More importantly, such uniqueness will benefit multichannel design of 802.15.4 networks particularly and plays a key role in our study.

For a given network with a certain spectrum band, nonorthogonal channel assignment provides more available channels. However, comparing to the traditional orthogonal channel assignment, it introduces a critical challenge, i.e., the interchannel interference may affect the transmission significantly. Thus, to decide a reasonable frequency distance between neighboring-channels, the trade-off between larger number of channels and weaker inter-channel interference has to be carefully considered. Through our following experiments, we verify that assigning each channel with the channel distance that guarantees orthogonality (i.e., 9MHz for 802.15.4) cannot fully utilize the bandwidth medium. Moreover, the default CFD setting of ZigBee, i.e. 5MHz, is inefficient as well. Our interesting observation is that the assignment based on a smaller CFD, e.g., 3MHz, provides better bandwidth utilization. Specifically, if we assign each channel with the CFD as 3MHz and generate saturated traffic on each channel, the overall throughput on a given spectrum bandwidth would be improved significantly comparing to the orthogonal channel assignment scheme. Comparing with the result obtained with the ZigBee default setting, more than 40% throughput gain could be achieved by leveraging smaller CFD, showing that smaller CFD better exploits the bandwidth.

To further study how to better leverage the non-orthogonal channels with smaller CFD, e.g., 3MHz, we verify the feasibility of concurrency between assigned non-orthogonal channels. Different to the collision of co-channel interference that collided packets cannot be both decoded successfully, packets transmitted simultaneously from two non-orthogonal channels

(e.g., CFD=3MHz) could be decoded successfully in most power settings or just be slightly corrupted. According to this unique observation in 802.15.4 networks, we propose a new scheme DCN (Dynamic CCA-threshold for Non-orthogonal transmission) that can dynamically modify CCA-threshold<sup>1</sup>. By doing so, non-orthogonal channels possess the capability of concurrency, which is usually supported by orthogonal channel assignment. We also discuss that the packet recovery scheme could be integrated with DCN to rescue the slightly corrupted packets in some special cases. The empirical experiments show that our scheme DCN can achieve about  $38.4\% \sim 55.7\%$ bandwidth throughput improvement with CFD=3MHz, comparing to the default multi-channel settings of ZigBee.

In this paper, we for the first time investigate the feasibility of non-orthogonal multi-channel design for ZigBeebased WSNs and propose a CCA-threshold adaptation scheme to maximize the bandwidth throughput. As a summary, we have the following contributions: 1) we empirically verify that the default setting of CFD=5MHz in ZigBee is quite conservative. The assignment with smaller CFD could achieve better throughput on a given bandwidth; 2) we observe that different to co-channel interference, the inter-channel interference introduced by non-orthogonal assignment is tolerable in most of the communication settings (e.g., transmission power, CFD). The collided packets caused by such inter-channel interference could be decoded successfully or only have a small portion of bit errors. Thus, we propose a new scheme DCN to exploit the concurrencies on non-orthogonal channels; 3) with the comprehensive experiments on a real testbed, we verify that our DCN could obtain significant throughput improvement comparing to the traditional ZigBee setting.

The rest of the paper is organized as follows. We discuss the related work in Section II. In Section III, we introduce a concrete example which motivates our investigation. Section IV is devoted to the detail analysis of non-orthogonal multichannel design, which consists of the study on the co-channel interference and inter-channel interference; while Section V presents our scheme DCN. The extensive experiments of our proposed design is shown in Section VI and in Section VII we will have a further discussion on the packet recoverability and the upper bound of bandwidth throughput with DCN. Finally, a conclusion for the paper will be made in Section VIII.

## II. RELATED WORK

It has been well studied that using multiple channels can significantly enhance the network capacity in wireless networks [17]. In recent years, there are also some studies on efficient delivery in wireless sensor networks by making use of multi-channel, such as MCMAC [6], TMMAC [21], MMSN [22], etc. However, all these works assume the channels are orthogonal and they all evaluated by simulation only. Wu et al. proposed TMCP [18], a realistic multichannel protocol based on empirical experiments. In their conclusions, they complained that the small number of available channels limits the multi-channel design of WSNs. Therefore, they find fully orthogonal and high-quality channels first and partition the whole network into sub-trees according to the number of available channels. However, in our experiment, we come out an interesting observation that though the non-orthogonal channel interference affects the transmission, such interference is tolerable. Thus, we use non-orthogonal channels in our scheme with CFD smaller than the default setting of ZigBee to provide more available channels.

