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Revisiting the So-called Constructive Interference in Concurrent Transmission

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***Abstract*—Many works attributed the successful reception of concurrent transmission (CT) to the constructive interference. However, due to the inevitable carrier frequency offset (CFO) and the resulted beating effect, the claim of constructive interference is actually not valid. To clarify the reason behind the successful receptions under CT, we conduct extensive evaluations and identify the following findings. *1)* We show that the IEEE 802.15.4 receivers survive the beating effect mainly because of the direct sequence spread spectrum (DSSS), while systems without the protection of DSSS are not applicable to CT. *2)* We identify a counterintuitive phenomenon that the IEEE 802.15.4 receiver could survive only the beating results from large CFO, while performing poorly when CFO is small. *3)* We demonstrate that, even if the receivers survive, CT links lead to little performance improvements compared to conventional signal transmission links from the SNR point of view.**

I. Introduction

In recent years, concurrent transmission (CT), a technique that intentionally transmit duplicated signals simultaneously through multiple independent but synchronized transmitters, has revolutionized the design of the IEEE-802.15.4-based multi-hop wireless sensor networks (WSN). While CT are conventionally believed to be harmful in previous wireless communication researches [1], practical experiments have shown that the IEEE 802.15.4 receivers can successfully decode the concurrent transmitted packets with high probability if they are well synchronized [2]. With this insight, many fast and energy-efficient protocols are inspired (e.g., [2–5]), which spare the multi-hop networks from complicated routing mechanisms and redundant back-off time. The evaluation results show that CT helps to realize more reliable and low-latency WSN.

Although many experiments have shown the CT improves the network performance, the reason of successful receptions under CT are still under debate. One straightforward explanation is to attribute it to the capture effect [6], which refers to a phenomenon that the strongest one of multiple co-channel signals would be demodulated. However, the capture effect itself can not depict the whole picture of CT, since experiments show that packets with the same power level could still be successfully decoded.

Toward this, Ferrari et al. [2] claim that the combination of well synchronized packets results in constructive interference. However, it is well known that that the inevitable CFO and phase offset between transmitters prohibit the constructive interference. Especially, the beating effect resulted from the CFO, which brings dramatic variation to the constant envelope packets and leads to significantly SNR degradation in the deep faded beating valley, usually damage the the receiver performance significantly [1]. Therefore, the claim of constructive interference is debatable, and the reason for successful receptions needs further investigations.

To this end, we strive to clarify the mechanism and condition for the receiver to survive CT, and to fairly evaluate the gain and loss of CT against the conventional single transmitter (1-Tx) links. We distinguish ourselves from the other works by our comprehensive consideration on the following three aspects. Firstly, all relevant transmitter impairments, including the power offset, timing offset, phase offset, and most importantly the carrier frequency offset (CFO) between transmitters are modeled and evaluated jointly. We particularly focus on CFO and the resulted beating effect, which is important but not yet comprehensively investigated in previous works. Secondly, a discerning metric that faithfully reflects the gain and loss of CT is adopted. Instead of using the commonly used but degradation-insensitive packet reception rate (PRR), we adopt the packet error rate (PER) over SNR performance as a evaluation metric of CT. With this metric, the actual performance difference between the CT and 1-Tx links can be precisely measured. Thirdly, our evaluations platform provides reproducible and fine-grained control of all the transmitter impairments. Specifically, in our simulation/emulation platform, the CT packets with impairments are generated by a software simulator, and the receiver performance is evaluated by both simulations and real-chip emulations to obtain convincing results.

Our major contribution is the following findings.

- We clarify that the direct sequence spread spectrum (DSSS) adopted in IEEE 802.15.4 plays a key role on correcting the deep-faded chip by the beating effect. Our evaluations show that DSSS allows a surviving zone of reception even without capture effect, which is crucial for successful reception under CT. We also verify that system without DSSS or other error correcting mechanisms is vulnerable to CT links.
- We find the width of the beating valley matters. Our results shows a counterintuitive phenomenon that small CFO deteriorates the receiver performance significantly, while the narrow beating from large CFO is not harmful. This can be explained by the characteristic of the DSSS,

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where multiple consecutive bits are assembled into a longer symbol. Only if the width of beating is narrow enough compared to the DSSS symbol length and there are still enough correctly demodulated chips, DSSS could help to recover the symbol.

- We verify that CT results in little SNR performance improvement even within the surviving zone of reception. This implies that the performance improvement observed from previous results are not from the constructive interference, but from the spatial diversity provided by independent multiple transmitters.
- In order to quickly evaluate the possible degradation caused by any random beating patterns, we present an indicator, the maximum valley width ratio (MVWR), to determine whether if the beating is harmful or not.

