

Murphy loves CI: Unfolding and Improving Constructive Interference in WSNs

Vijay S. Rao*, M. Koppal†, R. Venkatesha Prasad*, T.V. Prabhakar†, C. Sarkar* and I. Niemegeers*

* Embedded Software, Delft University of Technology, The Netherlands

Email: {V.Rao, R.R.VenkateshaPrasad, C.Sarkar, I.G.M.M.Niemegeers}@tudelft.nl

† ZENLAB, DESE, Indian Institute of Science, Bengaluru, India

Email: {madhusudansk, tvprabs}@dese.iisc.ernet.in

Abstract—Constructive Interference (CI) phenomenon has been exploited by Glossy, a mechanism for low-latency and reliable network flooding and time synchronization for wireless sensor networks. Recently, CI has also been used for other applications such as data collection and multicasting in static and mobile WSNs. These applications base their working on the high reliability promised by Glossy regardless of the physical conditions of deployment, number of nodes in the network, and unreliable wireless channels that may be detrimental for CI. There are several works that study the working of CI, but they present inconsistent views. We study CI from a receiver’s viewpoint, list factors that affect CI and also specify how and why they affect. We validate our arguments with results from extensive and rigorous experimentation in real-world settings. This paper presents comprehensive insights into CI phenomenon.

With this understanding, we improve the performance of CI through an energy-efficient and distributed algorithm. We cause *destructive* interference on a designated byte to provide negative feedback. We leverage this to adapt transmission powers. Compared to Glossy, we achieve 25% lesser packet losses while using only half of its transmission power.

I. INTRODUCTION

Many wireless sensor network (WSN) applications rely on network flooding. Typical uses of network flooding are to disseminate data through the network and time-synchronize the nodes. Data dissemination is used to query sensor values or perform network house-keeping tasks such as distributing configuration parameters and updating software codes. Time synchronization is used by real-time, high-rate data collection systems [1]. Thus building an efficient network flooding technique is essential. Several techniques for flooding had been proposed in [2], [3], [4], which aim to minimize latency or achieve energy-efficiency. Recently, Ferrari *et al.* [5] made a major contribution through their flooding technique called Glossy. It achieves latency close to the lower theoretical limit and also implicitly synchronizes the nodes with sub-microsecond accuracy with high reliability.

Constructive interference (CI) mechanism is used by Glossy to eliminate the need for contention to access the wireless medium. CI occurs when two or more nodes transmit the same data concurrently, which makes the signals superpose. Hence, receivers can decode the packet successfully with high probability due to, supposedly, the increased signal power at the receivers. To achieve CI successfully with IEEE 802.15.4 radios operating in 2.4GHz band, the maximum tolerable

temporal displacement by the concurrent transmissions is one chip duration, which is $0.5\mu\text{s}$. Ferrari *et al.* [5] achieve this tight bound with radio-triggered synchronization mechanism and demonstrate on Tmote Sky wireless sensor nodes.

Ferrari’s work generated huge interest in the research fraternity to study CI. However, from the previous studies, there appears an inconsistent and often opposing picture about the working of CI. For example, while it is claimed that CI does not depend on number of transmitters in the network [5], Noda *et al.* [6] report otherwise – a significant decrease in packet reception when the number of transmitters increases. Another instance is that Ferrari *et al.* [5] claim that out-of-phase carrier waves from three or more concurrent transmitters do not hamper the decodability of the received signal although Wang *et al.* [7] derive a sufficiency condition for phase of the concurrent signals such that they interfere constructively. This clearly demonstrates that we lack a complete picture about the CI phenomenon.

Several factors influence the performance of CI since commercially-off-the-shelf IEEE 802.15.4 hardware are designed to work with a single carrier: (a) Since sensor nodes are designed to be inexpensive, they have low accuracy crystals. Clock drifts can creep in to hamper CI. (b) Clocks on the radio are allowed to have large drifts since compensating for drifts within one signal is easy. However, this is not the case for CI. (c) There is a high chance that the signals arrive with different phase offsets at the receiver for several reasons, including, distance between the transmitters and physical phenomena such as multipath effects, leading to failures in decoding packets. (d) Furthermore, if nodes transmit with different powers, then the phase of the resultant signal is influenced by the strongest signal. Fig. 1 shows the resultant signal under the influence of some of these factors.

These aspects have not been studied holistically. This article aims to provide comprehensive insights into the impact of these factors with rigorous experimentation at several locations. Based on these insights, we design Destructive Interference based Power Adaptation (DIPA), a transmit power adaptation based heuristic that improves the performance of CI. Glossy can benefit from DIPA to improve both performance and save power on the nodes. This paper makes the following contributions:

- 1) We study an exhaustive set of factors influencing CI from

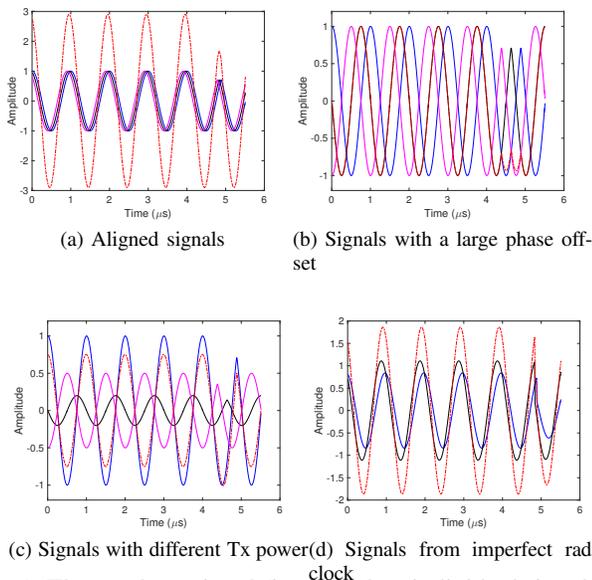


Fig. 1: The resultant signal (in red) when individual signals are aligned, have a temporal offset, have varying transmit powers and are subject clock errors on the radio.

a receiver's perspective. Using the resultant signal, we derive the maximum tolerable phase offset for CI to be effective. Furthermore, we show the influence of various parameters from the expressions of the resultant signal.