Although non-orthogonal channel interferences have been addressed in wireless networks [15] [16], related empirical works in WSNs are rare. Incel et al. have conducted a measurement study for adjacent channel interference in WSNs using Ambient uNode [11]. In our work, more popular MicaZ motes [8] are used. Besides, they disabled the MAC layer behaviors of sensor node to introduce collisions; but we have studied a new dimension: setting different CCA-threshold instead of disabling entire CSMA policy. By varying CCA-threshold, we can control the power level of introduced interference and demonstrate the different throughput performance. Recently, Xing et al. studied the interference of adjacent channel in WSNs [19], but they use the channel assignment according to ZigBee [10], while we use even smaller frequency distance to partition channels for maximizing the utilization on bandwidth.

There are also some works discussed the optimal setting of CCA-threshold [3] [23]. However, since their works are based on single channel design where there is no neighboringchannel interference, they only consider co-channel interference. Our study is a multi-channel design that exploits non-orthogonal channels, thus the uniqueness of our CCAthreshold setting scheme (DCN) is the differentiation of the interference from co-channel and neighboring-channels, with an emphasize on dealing with the neighboring-channel interference. More, Bertocco et al. used White Gaussian noise generated by signal generator as interference source [3]. However, in densely deployed WSNs applications, the main interference is transmitting packets, i.e., valid IEEE 802.15.4 packets. Obviously, signal generator cannot emulate a real interfering network: first, White Gaussian noise is different from a valid packet; and second, constant noise cannot simulate the traffics of a transmitting network. In this work, we use actual testbed to generate interference from multiple channels.

#### III. MOTIVATION: FEASIBLE NON-ORTHOGONAL DESIGN

In this section, we focus on a simple example to demonstrate the feasibility of non-orthogonal multi-channel design. Through the experiment, we find that comparing to the CFD which guarantees the orthogonality, smaller and nonorthogonal CFD may have better utilization on the given bandwidth but we also point out that there is a trade-off. To further explain the advantages of non-orthogonal channel design, we study the concurrency between non-orthogonal channels. We observe that the concurrent transmission between

<sup>&</sup>lt;sup>1</sup>CSMA exploits clear channel assessment (CCA) method, which determines the state of channel by checking whether the in-channel energy is above a given threshold (CCA-threshold) and transmission can only happen if the channel appears idle.



Fig. 1.Bandwidth Throughput with Fig. 2.Uniqueness of 802.15.4 Net- Fig. 3.Different Frequency DistanceworksSendernon-orthogonal channels is feasible which implies the potentialconbandwidth improvement.ser

#### A. Channel Distance vs. Overall Throughput

We first evaluate different CFD=9, 5, 4, 3, 2MHz with ZigBee default protocol on a given bandwidth of 12MHz: for CFD=9MHz which almost guarantees the fully orthogonality, we only have 1 channel while for CFD=5MHz which is the default setting of ZigBee, we have 2 channels. We also try smaller CFD (e.g., 4, 3, 2MHz) which could assign more number of channels but introduce severer inter-channel interference. For each assigned channel, we have 4 MicaZ nodes with maximum transmission power (i.e., 0dBm). All the nodes are sending packets at the maximum data rate, generating a saturated traffic of the channel.

As shown in fig. 1, it demonstrates that the orthogonal channel assignment will not provide the maximum throughput (e.g., in Fig. 1 the maximum throughput is achieved at CFD=3MHz). The reason is that, though the throughput for a single channel is maximized by orthogonal CFD setting (i.e., CFD=9MHz), but the overall throughput for orthogonal CFD setting is poor due to the limited number of channels. However, smaller CFD (e.g., CFD=2MHz) may not always benefit the overall throughput since severer inter-channel interference may corrupt more and more packets.

This example indicates that: 1) default setting of CFD=5MHz in ZigBee is quite conservative, smaller CFD for multi-channel design could obtain better bandwidth throughput; 2) there is a tradeoff between throughput benefit from more number of channels and harm from severer inter-channel interference. To further get the understanding of how to leverage the non-orthogonal channels to achieve the maximum bandwidth throughput, we study the concurrent transmission between non-orthogonal channels in the following subsection.

### B. Concurrency between Non-Orthogonal Channels

In this subsection, we verify the feasibility of concurrent transmissions in non-orthogonal channels. In 802.11 networks, concurrent transmissions on non-orthogonal channels is infeasible. It is because inter-channel interference acts as valid packets and force receiver to decode it (even the interference is from three channels away, i.e., 15MHz away); during the decoding, the receiver lose desired packet that is sent simultaneously in the same channel (see experiments result conducted by Mishra et al. [15] as shown in Fig. 2). As the comparison, in our experiment on 802.15.4 (ZigBee) [10]



compliant devices (Crossbow MicaZ motes [8]), we found that sensor device cannot decode packets from inter-channels, even the packets are from only 1MHz frequency distance away. Therefore, inter-channel concurrency is feasible for 802.15.4 networks.