In the rest of the paper, we will review the history and related physical-layer studies of CT in Sec II. We will then discuss the CFO, the beating effect, and the significance of DSSS in Sec. III, and present our consideration on how to conduct comprehensive evaluation on Sec IV. Sec. V is the main body of this paper which consists of four evaluations that validate our arguments. Specifically, Evaluation 1 shows a comprehensive IEEE 802.15.4 receiver performance simulation and emulation under the joint effect of multiple transmitter impairments, which not only revisit the well-investigated capture effect and timing offset, but more importantly confirm the effect of CFO and beating. Evaluation 2 shows a similar evaluation on IEEE 802.15.4g receivers, which proves that CT results in significant performance degradation in the systems without DSSS. Evaluation 3 proves the validity of the presented MVWR, and Evaluation 4 is an over-the-air experiment that double confirms the previous conclusions in real environments. Finally, Sec VI concludes this paper.

II. Related Work

In this section, we overview the related works of CT. We will first show that CT is actually a long existing but abandoned technology in the area of wireless communications. Next, we discuss the recent studies on the physical-layer receiver performance under CT due to its recent revival in the IEEE 802.15.4 multi-hop sensor network areas. Through the discussions, we show that the main contribution of this work, i.e., the studying on the DSSS on combating the beating effect from CFO, have not been well investigated in both areas.

A. Reviewing the CT history

CT is the most simple way to utilize the spatial diversity of multiple antennas to increase the coverage or reliability, since it requires no cooperations between the transmitters except for the synchronization. There are several close relatives of CT in the area of wireless communications. It can be viewed as a simple case of the simulcast systems [7] or a naive cooperative MIMO system [8].

Due to its simplicity, CT used to be adopted in several old wireless communication systems, such as famous POCSAG and FLEX high rate data paging system, to provide large area coverage. However, because of the phase offset resulted from the propagation path difference and the channel effects, CT in many situations results in destructive combination and hence performance degradation. To avoid dead zones of reception resulted from destructive combinations, careful power/delay managements of the transmitters are required [1]. Moreover, in practical systems where the synchronizations are not perfect, the beating effect occurs in both time and frequency domain [1]. The valley of beating generally leads to significant SNR degradation and demodulation error floor [9, 10]. In addition, timing and frequency offsets also result in inter-symbol interference (ISI) and inter-carrier interference (ICI). To guarantee the performance in simulcasting systems, ITU-R imposes strict regulations on the timing and frequency synchronization [11].

In view of the risk of performance degradation, later systems usually avoid transmitting duplicated waveforms when performing simulcasting. Instead, more sophisticated cooperations between transmitters are adopted to guarantee coherent (or at least nondestructive) combination in the receivers, such as beam forming [12], space-time block coding (STBC) [13], and opportunistic transmitter selection [14]. Adding optimized timing or frequency offsets is also a simple but effective countermeasures of destructive interference, such as time-domain cyclic delay diversity (CDD) [15] adopted in 802.11, or frequency offset adopted in the wide area ubiquitous network (WAUN) [16].

It was not until recently that CT revived in the application of IEEE 802.15.4 multi-hop networks. Experimental results have shown that IEEE 802.15.4 system is robust to CT, and many CT-based protocols have been proposed. To name a few examples, there are Flash Flooding [3], Glossy [2], Splash [4], and P^3 [5]. There are also many attempts to apply CT to other technologies, such as SourceSync with 802.11 [17] and CXFS with 802.15.4g [18]. However, unlike IEEE 802.15.4 where CT can be applied straightforwardly, pre-coding or extra error correcting mechanisms are found to be necessary for reliable connections. For example, the STBC is applied in SourceSync, and Hamming code is adopted in CXFS.

B. Related Studies on Receiver Performance

To prove the general applicability of CT, it is essential to provide a comprehensive analysis on why the receiver survives CT. Many researches attributed the success of receptions to the low SINR requirement of IEEE 802.15.4, which allows capture effect to happen easily. Specifically, many experimental results [19–21] verified that only a 3 dB power difference is sufficient for the strongest signal to survive. Next, Ferrari et al. [2] highlighted the timing offset issue, and concluded that the receiver survives as long as the synchronization error is within 0.5 μs. A further study of the distribution of the synchronization error was presented in [22], and the error accumulation issue was tackled in [23]. However, these works obviously overlooked one important factor, i.e., the effect of aforementioned CFO and phase offset.

After many reports of experiment results, an analytical model of the receiver performance under CT based on a coherent matched-filter architecture was provided in [24]. Besides the capture effect and timing offset, Wilhelm et al. [24] further took the static phase offset into consideration. Although they considered by far the most extensive impairment model, the CFO and beating issue were not tackled. Moreover, since their model is based on the assumption of coherent receivers and perfect phase and frequency synchronization, their mathematical analyses are not valid in real scenarios with CFOs. Finally, there are a few works addressed the beating issue in CT, e.g., [25]. However, only limited experimental observations that address the possible degradation are presented, while the conditions and mechanisms for IEEE 802.15.4 receiver to survive beating were still unclear.

III. CFO, Beating, and DSSS

While power and timing offset have been investigated in previous works, the effect of CFO is often overlooked due to its inaccessibility and uncontrollability. In this section, we discuss the CFO, the resulted beating effect, and how DSSS helps to combat them.