- 2) We are the first to conduct an exhaustive experimental study of CI considering minute details in real-life settings. We validate the dependency on the factors through these experimental results.
- 3) One important result that we establish is that varying transmit powers can be beneficial to improve packet reception. Based on this, we propose DIPA, a local heuristic that adapts transmit power based on feedback.
- 4) We propose to use *destructive* interference as a negative feedback mechanism for DIPA. We evaluate this heuristic with our setup in different scenarios. We also include random deployment scenarios since most real-life deployments are random in nature. To further show the applicability, we evaluate it on a real-life testbed wherein some links are non line-of-sight as well. We show the improvement in performance of CI as well as energy-efficiency.

The paper is organized as follows. Sec. II summarizes the theory of constructive interference and the related work. We also list the claims and counter-claims made in the literature about the working of CI. Sec. III describes the experimental setup. In Sec. IV, we give expressions for the resultant signal and show through these equations, how CI depends on various parameters. We corroborate these with experimental results and draw our conclusions about CI also in Sec. IV. We establish that obtaining an optimal transmit power set has exponential complexity, and propose our heuristic with its evaluation in Sec. V. We make concluding remarks in Sec. VI.

II. CONSTRUCTIVE INTERFERENCE

In this section, we first summarize the theoretical background of constructive interference, and then briefly describe literature that have studied CI and applications that use CI.

A. Theory of Constructive Interference

When two nodes transmit the same packet simultaneously on the same frequency band to a receiver within their transmission ranges, the transmitted signals superpose leading to *constructive* interference at the receiver. On an IEEE 802.15.4 node operating in the 2.4 GHz band, the data to be transmitted is first split into 4-bit groups each forming a symbol. Each symbol goes through a Direct Sequence Spread Spectrum (DSSS) modulation. Every symbol is modulated with a pseudo-random noise (PN) sequence of 32 chips. The symbol-to-chips mapping is defined in the IEEE 802.15.4 standard [8]. This baseband signal is then modulated on to the carrier with Offset-Quadrature Phase Shift Keying (O-QPSK), which is transmitted over the wireless medium.

At the receiver, a coherent detection method is used to demodulate the carrier signal. The signal is down-converted into chips, which are then mapped back to the symbols using Maximum Likelihood Estimation (MLE). Redundancy introduced by the PN sequence allows for coping up with errors caused by soft-decisions at chip-level or by errors caused on the channel. This redundancy improves the receiver sensitivity level at the cost of reduced data rate.

For CI to occur, the tolerable temporal displacement between signals is $0.5 \mu\text{s}$ [5], since the chips on quadrature-phase (Q-phase) are delayed by the chip time, $T_c = 0.5 \mu\text{s}$ with respect to the in-phase (I-phase) carrier. As mentioned in [9], let the O-QPSK signal be represented by,

$$S(t) = I(t) \cos \omega_c t - Q(t) \sin \omega_c t. \quad (1)$$

Here, $I(t)$ is the I-phase, $Q(t)$ is the Q-phase component, and $\omega_c = \pi/2T_c$ is the radial frequency of half-sine pulse shaping. The resulting constructively interfered signal is given by,

$$S_r(t) = \sum_{i=1}^K A_i S_i(t - \tau_i) + N_i(t), \quad (2)$$

where, K is the number of concurrent transmitters, A_i is the amplitude and τ_i is the temporal offset of the i^{th} transmitted signal. $N_i(t)$ is the noise added to the signal.

B. Related Work

We group the related work on CI into two: articles that study or analyze the CI phenomena, and articles that use CI for providing services over WSN.

Work on CI: With concurrent transmissions, a packet can be decoded by the receiver even in the absence of capture effect. For concurrent transmissions to interfere constructively, precise timing requirements need to be imposed on the transmitter nodes. Ferrari *et al.* [5] analyze these requirements and outline a method to achieve them on CC2420 radios, specifically trying to make overall delay deterministic in nodes

that have low accuracy clocks. Furthermore, they propose Glossy, a mechanism to flood the network within a few milliseconds. Importantly, they show through experiments on testbeds that (i) as the number of concurrent transmitters increases the packet reception ratio (PRR)¹ increases; (ii) the only factor that affects CI is not meeting the temporal offset of $\leq 0.5 \mu\text{s}$ among concurrent transmissions.

Wang et al. [9] studied the scalability of CI. They argue that PRR of CI decreases with increasing number of nodes due to non-deterministic delays. They show scalability is an issue, and propose an algorithm to handle it. The scalability issue has also been studied in [6], which demonstrates with experiments that more number of transmitters will affect the received signal severely.

A model for computing the success of packet reception under both CI and capture effect is proposed in [10]. Improving PRR in CI has been considered in [7] and [11]. Increasing the power difference among transmitters combined with the use of a forward error correction scheme is the method proposed in [11]. It is claimed in [7] that signals transmitted within $0.5 \mu\text{s}$ is not enough for CI due to the noise in the received signals. Further, they propose algorithms to achieve chip-level synchronization and select only those transmitters that improve the received signal power, with simplifying assumptions. From these studies, we enlist below some interesting observations.