To generate inter-channel concurrencies, we set two links on non-orthogonal channels sending out packets simultaneously by disabling their carrier sense module. Since it is hard to synchronize the collision of two packets, we design the sender of one link as an attacker which sends out packets at an extremely fast rate, i.e., 1 packet for each 3ms. With such high channel occupancy, all the packets from the normal sender on the other link would be collided as shown in Fig. 3.

We focus on the node's capability of decoding with interference by computing the Collided Packet Receive Rate (CPRR) for both the attacker and normal sender. By evaluate different CFD with the same transmission power, the experiment results shown in Fig. 4 address the feasibility of concurrency on adjacent channels: for CFD greater than 4MHz, both CPRR of the attacker and the normal sender is 100%; CFD=3MHz provides 97% CPRR which indicates that most collided packets could be decoded successfully; for the case of CFD=2MHz, CPRR decreases to around 70% due to the severer inter-channel interference; and for the extreme case of CFD=1MHz, it shows poor concurrent feature that less than 20% collided packets could be decoded successfully.

In this section, we observe that simply using smaller CFD design instead of traditional ZigBee setting or orthogonal assignment could achieve better bandwidth throughput. Above experiment results also show the feasibility of concurrent transmission in non-orthogonal channel which implies the potential bandwidth improvement that we can obtain.

# IV. CCA-THRESHOLD RELAXING FOR THROUGHPUT IMPROVEMENT

In previous section, we have shown that the concurrency is feasible for non-orthogonal channel design (e.g., CFD=3MHz) by disabling the carrier sensing module of senders to introduce the inter-channel collisions. However, there is another responsibility for carrier sensing module, to filter the co-channel interference. Thus, simply disabling the carrier sensing module is not a proper way to achieve better throughput. On the other hand, the CCA-threshold is fixed at -77dBm in the default setting of ZigBee. It assumes that the interference/noise over -77dBm would corrupt the packets, and thus makes the sender backoff when it hears the inter-channel interference but actu-





Fig. 5. Network Configuration without Co- Fig. 6. channel Interference

Link Throughput with Different CCA- Fig. 7. Overall Throughput with Different CCA-Threshold (Case without Co-Channel interference) Threshold (Case without Co-Channel interference)



Threshold (Case with Co-Channel interference) sion Power (Case with Co-Channel interference) Power (Case with Co-Channel interference) ally miss the chance that the sender can still do transmission since such inter-channel interference is tolerable as observed in previous section. Therefore, the conservative setting of CCAthreshold prohibits the concurrency opportunities and draws the throughput gap between orthogonal and non-orthogonal channel design as shown in Fig. 1. In this section, we modify the carrier sensing module, analyze and find a principle to select proper CCA-threshold for the throughput improvement.

We will focus on the case of CFD=3MHz in the following experiments since it shows that CFD=3MHz achieves best performance with default carrier sensing module in Fig. 1.

# A. Throughput Improvement without Co-Channel Interference

We start with a simple case without co-channel interference. For a single link transmitting with 4 neighboring-channel interference (i.e., CFD= $\pm 3$ ,  $\pm 6$ MHz, see Fig. 5) using the same power (0dBm), we enumerate different CCA-threshold for this particular link. In Fig. 6, with more relaxed CCAthreshold, such link sends out more packets since it turns to consider more interfered channel condition as a clear channel status. As such neighboring-channel interference is tolerable, more packets that the link sent out lead to better throughput. Meanwhile, we also notice that the packet receive rate (PRR) keeps almost 100%, which indicates the reliability of neighboring-channel concurrency and matching the result of our previous concurrency test (Fig. 4) as well.

Furthermore, we check the overall throughput to see whether such link throughput gain degrades other networks' throughput. As demonstrated in Fig. 7, the overall throughput also grows which indicates that the inter-channel concurrency has been leveraged successfully. Therefore, without co-channel interference, we could obtain better throughput gain by relaxing CCA-threshold. The next step is to answer what CCAthreshold to select by taking the co-channel interference into the consideration.

# B. The Case with Co-channel Interference

From the viewpoint of every sensor node, it not only has neighboring-channel interference but also encounters the cochannel competitors. Thus, the CCA-threshold should also be responsible for dealing with the co-channel interference.