A. CFO and the beating effect

CFO and phase offset play a key role when both of the power and timing offset of the concurrent transmitted packets are small. Due to the channel effect and propagation delay, there are always random phase offset between the concurrent transmitted signals, which result in sometime constructive but very often destructive combinations. Moreover, the phase offset is seldom static but constantly rotating due to the presence of inevitable CFO. With the shifting phase offset, the constructive interference keeps alternating with destructive ones and results in dramatic envelope changes, which is commonly referred to as the *beating effect*. Besides the beating effect, CFO also results in inter-carrier interference (ICI). However, since the ICI is minor in single carrier system such as IEEE 802.15.4, the discussion is omitted in this work.

The beating phenomena are similar to the fading effect in wireless channel, where the difference is that the frequency of beating is determined by the value of CFO between the transmitters. That is, the larger the CFO is, the faster and narrower the waveform beats. Both deep fading and the valley of beating result in demodulation errors due to insufficient SNR. Particularly, in deep fading scenarios, demodulation errors occur frequently, and channel coding and interleaver are conventionally adopted to mitigate the errors.

B. DSSS on combatting the beating effect

Although there is no channel coding and interleaving mechanism in IEEE 802.15.4 system, the DSSS, which encodes four contiguous bits into a longer symbol that consists of multiple cross-correlated chips, plays a similar role on combatting the demodulation errors. However, since the encoding is performed on contiguous bits, the width of the beating affects significantly the DSSS recovery capability. According to the width of beating, we then categorize the beating as following scenarios.

- **Narrow Beating**: As long as the beating is fast enough such that the width of the valley is narrower than the symbol length, the information from the successfully demodulated chips can be utilized to recover the error chips. Nodes that receive narrow beating packets could enjoy comparable reliability as 1-Tx links.
- **Wide and Very wide beating**: While the beating varies slowly such that most of the chips of a symbol could fall into the beating valley, the symbol and hence the whole packet could fails if the valley of beating occurs. Therefore, nodes that receive wide beating packets would suffer from constant demodulation errors. On the other hand, if the beating is even slower so that the width of beating is longer than the packet length, it is with a certain possibility that a packet could fortunately be out of the beating valley and survives. Nodes that receive such slow beating packets could experience unstable links where the receiving quality varies according to time randomly.

Fig. 1 (a) and (b), which shows the simulation result of the two-transmitter (2-Tx) CT cases based on IEEE 802.15.4 with 4 kHz and 32 kHz CFO, illustrates the narrow and wide beating scenarios, respectively. The signal power from the two transmitters are assumed to be the same. Although that bursty chip errors occurs in the valley of beating in both cases, bit errors can be found only in the wide beating scenario.

In addition, we emphasize that DSSS or other error correcting mechanisms are essential for successful demodulation. We will show that if a system is not protected by such a mechanism, the beating always leads to demodulation errors.

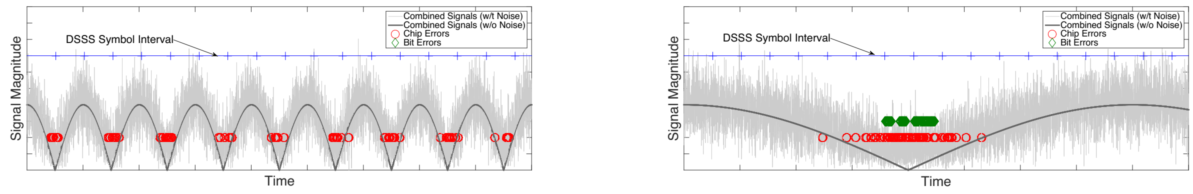
C. MVWR: The Indicator for the beating width

The width of beating matters, but is there any simple but effective indicator that could help us to judge whether the beating is harmful or not (like the 3 dB threshold in capture effect or the 0.5 μs in timing error)? Unfortunately, the beating pattern is regular only in 2-Tx cases and generally random in most of cases. Therefore, it is difficult to judge directly from the value of CFO. To tackle this, we present the *maximum valley width ratio (MVWR)*, which is defined as ratio between the width of the maximum valley in a random beating pattern and the DSSS symbol length.

Given that the strongest concurrent transmitted signal is normalized to unity, we define a valley of a beating pattern as a continuous sequence of chips whose magnitude is lower -3 dB. By searching the valley with the maximum width through a beating pattern, we then find the maximum valley width of a beating pattern. Finally, the MVWR can be calculated by finding the ratio between the maximum valley width and DSSS symbol length. Fig. 2 illustrates an example of the valleys and maximum valley width of a beating pattern.

Note that for regular beating in 2-Tx cases, the MVWR can be derived as

$$\frac{1}{\pi \cdot \Delta f \cdot L} \cos^{-1} \frac{2\alpha^2 + 1}{4\alpha}, \quad (1)$$



(a) Narrow Beating

(b) Wide Beating

Fig. 1: The illustrations of narrow and wide beating. The dark and light gray lines present the CT signal without and with the effect of thermal noise, respectively. The red circles and magenta crosses show the location of chip error and bit error, respectively. The length of each DSSS symbol interval is also shown for reference. There are no bit errors in the narrow beating case while many in the wide beating one.