Claim 1: Temporal offset among concurrent IEEE 802.15.4 transmitters not exceeding $0.5 \mu\text{s}$ will generate constructive interference with high probability [5].

Contradicting claim: Concurrent transmissions with delay less than $0.5 \mu\text{s}$ is insufficient to guarantee CI due to noise in the radio signals [7].

Claim 2: Out-of-phase carrier waves allow correct detection with high probability, when number of concurrent transmitters are greater than or equal to three [5].

Contradicting claim: Not all out-of-phase carriers allow decoding of the packet correctly. A maximum tolerable phase offset to generate CI is derived in [7].

Claim 3: Number of concurrent transmitters have less impact on PRR [5].

Contradicting claim: CI does not scale with the number of transmitters due to lack of coherence among carrier signals [6].

Claim 4: Non-deterministic delays are present and affect CI negatively [9].

Claim 5: Power imbalance ($> 5 \text{ dBm}$) improves PRR [6], where power imbalance is defined as two concurrent transmitters having transmission power levels that differ by a certain value. A similar claim is made in [11], in which power imbalance ($> 2 \text{ dBm}$) improves PRR.

Claim 6: PRR decreases when packets become longer [5].

It is apparent that there is an inconsistent view on the working of CI, and some claims are not completely explained and also need substantiation. In this article, we shall establish

¹Packet reception ratio is the ratio of data packets successfully delivered to number of packets transmitted regardless of number of transmissions involved in delivering each packet.

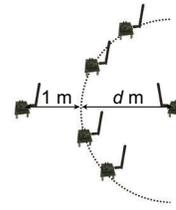


Fig. 2: Data collection setup in which concurrent transmitters are placed on an arc to make them equidistant from the receiver.

how these parameters affect CI and perform experiments to validate them in various real-world scenarios.

Work that employ CI: A node density estimation algorithm by counting the number of combined signals in CI based on the received power is proposed in [12]. Splash protocol pipelines transmissions for parallel data dissemination over a tree using Glossy [13]. This work demonstrates certain weaknesses of CI such as less reliability with larger packet sizes and that not all tightly synchronized transmissions are helpful. Splash uses several techniques, such as diversity in transmission density, opportunistic overhearing, channel cycling and XOR coding, to improve PRR. Ferrari *et al.* [14] propose a protocol utilizing Glossy to convert the multi-hop WSN to a shared, low-power wireless bus. This bus supports one-to-many, many-to-one and many-to-many traffic. Another work [15] modifies Glossy to make it a data collection protocol. While such protocols require all nodes to participate in concurrent transmissions, the authors of [16] propose a method to reduce them by selecting the nodes only in the direction of the destination. These protocols require reliable working of CI, which we investigate in this article.

III. EXPERIMENTAL SETUP

To study the characteristics of CI, we conducted experiments with thirteen identical nodes. The setup is shown in Fig. 2. An initiator node is placed 1 m away from the set of relay nodes that also act as the concurrent transmitters. These nodes are placed on an arc, formed by the circle of radius d . A receiver is placed d m away, i.e., center of the circle, making receiver equidistant from the concurrent transmitters.

The distance between the receiver and concurrent transmitters is chosen such that the network remains connected when any of the concurrent transmitters sends a packet at -6 dBm . Consequently, d varies in each setup. In each setup, we verified that connectivity exists and all packets were received between every concurrent transmitter node and the receiver. We used CC2530 system-on-chip solution from Texas Instruments [17], which supports IEEE 802.15.4 radio. CC2530 is controlled by an industry-standard 8051 microcontroller unit in the chip. The chip is low-power (consumes 24 mA in active-mode receive operation with CPU idle), with high receiver sensitivity (-97 dBm) and allows to choose transmit powers from -28 dBm to $+4.5 \text{ dBm}$ in 17 predefined steps. The radio also allows us to choose payload sizes from 1 B to 127 B. For our experiments,

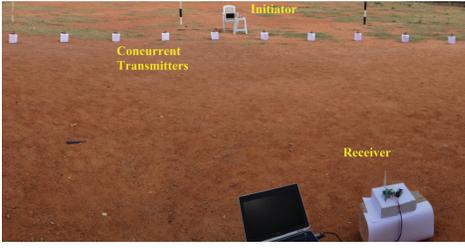


Fig. 3: Experimental setup in the field.

we used $\lambda/4$ antenna² with a reverse polarity SMA connector. We implemented CI following the guidelines given in [5], and verified its working.

Power: All nodes were powered by batteries that provided sufficient voltage levels throughout the experiments. We ensured that batteries had not caused any problems, by checking the voltage levels before and after the experiments to confirm the measurements made were in good order.

External interference: Before each experiment, we ascertained that we used a channel in which there was no external interference from nearby WiFi or Bluetooth devices. No microwave appliances were nearby as well.

A. Locations

We conducted experiments at four different locations.

A model fuselage: The fuselage is of dimensions 12 m \times 3 m. The curved enclosure is made up of tin, and has wooden flooring. In this location, the radius of the arc, d , was 10.5 m.

Corridor: The corridor is 2 m wide and 27 m in length. Here, d was 23 m.

Office space: An empty office was another location for our experiments. It is 10 m \times 7 m. In this location, d was 8 m.

Soccer field: An outdoor location free from any construction was chosen. In this case, the radius of the arc was 8 m. Fig. 3 shows the setup in the field.