Based on previous experiment, we introduce 3 additional links working together with that particular link at the same channel. The result in Fig. 8 shows that relaxing CCAthreshold will not always benefit the throughput.

To further explain it, in the experiment case, the co-channel interference is stronger than the neighboring-channel interference (the vertical line shows the minimum power level of cochannel interference) and once we relax CCA-threshold more, the co-channel interference would be introduced which leads to a disaster. For two collided packets in the same channel, current common used modulation component of sensor node could only decode at most one of them; or in the worst case, both packets are corrupted. The throughput will not benefit from the co-channel interference but be harmed.

As a short summary, through the experiments above we observe that relaxing CCA-threshold could exploit more interchannel concurrent opportunities to improve the throughput where the default CCA-threshold setting is quite conservative for leveraging inter-channel concurrency. On the other side, the co-channel concurrency should be avoided since decoding cochannel interfered packets would robber the time for normal



#### Fig. 11. Architecture of DCN

transmission. This observation would be a basis to propose our dynamic CCA-threshold scheme in next section.

#### C. Effect of Transmission Power

In all the experiments above, we discuss feasibility of concurrency and relaxing CCA-threshold with the setting of the same transmission power. To further verify whether our observation holds for different power setting, we will evaluate the effect of transmission power in this subsection.

Fig. 9 illustrates that with different transmission power, there would always be some throughput improvement by relaxing CCA-threshold to introduce the inter-channel inter-ference. Without surprise, the gain is different with different transmission power due to the node's capability of decoding with interference. However, we found that for most of the cases, i.e., transmission power is greater than -22dBm, the PRRs are all 100% (in Fig. 10). Even for the case that link's transmission power is -22dBm vs. 0dBm of the interference, the PRR is higher than 80%. Such experiment results provide a support for our observation so that we could design our scheme for most general cases.

# V. DESIGN AND IMPLEMENTATION

As a conclusion in previous section, in terms of bandwidth throughput the CCA-threshold should be relaxed to introduce concurrencies with neighboring-channel transmissions. However, the CCA-threshold could not be relaxed in an arbitrary way since there is also a responsibility for it to prohibit the co-channel collisions. Thus, the CCA-threshold must be able to introduce the inter-channel interference and filter the co-channel interference at the same time. Towards this end, we design and implement DCN, a scheme of Dynamic CCA-Threshold for Non-orthogonal transmission. In DCN, we modify sensor MAC protocol by adding an new component, CCA-Adjustor. In the following subsections, we first show the architecture of our DCN, followed by the design of CCA-Adjustor and finally introduce the implementation in detail.

# A. Architecture

In the traditional CSMA/CA policy (see Fig. 11), the upper layer wishing to send packets has to first sense the power of using channel to check whether there is any activity on the channel by comparing the sensing power with a predetermined



Fig. 12. Setting of CCA-Threshold

CCA-threshold. If the sensing power is stronger than the CCAthreshold, it regards the channel as currently occupied and postpones the transmission request; otherwise, the channel is available and the packet will be transmitted immediately.

Based on the CSMA/CA policy above, we add a new component, CCA-Adjustor, in our design to adjust the CCAthreshold dynamically, instead of using the fixed value. The purpose of such CCA-Adjustor is to relax the CCA-threshold according to different transmitting power of interference, for leveraging neighboring-channel concurrencies while avoiding the co-channel collisions.

#### B. Design of CCA-Adjustor

There are two types of interference information we could obtain from the sensor node: 1) RSSI of co-channel interference packets; 2) in-channel sensing power which means the signal power of current using channel, including not only cochannel packets but also inter-channel interference. To avoid the co-channel collisions, a safe principle for CCA-threshold setting is to be smaller than the power level of any cochannel interference packets and with such constraint as high as possible to introduce the concurrencies on non-orthogonal channels.

Concretely, CCA-Adjustor modify the CCA-threshold in two phases: *Initializing Phase* which focuses on getting a conservative initial CCA-threshold setting without any relaxing; and *Updating Phase* which is devoted to update the CCAthreshold according to most recent interference traffics.

1) Initializing Phase: In the initial stage when sensor nodes have just started, aggressive CCA-threshold setting may introduce unexpected co-channel interference. Thus, the CCA-threshold should be determined cautiously to avoid any potential co-channel interference in the initializing phase.