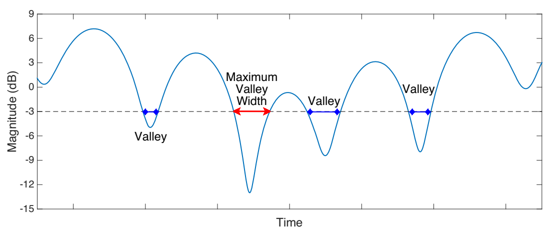


Fig. 2: The illustrations of beating valley and maximum valley width. A valley is identified as a continuous sequence of chips with magnitude smaller than -3 dB. The maximum valley width is the width of the most widest valley.

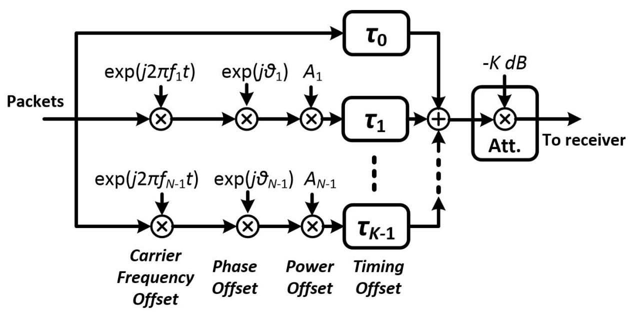


Fig. 3: Channel and impairment model for CT, which consists of multiple transmitter branches with independent CFO, phase offset, power offset, and timing offset. The first transmitter is assumed to be the most powerful and without any offsets. After the combination, a common attenuator is adopted to control the total power.

where Δf and α are the CFO and power ratio between the small and large signal, and L is the DSSS symbol length (16 μs). Note that the magnitude of the signal goes below -3 dB only if $\alpha \geq 1 - 1/\sqrt{2}$.

IV. Evaluation Methodology

In this section, we discuss our consideration on how to conduct fair and comprehensive evaluations for receiver performance under CT. Specifically, we will elaborate the impairment modeling, evaluation metric, and evaluation platform in the three subsections.

A. Impairment models

Without a comprehensive modeling of transmitter impairments, the reliability of CT could be overestimated. In this work, we build a extensive model that takes all the relevant impairments into account, including not only the power, timing, and phase offset, but more importantly the CFO. Moreover, instead of investigating the impairments individually, we evaluate their joint effect to the receiver performance by multi-dimension evaluation.

Fig. 3 illustrates our impairment model. It is an one-hop additive composite model, where IEEE-802.15.4-compliant packets are transmitted by multiple transmitters, and each of them has independent offsets. Without losing the generality, we assume that the first transmitter always has the strongest power and zero offsets, and the power offset of the other transmitters are always negative. The signal from each transmitters are then combined additively, attenuated by a common attenuator K, and fed to the receiver. We will show later that the common attenuator is important for our evaluation metric.

B. Evaluation metrics

A discerning metric that faithfully reflects the gain and loss of CT links is crucial for fair evaluations. The most commonly adopted metric for reliability evaluations, the PRR, is often over-optimistic. Instead of indicating how much margin is left for reliable receiving, PRR simply reflects the error rate performance under a particular received power level. In usual cases where the nodes are deployed to allow reliable receptions in 1-Tx links with power margins, the possible degradation resulted from CT might be underestimated. To this end, we argue that it is the receiver PER vs. SNR performance that should be measured. In this work, we use the *sensitivity gain* between CT and 1-Tx link as a fair and discerning for our evaluations.

Sensitivity, defined as the minimum received power to guarantee a certain error rate performance, is widely adopted to evaluate the capability of receivers. For example, the sensitivity specification in IEEE 802.15.4 standard is to be able to receive a 20-byte packet whose input power is less than -85 dBm with less than 1 % PER. However, conventional sensitivity measurement normalizes the power in the receiver input, and therefore is not able to reflect the power gain from multiple transmitters in CT.

To tackle this, we define the gain and loss of sensitivity calculation in CT as following. Referring to the impairment model illustrated in Fig. 3, wfine-grainde assume that the first transmitter has unity transmission power, while the others are with a negative power offset against the first transmitter. After the combination, the signal are attenuated by K dB before fed to the receiver. In our evaluation, we gradually increase the attenuation K until the PER reaches 1 %, and record the K value as the *maximum allowable attenuation*. Since what we really care is the gain between CT and 1-Tx links, the absolute K value, which strongly depends on the noise level and the receiver architecture, is irrelevant in this work. As the final outcome of our evaluation, we calculate the relative difference of K value between the CT and the 1-Tx links, and refer to this difference as the *sensitivity gain* in this work.

C. Simulation and emulation platform

The evaluations in previous works are mainly conducted experimentally on local or public testbeds. However, the reproducibility on local testbeds and the controllability of the public testbeds are of great concerns. Particularly, the testbeds usually provide no accessibility to the CFO of the nodes as well as the link attenuation of the links.