B. Data collection scenarios

All the experiments were conducted in a line-of-sight setting. We created seven scenarios for rigorous experimentation of CI. At each location, we collected data from at least 10,000 packets for various packet sizes in each scenario. Below is the list of scenarios.

Scenario 1: We started off with data collection with one transmitter and one receiver. At each step, we added one more transmitter. The transmission power of each concurrent transmitter was set to -6 dBm. This scenario studies the effect of number of concurrent transmissions on a receiver.

Scenario 2³: In this scenario, alternate nodes were set to -6 dBm and -3 dBm.

Scenario 3: In this scenario, alternate nodes were set to transmission powers of -6 dBm and 1 dBm.

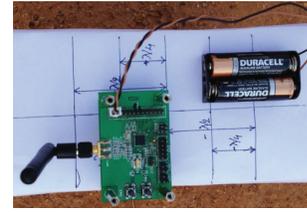


Fig. 4: Node movement for scenarios 6 and 7.

Scenario 4: In this scenario, every node chose a random transmission power between -10 dBm and +4.5 dBm.

Scenario 5: In this scenario, we considered 9 nodes out of which we created groups of three nodes. In each group, nodes transmitted at -6 dBm, -3 dBm and 1 dBm.

Scenario 6: In this scenario, 9 nodes were used. Alternate nodes were separated by a distance of $\lambda/2$. Here, λ is the wavelength of the carrier wave. This scenario studies the effect of distance between transmitters on phase difference. The distance $\lambda/2$ was chosen since this would create a 180° phase offset between carrier signals of adjacent nodes.

Scenario 7: In this scenario, we experimented with distances of $\lambda/4$ between nodes. 9 nodes were used and the alternate nodes were separated by a distance of $\lambda/4$.

IV. UNFOLDING CI

In this section, we derive the amplitude and phase of the resultant signal. Based on these expressions, we analyze an exhaustive set of parameters on how they impact CI. Furthermore, we corroborate this study with experimental results in this section.

A. Phase offset

Carrier phase offset among the interfering signals can hinder constructive interference. Wang *et al.* [7] state that for CI to occur, the individual signals must also satisfy a sufficiency condition: for signals to interfere constructively, the phase offset of the i^{th} arriving signal should not exceed $|\phi_i| \leq \arccos(\sqrt{P_i/P_S}/\omega_c)$ from the strongest arriving signal with power P_S . Here, P_i is the power of the i^{th} signal. The parameter ω_c in the denominator, which is in the order of 10^6 , makes the value of the numerator highly insignificant for any $0 \leq P_i \leq P_S$. While the condition seems intuitively right since the I and Q components are offset by $\pi/2$, it does not completely capture the picture especially when the powers are different. We will show that even if P_i is only slightly less than P_S , but has a $\phi_i > \pi/2$, the signal can be decoded correctly.

To obtain the correct sufficiency condition, we take a more holistic approach to compute the phase, i.e., we derive the resultant signal and the tolerable phase offset. Let R_S represent the receiver sensitivity.

Lemma 1. *Constructive interference is said to have occurred when individual arriving signals S_i , when a maximum phase offset of $\pm\pi/4$ is created at the receiver with respect to the transmitted signals.*

²<http://www.lsr.com/downloads/products/330-0016.pdf>

³Scenarios 2–5 are created to study the effect of power imbalance among concurrent transmitters.

Proof. Eqn. (2) can be represented as $S_r(t) = \sum_{i=1}^K A_i \cos(\omega_c t + \phi_i)$, where ϕ_i is the phase of the i^{th} signal. For the sake of understanding the influence of the phase differences, we neglect noise from this equation. However, negative influence from noise in phase detection and symbol recovery is part and parcel of the CI phenomenon, which is difficult to quantify.

From the Harmonic Addition theorem, the summation is given by,

$$S_r(t) = \sum_{i=1}^K A_i \cos(\omega_c t + \phi_i) = B \cos(\omega_c t + \hat{\phi}), \quad (3)$$

where,

$$B^2 = \sum_{i=1}^K A_i^2 + 2 \sum_{i=1}^K \sum_{j>i}^K A_i A_j \cos(\phi_i - \phi_j), \quad (4)$$

$$\text{and } \hat{\phi} = \arctan \frac{\sum_{i=1}^K A_i \sin \phi_i}{\sum_{i=1}^K A_i \cos \phi_i}. \quad (5)$$

Here B is the amplitude of resultant signal and $\hat{\phi}$ is the phase of the resultant signal. At the decoder, if $\hat{\phi} > 0$, then the constellation is rotated by that value. In many implementations of O-QPSK based receiver (e.g., [18]), symbol recovery is done by taking hard decisions on the constellation. Each axis acts a ‘threshold’ for detecting a symbol. In case that $\hat{\phi}$ is off by more than $\pi/4$ with respect to the original transmitted signal, then the decoded symbols will result in error. Therefore, to decode correctly, the arriving signals are said to interfere constructively when a maximum phase offset of $\hat{\phi} \leq \pm\pi/4$. \square

We now look at various sources that can alter the phase even if the temporal offset among transmitters is less than $0.5 \mu\text{s}$.

1) *Clock errors and number of transmitters:* There is a heavy reliance on the on-board clock to maintain synchronization. Typically, a crystal oscillator sources the clock for the microcontroller to execute instructions. In CC2420, a digitally controlled oscillator (DCO) acts as the source, which operates at a maximum of 8 MHz. However, this DCO is subject to errors of about $\pm 20\%$ from the nominal value, and temperature and voltage cause deviations of about $-0.38\%/^{\circ}\text{C}$ and $5\%/V$ respectively [5].