More specifically, assume we obtain the RSSI  $S_i^I$  of cochannel interference packet  $MSG_i^I$  in the initial stage and the in-channel sensing power sequence of  $\{P_j^I\}$ . The CCAthreshold  $CCA_I$  should satisfy:

$$\forall i, \ CCA_I < S_i^I \tag{1}$$

and be even lower as shown in Fig. 12 (2) to avoid the potential co-channel interference occurring in the gap between current co-channel and inter-channel interference records:

$$CCA_{I} = \min\{S_{1}^{I}, S_{2}^{I}, ..., \max\{P_{1}^{I}, P_{2}^{I}, ...\}\}$$
(2)

where the CCA-threshold is initialized as the *smaller one* between minimum power level of co-channel interference and maximum power level of the inter-channel interference.

Generally, sensor nodes would not only consider  $S_i^I$  the RSSI of co-channel packets, but also  $P_j^I$  the in-channel sensing power in the initializing phase. According to these information, the nodes make a conservative CCA-threshold setting.

2) Updating Phase: Note that, the in-channel sensing power  $P_j^I$  would result extra CPU overhead on sensor nodes. Therefore, it is not cost effective to do in-channel power sensing after initialization. In the following updating phase, CCA-Adjustor would only record the RSSI  $S_i^U$  of recent co-channel interference packet MSG<sub>i</sub><sup>U</sup> and dynamically update  $CCA_U$  to avoid co-channel collisions.

Concretely, the CCA-threshold would be updated in the following two cases:

**CASE I:** if the RSSI of a received packet is smaller than current  $CCA_U$ , the CCA-threshold would be updated as such RSSI immediately:

$$CCA_U = S_i^U \text{ if } S_i^U < CCA_U \tag{3}$$

**CASE II:** if no update has been done by Case I in last  $T_U$  seconds (e.g.,  $T_U = 3$  seconds in our experiments), the CCA-threshold would be updated as the minimum RSSI of co-channel interference packets recorded in last  $T_U$  seconds:

$$CCA_U = \min\{S_1^U, S_2^U, ...\}$$
 (4)

In the updating phase, different from in-channel power sensing, obtaining RSSI information would not introduce extra overhead since the co-channel interference packet would be buffered automatically in current design of sensor nodes (i.e., MicaZ node in our experiments).

#### C. Implementation

We implement our DCN on the testbed consists of 35 MicaZ motes [8], which are equipped with Chipcon CC2420 Transceiver module [4]. The main information that our CCA-Adjustor would leverage, RSSI value of packets, can be obtained from RSSI field of each received packet [5]. Besides recording the RSSI of packets, in-channel power sensing could be performed by accessing the RSSI register RSSI.RSSI\_VAL of CC2420 transceiver [5], which is an average of previous 8 symbol periods ( $128\mu$ s).

In our implementation, after the start-up of sensor node, it first enters the *Initializing Phase* which lasts for  $T_I = 1$  second and checks the RSSI  $S_i^I$  of co-channel packets during that period of time and keeps the minimum record. Meanwhile, it senses the in-channel power  $P_j^I$  every millisecond and holds the maximum one. The initial CCA-threshold would be set as Equ. 2. After moving into the *Updating Phase*, the node dynamically maintain the minimum RSSI value of received cochannel packet in last  $T_U = 3$  seconds. The CCA-threshold would be updated immediately once the record is smaller than current CCA-threshold setting. If no update happens in last  $T_U$ seconds, the CCA-threshold would be modified as the current record of minimum RSSI value in last  $T_U$  seconds.

# VI. EVALUATION

In this section, we evaluate the performance of our DCN when compared to the original ZigBee design. We divide our evaluation in two main subsections. First, we apply our DCN on five networks (each network consists of 4 MicaZ nodes) with different channel frequencies and evaluate the impact of CFD on the performance of DCN. This evaluation answers what CFD should be selected in our implementation of DCN. Next we evaluate our DCN for the entire non-orthogonal multi-channel design. Given a spectrum bandwidth, e.g., from 2458MHz to 2473MHz, our DCN separates nodes into 6 networks with CFD=3MHz. We give a detailed account of throughput compared with ZigBee standard (i.e., 4 networks with CFD=5MHz). Finally, we conclude our evaluation by verifying DCN with different network configuration.

Our data analysis mainly focuses on network throughput and discusses the impact of transmission power and the fairness issue. We also conduct extensive experiments with various network configuration such as topology, power variation, etc.

# A. Effect of CFD on DCN

In order to find the CFD influences of our DCN on the network throughput, as illustrated in Fig. 13, we evaluate two typical CFD=2MHz and 3MHz on 5 networks. The primary reason to compare CFD=2MHz and 3MHz is that, the experiment results in Fig. 1 and Fig. 4 realize the observation that CFD= 3MHz achieves best throughput performance without introducing DCN and CFD= 2MHz with a little bit lower throughput still has potential since its CPRR has about 30% room to improve.