To provide fine-grained and reproducible control to the attenuation and offsets, a software simulation and a real-chip emulation platform are adopted in our evaluation. While the simulation platform allows us to gain more insight of the how CT affect receiver, the emulation platform provides important reference for the validity of the simulation. Specifically, we first implement a software IEEE-802.15.4-compliant packets generator and a transmitter impairments simulator on Matlab to generate the baseband packets under CT. The packets are then fed to a software demodulator in simulation and off-the-shelf RF chips in emulation for demodulation.

In our simulation, we assume that the timing and phase is prefectly synchronized to the strongest signal. The received signal is demodulated by a limiter-discriminator [26] and de-spread by a hard-input de-spreader. Note that the modulation in IEEE 802.15.4 is O-QPSK [27], which can not only be treated as QPSK and received by coherent demodulator, but also can be viewed as MSK and demodulated by non-coherent FSK receiver [28]. Although the coherent-based demodulator enjoys better SNR performance, the non-coherent one is simpler and more robust against the CFO. Therefore, the non-coherent FSK limiter-discriminator demodulator is adopted.

To prove that our analyses are valid not only in our simulation model but also in real RF transceiver, real-chip emulations are further conducted. An Agilent N5182A MXG vector signal generator is adopted to up-convert the baseband packets to 2.4GHz band. Next, we configure a famous sensor mote, TelosB which is equipped with the representative 2.4 GHz IEEE 802.15.4 compliant transceiver chips, TI CC2420 [29], to perform demodulation of the RF packets. Fig. 4 illustrates our emulation platform.

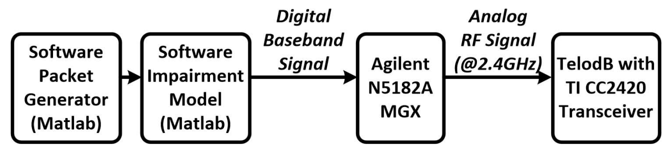


Fig. 4: The illustration of the emulation platform. The IEEE 802.15.4 packets are generated by the software baseband generator (Matlab), passed through the impairment model (Matlab), converted to 2.4GHz analog RF signal by Agilent MGX, and finally received by TelosB with TI CC2420 chips.

V. Evaluation Results

A. Evaluation 1: Effects of transmitter impairments

Our first evaluation is a general measurement of the performance of IEEE 802.15.4 receivers under CT. Our goal is to evaluate the joint effect of all the relevant transmitter impairments.

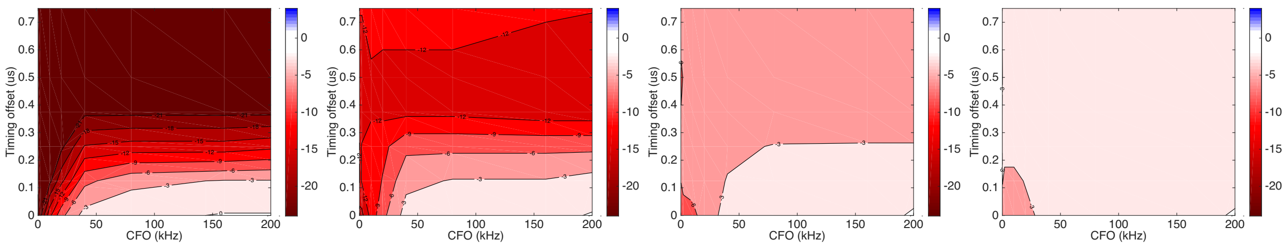
1) Scenarios and parameters: For simplicity, we consider CT with 2-Tx case with the first one having larger power and zero offsets. We extensively test the receiver performance under different power offsets, timing offsets, and CFOs of the second transmitter in a three-dimension impairment space. Specially, the power offsets of 0, 1, 3, and 5 dB are tests For each power offset, we sweep the timing offset and CFO from of 0 μs to 0.75 μs and 0 Hz to 200 kHz, respectively. Note that we choose the parameter because 200 kHz is slightly over the maximum allowable CFO in IEEE 802.15.4, and 0.75 μs is 1.5 times of the chips time. In addition, the phase offset of the second transmitter is set to be random in every packet.

For each combination of the offsets, the PER performance will be evaluated over difference attenuations. Each PER evaluation is measured with more 1000 randomly generated 20-byte packets in both the simulation and emulation. The maximum allowable attenuation that guarantees less than 1 % PER for each combination will be recorded, and compared with that of the 1-Tx link to calculate the sensitivity gain.

2) Results and observations: Fig. 5 and 6 show the evaluation results of the sensitivity gain for the simulation and emulation, respectively. Each subplot in the figures represents the results for a specific power offset. Specifically, subfigure (a) to (d) corresponds to 0, 1, 3, 5 dB of power offset, respectively. For each subplot, the X- and Y-axis indicate the CFO and timing offset, respectively. We use the colored-coded 2D contour maps to illustrate the sensitivity gain, where the blue color indicates positive sensitivity gain, and the red color indicates minus one, or more intuitively, sensitivity loss. The deeper the color is, the larger the gain or loss is, and white color indicates that CT performance evenly with 1-Tx links.