Wang *et al.* [9] state that there can be uncertainty in time due to software delays, radio processing delays and clock drifts in each hop. Let p_e be the probability mass function (pmf) of the uncertainty of time on a node. With K concurrent transmitters, the effective pmf will be p_e^K . The probability that there are no clock drifts, i.e., no phase offsets with K concurrent transmitters decreases exponentially with increasing number of transmitters. The exponential curve represents the lower bound of success, i.e., occurrence of no clock drifts. However, from Lemma 1, we can tolerate clock drifts as long as the resultant phase is within bounds. Nevertheless, we can conclude that non-deterministic delays are present and can influence the resultant phase.

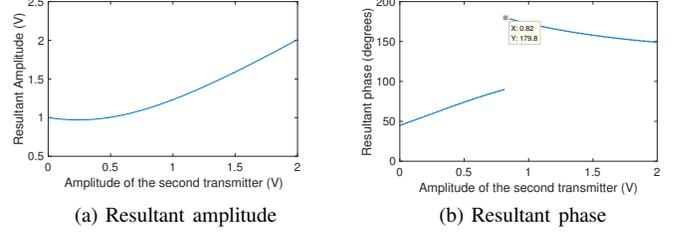


Fig. 5: Resultant amplitude and phase when $A_1 = 1 \text{ V}$ and $\phi_1 = \pi/4$. Amplitude A_2 is varied from 0 to 2 V in steps of 0.01 V and its phase is $\phi_2 = 5\pi/6$.

2) *Distance between transmitters:* Phase of the resultant signal is given by the following relation when two concurrent transmitters (assuming transmission powers are equal) are placed at distances d_1 and d_2 from the receiver respectively,

$$\phi = \frac{2\pi(d_1 - d_2)}{\lambda}, \quad (6)$$

where, λ is the wavelength. It is apparent that if these two transmitters are separated by a distance of $\lambda/2$, then they cancel each other. A generalization of this statement is that path differences between transmitters cause phase offsets, which in turn affects the resultant amplitude and hence, decodability of the signal. For 2.4 GHz radios, the wavelength is $\approx 12.5 \text{ cm}$. Hence, small path differences can create undesirable phase offsets.

3) *Transmission power:* Intuitively, the signal with more power should dictate the amplitude and phase of the resultant signal. This is evident from Eqn. (4) and (5), i.e., when there is a stronger signal $S_i > S_j$, the value of B and $\hat{\phi}$ tends towards the value of A_i and ϕ_i . We demonstrate this with the following example. We consider two concurrent transmitters. We fix the amplitude and phase of one signal to constant values, namely $A_1 = 1 \text{ V}$ and $\phi_1 = \pi/4$. We fix only the phase of the second signal at $\phi_2 = 5\pi/6$ and vary only the amplitude from 0.00 V to 2.00 V in steps of 0.01 V. Fig. 5 shows the amplitude and phase of the resultant signal computed from 4 and 5. There is a point of discontinuity in phase at certain point, and begins tending towards the second signal, as it gets stronger.

In this example, the resultant signal cannot be decoded only when the power of the second signal is between 0.82 and 1.01 V, since the phase correct is incorrect. When there is a stronger signal even with a phase offset, current receivers can compensate this phase offset, hence decoding correctly. It is evident from Fig. 5 that when the powers of the two signals vary, the resulting signal can be correctly decoded though A_2 has a phase-offset greater than $|\phi_2| > \pi/2$. This is in contradiction with the sufficiency condition from Wang *et al.* [9].

4) *Physical environment:* Another factor that affects the phase of the resultant signal is the physical environment where the sensor nodes are deployed. Multipath effect is unavoidable in most real-world deployments. Due to this

effect, concurrently transmitted signals travel different path lengths. Therefore, the receiver will see different phase offsets of the signals. Although several channel models exist, it is difficult to quantify the exact influence of multipath signals on the received signal. Nevertheless, it should not be neglected and can clearly be seen in an actual deployment. We shall demonstrate this in the following section.

Theorem 1. *A packet can be decoded with high probability with concurrent transmissions of the same packet are made when (a) the temporal offset between transmissions is $\leq 0.5 \mu\text{s}$; (b) the phase offset of the resultant signal is $\leq \pi/4$ of the original transmitted signals; (c) the transmission powers of the individual transmissions are different.*

Proof. Conditions (a) and (b) are necessary and sufficiency conditions for constructive interference, while (c) is for capture effect. Condition (a) has been proven in [5] and condition (b) has been proven in Lemma 1. When the transmission powers of the individual signals vary with time offset close to $0.5 \mu\text{s}$, which is much lesser than the preamble time, there is a non-negligible chance of (power) capture effect taking place [4], i.e., the ability of the radio to receive a strong signal regardless of other concurrent transmissions. When the tight time synchronization of $0.5 \mu\text{s}$ cannot be met due to synchronization errors or clock drifts, there is still a high probability of packet being decoded correctly. \square

The significance of Theorem 1 is as follows: concurrent transmissions increase the probability of packet reception either through constructive interference or capture effect (when different transmission powers are employed). It is difficult to quantify the probability of correct reception though due to noise and other various parameters affecting the signal.

5) *Observations:* Since we are investigating the phenomenon of CI over one hop, we look at statistics of each transmitted packet rather than PRR. Here, we are interested in received signal strength (RSSI), bit error rate (BER) and packet losses. Due to paucity of space, we present selected data from different scenarios to best describe the effect of parameters on CI. The conclusions drawn here are applicable to data from all scenarios since the trends were similar. While some conclusions can be derived from previous work, we present them here for the sake of completion. Together with our conclusions, this work provides comprehensive insights into CI.