We grasp this observation and first apply our DCN only on network  $N_0$  (i.e., the network with median frequency) to check how it beats traditional CCA-threshold fixed scheme. It can be seen in Fig. 14 that, our DCN achieves about 27% throughput improvement on network  $N_0$  for both CFD=2MHz and 3MHz. However, from the viewpoint of other networks (i.e., Network  $N_1, N_2, N_3, N_4$ ), the throughput is degraded by around 5% in Fig. 15. The results explain the influence of inter-channel interference of non-orthogonal design. More over, as shown in Fig. 14, for CFD=3MHZ its throughput reaches around 250 packets/s which is almost the same as the orthogonal channel assignment (e.g., CFD=9MHz in Fig. 1). It implies that for CFD=3MHz, after applying DCN, network  $N_0$  achieves nearupper bound of throughput by beating other networks which are not applied DCN scheme.

To further evaluate the interaction of DCN scheme on multiple networks, we apply our DCN to all 5 networks. We see in Fig. 16 (CFD=2MHz) and Fig. 17 (CFD=3MHz) that the throughput of every network improves. It indicates a good collaboration of our DCN: all the networks can tolerate the inter-channel interference and leverage concurrency as well. Note that the throughput improvement varies between different networks. For example, in Fig. 17, network  $N_4$  has 4.6% throughput improvement which is lower compared with 16.5% improvement of network  $N_0$ . The reason is that, network





 $N_4$  works on the boundary frequency which faces less interchannel interference as shown in Fig. 13 and thus has less concurrency opportunities to leverage.

Back to the target of this subsection, to see the CFD influence of our DCN on the overall throughput, we calculate the overall throughput in Fig. 18. Clearly, for CFD=3MHz, DCN improves the overall throughput by 10% and reaches about 1300 packets/s which is 1.37 times compared with the setting of CFD=2MHz. The experiment results show that CFD=3MHz provides better overall throughput. Therefore, we select CFD=3MHz for our non-orthogonal multi-channel design in the following experiments.

## B. DCN on Non-orthogonal Multi-channel Design

In this subsection, we thoroughly evaluate the performance of DCN on non-orthogonal multi-channel design in terms of throughput, transmission power effect, fairness concern, and network topology. Our major performance benchmark is to improve the overall throughput for a given spectrum bandwidth by better utilizing the wireless medium. Given a spectrum bandwidth of 15MHz (i.e., from 2458MHz to 2473MHz), we first compare the performance of DCN with the default design of ZigBee. Next we verify the general applicability of our DCN with different transmission power setting. The fairness issue is also evaluated and we finally testify our DCN with more general cases of various network configuration.

1) Comparison with Default ZigBee Design: In our nonorthogonal multi-channel design, we select CFD=3MHz and apply DCN on 5 networks for the given spectrum bandwidth of 15MHZ. The corresponding ZigBee design only assign 4 channels with CFD=5MHz and fixed CCA-threshold scheme. In Fig. 19, we see that each individual network's throughput of DCN is better than the ZigBee channel (about 5.4% improvement for an individual network), because frequency distance of 5MHz cannot guarantee the orthogonality, and thus the network with fixed CCA-threshold would be affected by the non-orthogonal transmission from neighboring channels. On the contrary, our DCN design better exploits the interchannel concurrencies even with severer interference introduced. Besides, we have more channels assigned in our DCN design due to small CFD setting. Therefore, the result shows that our DCN design has 58% overall throughput improvement compared with default ZigBee design.

2) Impact of Transmission Power: In previous Section IV, we've already shown the effect of transmission power on concurrency. The results in Fig. 9 and Fig. 10 present the feasibility of concurrency. Based on that, we evaluate the effect of transmission power on our DCN design. We focus on network  $N_0$ , the one with central frequency of the spectrum band and suffers almost the severest inter-channel interference, and vary the transmission power of network  $N_0$  from -33dBm to 0dBm. Meanwhile, for the sensor nodes in other networks, we keep the same transmission power of -0.6dBm.

Fig. 20 testifies the fact that with increasing transmission power of  $N_0$ , the corresponding throughput would improve. To further analyze in detail, we notice that the throughput improvement could be divided into two phases: 1) for transmission power lower than -15dBm where the packet receive rate is not 100%. Increasing transmission power could provide better SINR so as to bring better PRR and improve the throughput; 2) for transmission power greater than -15dBm







Fig. 21. Throughput of Networks Except N<sub>0</sub>

Fig. 19. Overall Throughput Comparison between ZigBee and our Design with DCN

where PRR almost reaches to 100%, the grown of transmission power for  $N_0$  would only bring larger CCA-threshold setting of  $N_0$  in our DCN design (see Equ. 4). Thus, such relaxed CCA-threshold could introduce more concurrency opportunities and benefit the network throughput.