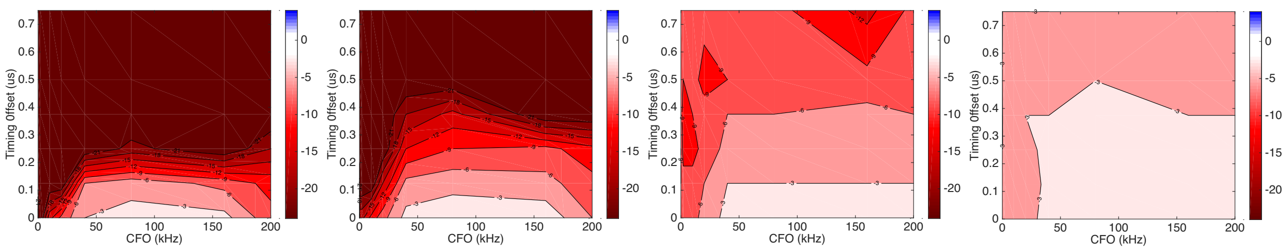
From Fig. 5 and 6, we first present a few straightforward observations. First, the simulation and emulation show great similarity, which indicates the validity of our receiver model and evaluation platform. If we observe the colors, it is clear that red color dominates most of the area, and blue are rarely found. This indicates that CT leads to either no improvement or very often loss of sensitivity in most of the situation.

Second, we can see the light-color area increases with the power offset, and the values of timing and carrier frequency offsets become less relevant. This matches the expectation that when capture effect take place, the CT link behaves like 1-Tx ones. The 3dB threshold is generally correct, but there are still some minor degradation observed in the large timing



(a) Power offset: 0dB (b) Power offset :1dB (c) Power offset: 3dB (d) Power offset: 5dB

Fig. 5: Simulation results for sensitivity gain over different power offset, timing offset, and CFO. The system is based on IEEE 802.15.4 with 2-Tx CT. Each subplot represents a 2-D contour map of sensitivity gain for a specifically power offset. The X- and Y-axis are the CFO and timing offset, and the red and blue color indicate sensitivity loss and gain, respectively.



(a) Power offset: 0dB (b) Power offset: 1dB (c) Power offset: 3dB (d) Power offset: 5dB

Fig. 6: Emulation results for sensitivity gain over different power offset, timing offset, and CFO. The system is based on IEEE 802.15.4 with 2-Tx CT. Refer to Fig. 5 for the other details.

offset area. In addition, the timing offset is crucially harmful in the small power offset region. Moreover, we point out that 0.5 μs of timing offset still cause significant sensitivity loss, and 0.25 μs is a more accurate criterion for no-loss reception.

Third, we focus on the area of small power and timing offset, i.e., the lower half part of subplot (a) and (b). Both the simulation and emulation show a surviving zone for almost no-loss reception, which is approximate bounded by 20 kHz and 180 kHz CFO. This meets our expectation that narrow beating resulted form large enough CFO is not harmful for IEEE 802.15.4 receiver. This surviving zone is of great importance for the successful receptions in the scenario without capture effect. We will show later that system without the protection of DSSS does not enjoy the surviving zone and can only rely on capture effect for successful packet receptions.

Lastly, we see a mismatch between the simulation and emulation when the CFO is larger than 180 kHz. While the loss become signifiant again in the emulation, but the receiver in simulation is not affected. This can be explained by our simulation assumption that the receiver is perfectly synchronized with the first transmitter no matter the CFO is, while in real-chip, the large CFO could also affect the accuracy of the timing acquisition and phase recovery module.

B. Evaluation 2: Performance of non-DSSS systems

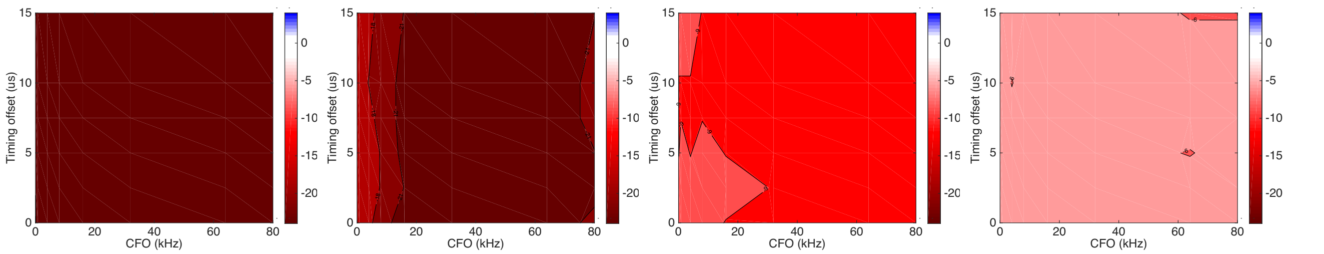
In our previous discussion, we focus on the analysis of the reception with the protection of DSSS. Here, we show that CT is not applicable to systems without the protection of DSSS or other error correcting mechanisms. The similar 2-D contour maps of sensitivity gain are adopted to illustrate the results. Note that this evaluation involves no emulation.