Fig. 6 shows the RSSI and BER values at the receiver. The RSSI increases with increasing number of concurrent transmitters before saturating at a certain power. However, when we look at the BER, we see that BER does not follow the nice trends as the RSSI; nor does high RSSI imply lower errors. The causes for lower BER could be due to one or more of the factors as discussed in the previous section. From this figure, we infer the following:

Inference 1: CI increases the energy in the wireless channel.

Inference 2: Higher RSSI does not imply lower BER of the packet.

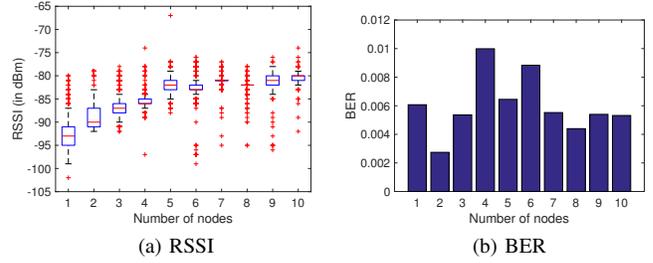


Fig. 6: RSSI and BER values in an empty office.

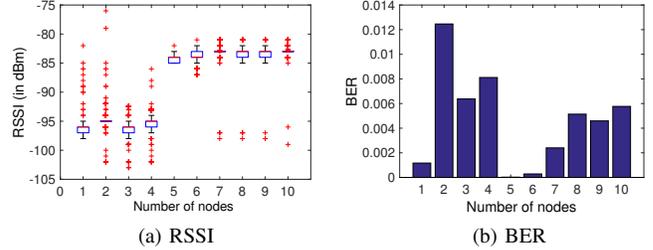


Fig. 7: Multipath effects in corridor.

Inference 3: Temporal offset $\leq 0.5 \mu\text{s}$ is necessary for CI to occur with high probability. However, achieving this tight synchrony is not always sufficient to reap maximum benefits of CI.

Inference 4: There is no relationship between BER and the number of nodes, i.e., we cannot conclude that number of concurrent transmitters will dictate the PRR.

Although we achieved a tight synchronization of $0.5 \mu\text{s}$ on the nodes, we saw that the BER shows variation in performance. This leads us to the third inference. The sufficiency condition in Lemma 1 was probably not satisfied here. We will now illustrate the fourth inference better with another dataset.

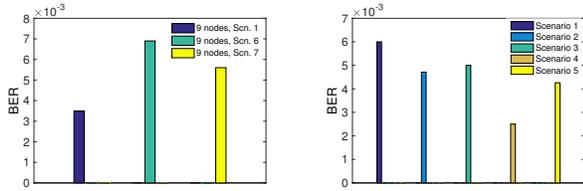
Fig. 7 shows the RSSI and BER for varying number of transmitters in the corridor environment. We strongly suspect that multipath effect is influencing the received signals. It seems that the signal from the fifth node is more ‘influential’ since the RSSI suddenly steps up after the fifth node is added and BER reduces as well. Note all nodes used the same transmit power. The fifth node was the third node from either side of the walls, much closer to the walls than nodes 1 to 4. We can therefore infer the following:

Inference 5: There is a definite influence of the set of transmitters on CI that are participating in concurrent transmissions.

Inference 6: Phase of the resultant signal is influenced by multipath.

Inference 5 is easily observable in Fig. 7(b), wherein adding the fifth node performed better than even with a single transmitter. When signals are bounced off, they take varied path lengths, which is one of reasons for Inference 6 (Inference 6 is also in line with the discussions in the previous section). We will illustrate it with another experiment.

Fig. 8(a) shows the BER for different scenarios when the



(a) BER in the fuselage under different scenarios. (b) BER in various scenarios with 9 concurrent transmitters in the soccer field for a payload size of 127 B.

Fig. 8: BER in various scenarios in two different locations.

nodes are displaced by $\lambda/2$ (Scenario 6) and $\lambda/4$ (Scenario 7). Here it is apparent that the change in path length has increased the bit errors.

Inference 7: Phase of the resultant signal is influenced by the distance between concurrent transmitters.

The last study is about transmit power difference among transmitters. For this study, we pick the data from soccer field with a payload of 127 B (worst BER case). We see the BER from various scenarios in Fig. 8(b). It is clear that different transmit powers have a positive effect on CI, as described in Sec. IV-A. Across experiments, it was difficult to infer whether 3 dBm or 7 dBm difference in transmit powers were performed better. But in all cases, when the transmit powers were randomly chosen (Scenario 4), the obtained BER was the least. Clearly, power imbalance is effective, but it is difficult to find a common threshold of the imbalance that improves the performance of CI.

Inference 8: Transmitting at higher powers usually results in better packet reception. However, power imbalance among concurrent transmitters can also aid packet reception.

B. Clock drifts on the radio and packet size

It is well-known that the bit error rate increases with increasing packet size. In the case of a single transmitter, this observation is attributed to the error-prone wireless channel. However, with CI, there is another factor that causes the increase in bit error rates with increasing packet size even if the channel is coherent throughout the transmission.

Apart from the DCO on the microcontroller, there is another oscillator in the radio module. IEEE 802.15.4 specifies that the radio can tolerate upto ± 40 ppm clock drifts [8] when receiving the carrier signal. That is, the total frequency offset between two concurrent transmitters can be up to 80 ppm. This causes the signals to be distorted (an example is shown in Fig. 1(d)). While an automatic frequency control unit can be employed for compensating the frequency offset, this is not employed due to additional circuitry and cost in the radios. This offset is fine when receiving a single carrier signal since it can be recovered easily at the cost of decreased sensitivity level. However, with CI given that the signals have non-zero phase offsets, the frequency offsets starts impeding the signal and the bits are decoded in error.