This observation illustrates that the performance of DCN is quite related to the co-channel transmission power. For higher signal strength of co-channel packets, DCN would have more relaxed CCA-threshold and introduce more interchannel concurrencies for better throughput. Furthermore, Fig. 21 shows that high co-channel transmission power would not result trouble for neighboring channels. The reason is that we select a proper CFD=3MHz in our design which could tolerate the inter-channel interference.

	$N_0$	$N_1$	$N_2$	$N_3$	$N_4$	$N_5$
Throughput						
(packets/s)	259.3	260.8	261.9	272.5	272.9	273.4
TABLE I						
FAIRNESS						

3) Fairness Issue: In DCN scheme, the CCA-Adjustor dynamically change the CCA-threshold according to recent records of co-channel and inter-channel interference. In order to show that DCN would not drive some networks against others, we compare the throughput of each individual network.

In our DCN design of 6 networks for 15MHz spectrum bandwidth, network  $N_0$  which uses middle frequency suffers greater inter-channel interference. It faces different interference condition compared to networks  $N_4$  and  $N_5$  located at the ends of spectrum band. However, as shown in Table I, the throughput difference among these networks is actually slight, with about 4% variation. It demonstrates that our DCN provides good fairness among all the networks, even though we are given a relatively narrow bandwidth, i.e., different networks suffer different inter-channel interferences.

4) Network Configuration: In this part, we evaluate DCN with various network configuration. We set three typical cases of network topology. Note that to behave like practical WSNs, we set different transmission power for different node within [-22dBm, 0dBm] at random in all of the following cases.

## Case I: all networks in one interfering region

Case I (see Fig. 22) reflects a common situation of dense deployed wireless sensor network. In this case, all sensor nodes interfere with each other at a strong interfering power level, since they are deployed close to each other. As a result, the performance of just using small CFD=3MHz without DCN could not benefit the overall throughput a lot as shown in Fig. 25. On the other side, our DCN achieves high throughput gain ratio, about 14.7% compare with CFD=3MHz design without DCN scheme and 55.7% against the default ZigBee design.

# Case II: all networks separated with each other

In Case II (see Fig. 23), we treat each network as a cluster formed by their locations, i.e., sensor nodes of the same network are located together. One example is that the sensor nodes are deployed in the building and all nodes in each office room organized as an individual network with their own channel. In such situation, the inter-channel interference becomes the relatively small. Thus, the throughput performance without DCN is better than Case I due to the weak interference . As a consequence, the throughput improvement ratio with DCN is about 10.4% which is smaller than 14.7% in Case I.

Case III: all networks with random topology

In the last case (see Fig. 24), all sensor nodes from 6 networks are randomly deployed in a large region. This is to simulate sensor nodes with various functionalities working together. In Fig. 27, we see the relaxing gain of performing DCN degrades significantly, comparing to above two cases. We explain the result like this: sensor nodes in the same network might be deployed far away from each other in this case, so the RSSI of overheard co-channel packets might be small. As studied in Fig. 20, lower co-channel interference power would constrain the CCA-threshold setting in DCN because the CCA-threshold needs to filter the co-channel interference. Thus, it also prohibit more concurrency opportunities from neighboring channels at the same time. As shown in Fig. 27, it only achieves 6.2% throughput gain by including DCN and 38.4% compared with default ZigBee design. The experiment for Case III actually illustrates one weakness of our DCN design: avoidance for weak co-channel interference sometimes limits the CCA-threshold relaxing and gives up the chance of concurrent transmission with neighboring channels.

As a summary, in this section we study the CFD selection for our DCN and use CFD=3MHz in our non-orthogonal multi-channel design. With extensive experiments, we analyze the network throughput, impact of transmission power, and the fairness issue in our DCN design. We also evaluate DCN with three general network configurations. The experiment results verify that our non-orthogonal multi-channel design with DCN could achieve  $38.4\% \sim 55.7\%$  improvement on the overall throughput for a given spectrum bandwidth.



Fig. 22. Network Configuration I



Fig. 23. Network Configuration II



Fig. 24. Network Configuration III



VII. DISCUSSION

In previous section, we have evaluated our DCN in different network settings. From the experiments, we have an interesting observation that: in some cases where the concurrency on nonorthogonal channels leads to packet loss, most of the packets are actually received with a small portion of error bits. Thus, some packet recovery schemes could be integrated with DCN to correct the CRC-failed packets. In addition, due to the limitations on experimental hardware, we only conduct the experiment on the bandwidth of 12MHz. For larger bandwidth, we study the theoretical bound of throughput improvement of DCN. We also discuss the intelligent approach of CCAthreshold rather than simply avoid the co-channel interference.