1) Scenarios and parameters: We choose the IEEE 802.15.4g standard [30] on sub-GHz band, a single carrier system similar to IEEE 802.15.4 with FSK-based modulation but no DSSS, for this evaluation. Specifically, we adopt the operation mode 2 of MR-FSK modulation using the 2FSK modulation with modulation index being and date rate being 1 and 100 kbps, respectively. Similar to the previous evaluation, a 2-Tx CT scenario is adopted and the power offsets is again swept from ranging from 0 dB to 5 dB. Since 802.15.4g system is not a DSSS system, each bit is directly modulated on a symbol, and the symbol length is then 10 μs. Besides, the maximum allowable CFO between two transmitter is about 80 kHz. Therefore, for each power offset, we sweep the timing and carrier frequency from of 0 to 15 μs and 0 to 80 kHz, respectively.

2) Results and observations: FIg. 7 (a) to (d) show the simulation results for the case of 0, 1, 3, and 5 dB power offset, respectively. We draw two conclusions from the figures - first, in the small power offset region, there is no similar surviving zone for reliable receiving no matter the value of timing offset and CFO, which is simply because the inevitable destructive interference results from CFO or phase offset prohibits the PER from being lower than 1 %. second, the threshold for capture effect to occurs is higher. We can see that the sensitivity loss is large even with 5 dB power offset. Therefore, we conclude that without the protection of DSSS, the applicability of CT is weak.

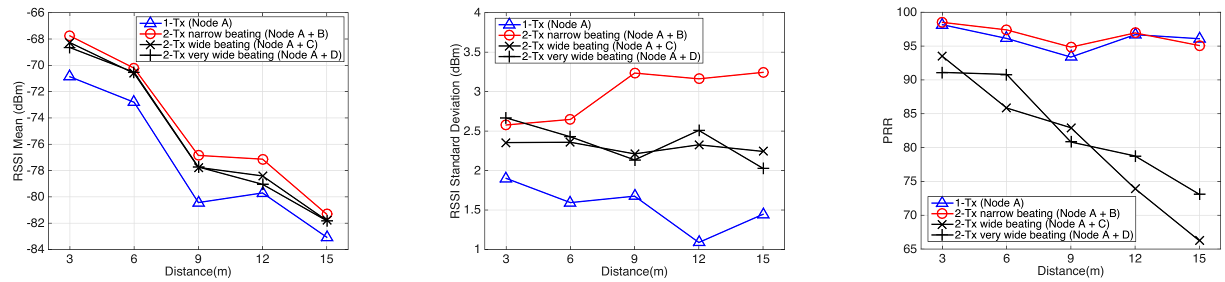
C. Evaluation 3: MVWR vs. sensitivity gain

In previous evaluations, we focus on 2-Tx cases where the width and period can be simply determined by the CFO.



(a) Power offset: 0dB (b) Power offset: 1dB (c) Power offset: 3dB (d) Power offset: 5dB

Fig. 7: IEEE 802.15.4g sensitivity gain simulation results over different power offset, timing offset, and CFO. The same as Fig. 5, each subplot represents a 2-D contour map of sensitivity gain for a specifically power offset.



(a) Mean of RSSI (b) Standard deviation of RSSI (c) Average PRR

Fig. 9: The measurement result of RSSI and PRR in the over-the-air experiments. Subplot (a) to (c) show the mean value of RSSI, standard deviation of RSSI, and PRR, respectively. The X-axis is distance between the receiver node and transmitter (relay) nodes. The four lines in each subplot represent the results for 1-Tx, 2-Tx with narrow beating, 2-Tx with wide beating, and 2-Tx with very wide beating, respectively.

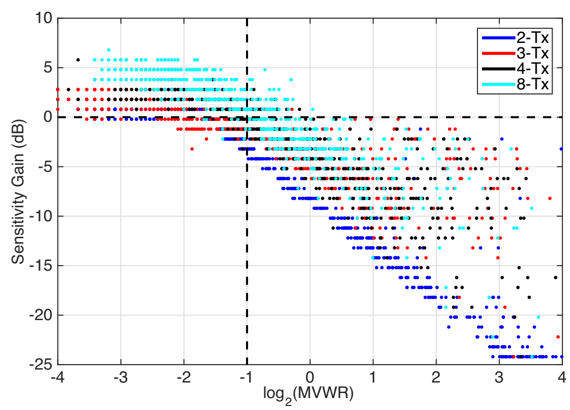


Fig. 8: The relationship between the sensitivity gain and MVWR. Different color dots indicate the case for different transmitter number. Note that the X-axis shows the log value (base 2) of MVWR.

In section, we prove that the MVWR defined in Sec. III is an effective indicator to reflect the performance degradation resulted from beating in multiple transmitter cases.