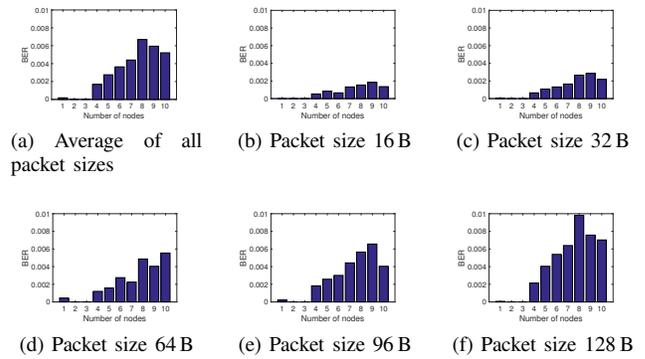


Fig. 9: BER in the soccer field for different packet sizes.

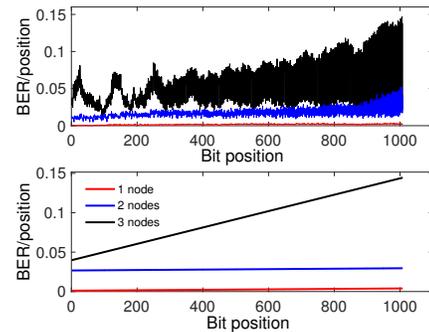


Fig. 10: Top: BER per position for a 127 B payload with varying number of concurrent transmitters. Bottom: Linear fitting to show the slope of BER at different bit positions.

Fig. 9 shows the BER for different packet sizes from the experiments in the soccer field. As expected, longer packet sizes are prone to error. To illustrate the clock errors on the radio, we plot the bit error rate per bit position in a payload of 127 B (1016 bits) in Fig. 10. We see huge variations in errors for 3 nodes and the trend of errors seems to increase with subsequent bit position. To capture this trend, we fit a line to the data which is shown in bottom figure of Fig. 10. The slope is increasing for both 2 and 3 nodes cases but seems negligible for 2, while it is clear the errors are increasing with 3 nodes.

Inference 9: Bigger packet sizes are more prone to errors from both wireless channel and low accuracy clocks in the radio.

Inference 10: The number of concurrent transmitters will influence the BER for bigger packet sizes due to erroneous clocks on the radio.

V. IMPROVING THE PERFORMANCE OF CI

Many works such as the ones mentioned in Sec. II-B employ CI over multihop wireless sensor networks. These works, including Glossy, transmit the packets more than once to ensure packet delivery. Given that CI can have a bad performance, there is a need to improve CI, which increases

the energy-efficiency of CI, without impeding the benefits of CI.

As demonstrated in the previous section, minimum BER from CI can be obtained only when all the parameters are just *right*, which is almost impossible due to many associated practical difficulties. Furthermore, in a random deployment, which is typical of a WSN, each receiving node may see a different BER. Nevertheless, there are two methods to improve CI: (a) reducing non-deterministic delays on the nodes; (b) choosing the transmission powers for each node that maximize CI. There has been considerable work to improve the performance of CI by reducing non-deterministic delays [7], [9]. However, while synchronization is necessary, the performance is still limited by the deployment as we have seen in the previous sections. To this end, setting transmission powers for each node is more beneficial (see Inference 8). Further, given that the wireless channel changes over time, the transmission powers must be adapted to the situation.

The problem of choosing the set of transmission powers for all concurrent transmitters that maximize CI, while achieving energy efficiency, in the network has exponential number of combinations. Energy efficiency is important since the nodes are battery-powered. Let each node have Γ transmission power levels to choose from. With K concurrent transmitters, in the worst case number of combinations that need to be evaluated are of the order $O(2^{K\Gamma})$. Furthermore, a static set of transmission powers will not help in the lifetime of the network.

Under these conditions, we propose a heuristic Destructive Interference based Power Adaptation (*DIPA*) that adapts transmission power based on the performance of CI. The performance is obtained through a *feedback*.

A. *DIPA* Heuristic

Given that CI achieves tight synchronization at chip level, we can achieve DI at a symbol level, i.e., 4 bits. At the receiver, if many dissimilar symbols overlap then symbol recovered is unlikely to be one of the transmitted symbols, since the chip sequences are *quasi*-orthogonal to each other. An exception is that capture effect can help receive the original symbol.

Typically, it is considered that if two or more dissimilar symbols overlap at the receiver, then the decoded symbol is less probable to be either of them. For example, if symbols 0x0, 0x1 and 0x2 are transmitted after spreading and modulation, the receiver demodulates to get the chip sequence. This sequence may not correspond to any of the symbols. A soft-decoding procedure is followed wherein MLE is used to map to the closest symbol.

We designed the *DIPA* heuristic considering a random deployment of nodes, wherein each receiving next hop node can experience a different BER and packet reception with the same set of concurrent transmitters. The intuition behind the heuristic is simple: increase transmit power if packets are not being received, and slowly decrease if the packet reception is stable. The idea is to make transmissions as reliable as possible while conserving energy.

The feedback bytes is appended to the data. Each concurrent transmitter takes this decision locally and independently, based on the feedback it receives from the next hop. Note that each concurrent transmitter might also see a different feedback due to the same effects as on CI and the probability of correct detection. A caveat to the working of this mechanism is that CRC of the packet should be computed in software except for the feedback. At the receiver, the CRC should be checked except for the feedback. This software based CRC computation is allowed in most radios [17].