#### A. Packet Recovery

As a complement result from Fig. 9, Fig. 28 shows that severed inter-channel interference with higher transmission power may bring trouble to decoding the concurrent low power transmitting packets. For the case of 0dBm interfering transmission against -22dBm link transmission power, a clear gap between number of packets sent out and received could be observed in Fig. 28 which indicates about 20% of packet loss rate.

By further checking the detail of such packet losses, we find that most of the lost packets are received (e.g., with preamble captured) but with some error bits and could not pass CRC-checksum. The statistic result in Fig. 29 shows that most of such CRC-failed packets only have a small portion of error bits (e.g., 87% CRC-failed packets have only 10% error bits). According to that, if some packet recovery scheme could be introduced to correct those, we can achieve better throughput as the line of "Recoverable" shown in Fig. 28 and the corresponding PRR will approximate to 100% as well.

However, even the best packet recovery scheme in the state of art, e.g., Partial Packet Recovery (PPR) [12] introduces extra overhead. Since the packet recovery scheme, in this work, is only necessary for some special cases (e.g., interchannel interference with much higher transmission power than the concurrent working link), an online dynamic recovery scheme which could identify the recover-demand for different links might be one of our future directions.

# B. Throughput Performance for More General Setup

In the general cases above, we verified 30% throughput improvement by assigning channels with smaller CFD (CFD=3MHz) without DCN; and 15% additional throughput gain from our proposed DCN. From Fig. 25, one interesting phenomena is that, DCN provides more throughput gain on the channel exploiting the middle bandwidth (e.g.,  $N_0$ ) than the ones on the boundary (e.g.,  $N_5$ ). To explain the reason, we conduct extra experiments on wider bandwidth. Note that to eliminate the effect of randomness in the general cases setting above, we fix the transmission power at 0dBm.

Recall Fig. 17, when the given bandwidth is 12MHz, we verified 10% improvement for introducing DCN compared with CFD=3MHz design without DCN; and the throughput of the channel located in the middle of the bandwidth shows the greatest improvement. If we have wider bandwidth, e.g., 18MHz which supports 7 channels, (see Fig. 30), the corresponding improvement is 13%. The reason for more improvement gain is, the network (channel) with more neighboring-channel interference will improve throughput more (the middle one). Therefore, wider bandwidth provides severer interchannel interference, then more concurrent transmissions can be leveraged and higher performance gain can be achieved.



Fig. 28. Packet Recovery for Severe Inter-Channel Fig. 29. Interference (Interference Power = -22dBm) Packets

(0.1, 0.87)

 $_{0}^{0}$ 

0.2

0.4

0.6



Portion of error bits of CRC-failed Fig. 30. Throughput Gain with 6 interfering networks

### C. CCA Adjustment

To preserve the simplicity of our DCN, in this work, we simply ignore all the inter-channel interference and prohibit all the co-channel interference. However, there is still much work to do: 1) non-orthogonal design anyhow introduces inter-channel interference, which might corrupt transmission in some cases. Therefore, ignoring all the neighboring-channel interference is unsafe. Future scheme should filter the neighboring-channel interference which is intolerable to provide better transmission reliability; 2) current CCA-threshold is bounded by the minimum power level of co-channel interference. Such setting cannot leverage all the possible concurrencies and constrains the relaxing gain. If some approach could differentiate the current interference (i.e., identify it as co-channel interference or not), then our DCN could leverage the inter-channel concurrency and avoid co-channel collision at the same time. This would be another direction of our future works.

# VIII. CONCLUSION

In this paper, we propose a scheme DCN (Dynamic CCAthreshold for Non-orthogonal transmission) for non-orthogonal multi-channel design in WSNs. We observe that most inter-interference generated from non-orthogonal neighboringchannels is tolerable which indicates potential concurrent transmissions between non-orthogonal channels. To capture such concurrency opportunities, our DCN adjust the CCAthreshold based on the recent records of interference. The comprehensive experiments on our testbeds verify a significant throughput improvement of DCN comparing to the default ZigBee design.

#### ACKNOWLEDGEMENTS

This research was supported in part by Supported by Huawei-HKUST joint lab project, Hong Kong ITC ITP/023/08LP, National Natural Science Foundation of China Grant No. 60933012.

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