1) Scenarios and parameters: We consider CT scenarios with 2, 3, 4, and 8 transmitters, which are denoted as 2-Tx, 3-Tx, 4-Tx, and 8-Tx, respectively. For each scenarios, more than 100 realizations of CFO combinations are randomly generated. For each combination, the MVWR of a packet as well as the PER vs. SNR performance in terms of the sensitivity gain are measured by simulation. To reduce the evaluation space, we set power offset and timing offset to be zero.

2) Results and observations: Fig. 8 shows the relation between MVWR and sensitivity gain by simulation. That horizontal axis represents the log value (base 2) of MVWR and DSSS symbol length, and the vertical axis indicates the sensitivity gain. Each point on the figure illustrates a realization of a random CFO combination.

We can see that regardless of the transmitter number, the receiver generally enjoys non-negative sensitivity gain as long as the MVWR is lower than 0.5. According to (1), this corresponds to a 28.8 kHz of CFO in the 2-Tx case with 0 dB power offset, which match the simulation and emulation results in Evaluation 1. In addition, while in 2-Tx case the sensitivity gain is mostly 0dB, higher sensitivity gains can be observed in the higher transmitter cases. On the other hand, once the MVWR is larger than 0.5, the receiver performance degrades accordingly. Note that, in 2-Tx cases, the beating pattern is regular and the minimum of the beating valley has zero power. Therefore, the degradation in 2-Tx case is particularly worse and highly correlated with the MVWR. In the other cases with more transmitters, the degradation can be alleviated, but the performance is still generally worse than the 1-Tx links.

D. Evaluation 4: Over-the-air experiments

In our final evaluation, we confirm that degradation results from wide beatings actually occurs in real over-the-air scenarios. Specifically, we demonstrate that the variation of RSSI values increases significantly due to the beating effect.

TABLE I: CFO of the nodes used in the experiment

	1-Tx	2-Tx narrow	2-Tx wide	2-Tx very wide
Node	A	A+B	A+C	A+D
CFO	N/A	37.8 kHz	3.8 kHz	0.2 kHz

Moreover, we show that the narrow beating results in no worse performance than the 1-Tx links, but wide and very wide beating hurt the performance significantly.

1) Scenarios and parameters: Based on the Glossy protocol implementation [2] and TelosB sensors, we build up the experiment environment with one initiator, one or two relays, and five receivers nodes. The initiator sends an packet, which triggers the CT of the relay nodes in the next Glossy slots. The PRR and RSSI of the CT packets will then be recored, while the trigger packet will be ignored.

The five receivers, located 3, 6, 9, 12, and 15 m away from the relay nodes, are programmed to record the PRR and RSSI. In order to test the small power offset scenarios, the relay nodes are placed close to each other. Like the previous simulation and emulation, random generated 20-byte packets are adopted, and the experiment is carried out on channel 26 whose center frequency is 2.48GHz. In addition, the output power of all the relay nodes is adjusted to -15 dBm.

We benchmark the 2-Tx CT links of narrow, wide, and very wide beating with the 1-Tx link. Specifically, four nodes are particularly selected as the relay nodes, whose carrier frequencies offset when operating at channel 26 are listed in Table I. We use Node A as the main reference node, and the CFO between Node A and Node B, C, and D correspond to narrow, wide, and very wide beating, respectively. Finally, the experiment is carried out over 16 independent places, including long corridors, large seminar halls, and open space.

2) Results and observations: Fig. 9 (a) to (c) show the results for the mean of the RSSI, the standard deviation of the RSSI, and the PRR, respectively. The horizontal axes are the distance between the relay and receiver nodes, and all of the three subplots are the averaged results over 16 places. We can see clearly that 2-Tx CT links indeed enhance the mean value of RSSI about 3 dB, but the standard deviation also increases significantly due to the beating effect. From the PRR point of view, we can see that the 2-Tx link with narrow beating performs evenly with the 1-Tx one, but the PRRs of the 2-Tx links with wide and very wide beating degrade significantly.

VI. Discussion, Conclusion, and Future Works

The most important message conveyed in this paper is simple - besides the timing synchronization, the main reason for IEEE 802.15.4 receiver to survive CT is the protection of DSSS. This indicates that CT is not universally applicable to any technology. On the other hand, it also implies that the success of CT relies on careful selections of many physical-layer parameters, such as an error correction algorithm.

Actually, we are convinced that CT is an efficient technology in the network and MAC layer, and we would also like to carry forward the application of CT. While the other advocators of CT often oversimplified the success of CT, we strive to mutually assess the pros and cons of CT and investigate the very essential parts that allow the success of CT. From our results, we have learned that the receivers must be able to tolerate frequency error, to be immune to the beatings, and to perform accurate timing synchronization. We are now studying the conditional for the success of CT from a more general viewpoint that take not only error correction but the whole physical-layer design into consideration. Specifically, we are investigating different modulations and receiver architectures for CT. Moreover, we are seeking the opportunity to apply CT to more commonly available technologies.

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