The intuition behind the heuristic is simple: (a) decrease power if packets are being decoded for G_{TH} consecutive successful reception; (b) increase power if feedback is negative; and (c) if at maximum power and feedback negative, choose a random power hoping for the best. The algorithm for adapting the powers based on feedback on a concurrent transmitter is given in Alg. 1. The heuristic is equally applicable when the concurrent transmitters are randomly placed, and when there is more than one receiver.

In a multihop case where Glossy is used, every node receiving a packet will rebroadcast it a predefined number of times. To use *DIPA* here, we simply include the feedback into the Glossy payload. The only change is in the notion of ACK in Alg. 1, i.e., the concurrent transmitters wait for actual data packets instead of ACK packets from the next hop nodes.

Algorithm 1 *DIPA* heuristic on a concurrent transmitter

```

1: // Let  $p_s$  be the next packet to be sent, and  $p_r$  be the packet that
   is received
2: Initialize  $nSuccess \leftarrow 0$ 
3: function ONRECEIVETIMEOUT
4:    $nSuccess \leftarrow 0$ 
5:   if  $GetTxPower() == MAX\_TX\_POWER$  then
6:      $ChooseRandomTxPower()$ 
7:   else
8:      $IncreaseTxPower()$ 
9:   end if
10:   $p_s.SetFeedback(NACK)$ 
11: end function
12: function ONRECEIVE(Packet  $p_r$ )
13:  if  $p_r.IsCRCValid() == FALSE$  then // Incorrect Tx
   power from the receiver
14:     $p_s.SetFeedback(NACK)$ 
15:  else
16:     $nSuccess \leftarrow nSuccess + 1$ 
17:     $p_s.SetFeedback(ACK)$ 
18:    if  $p_r.GetFeedback() == NACK$  then // Previous
   packets were not being received
19:      if  $GetTxPower() == MAX\_TX\_POWER$  then
20:         $ChooseRandomTxPower()$ 
21:      else
22:         $IncreaseTxPower()$ 
23:      end if
24:    else // Everything is just fine
25:      if  $nSuccess \geq G_{TH}$  then
26:         $DecreaseTxPower()$ 
27:         $nSuccess \leftarrow 0$ 
28:      end if
29:    end if
30:  end if
31: end function

```

Algorithm	Tx Power
Glossy (LP)	0.4
Glossy (HP)	1
DIPA (16B)	0.52
DIPA (32B)	0.58
DIPA (64B)	0.6

TABLE I: Transmit Powers

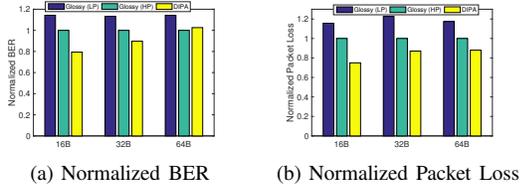


Fig. 11: Comparison between Glossy and DIPA.

B. Evaluation

We evaluate our algorithm in a real-life testbed w-ilab.t [19]. We used 45 nodes on the third floor of the w-ilabs.t office testbed. The testbed contains Tmote Sky nodes with CC2420 radio. We integrated our algorithm into Glossy for evaluation. We do not look at the PRR since we are interested in each transmission that occurs in Glossy. We compare DIPA for different packet sizes to Glossy with transmitting two different powers. All values are averaged over the data from all the nodes and experiments and are normalized with respect to Glossy (HP).

Our method is more energy efficient: while Glossy trades off energy for reliability, we adapt power to achieve lower packet losses than Glossy. Furthermore, as can be seen from Table I and Fig. 11, our method performs as good as Glossy with respect to BER, reduces packet losses and consumes lower power than Glossy for similar performance. Compare to Glossy with 16B packets, DIPA achieves better BER with 25% lesser packet loss and around 50% savings in transmission powers. Similarly, for 32B packets, we achieve a better BER with 10.5% lesser packet losses and 42% of power savings. While BER increased negligibly with 64B packets, we used 40% lesser power to achieve 12% lesser packet losses.

VI. CONCLUSIONS

Constructive Interference (CI), due to its simplicity, has re-defined services and applications, and opened up new avenues in wireless sensor networks. Various studies, hitherto, on CI portrayed an inconsistent view of its working, limitations and benefits. In this paper, we extensively studied CI from the point of view of receivers both analytically and experimentally. Specifically, we derived the expressions for resultant signal and listed the parameters that affect CI. We established how these parameters influence performance of CI and validated our arguments with results from exhaustive experiments considering minute details, such half wavelength distance differences among the transmitters, power, etc. Finally, we drew inferences on the working of CI in real-life settings capturing various situations. We believe that our work is one of the firsts

to provide a holistic view of CI and its effects in various scenarios. While the experiments were conducted in a line-of-sight scenario, they are applicable to other settings as well.

Further, we proposed *DIPA*, a distributed heuristic that is energy-efficient. It improves packet reception by adapting transmission powers. This heuristic leverages destructive interference to gain feedback about packet reception. We evaluated our heuristic on a real-life testbed against Glossy, and showed significant energy savings and packet reception. For 64B packet, our heuristic consumes 40% lesser transmission power and achieves 12% lesser packet losses, and for 16B packets, our heuristic saves up to 50% in transmission power and achieves 25% lesser packet losses as compared to Glossy.

ACKNOWLEDGMENTS

This article describes work partially undertaken in the Go-Green project sponsored by the Dutch Ministry of Economic Affairs, Agriculture and Innovation.

REFERENCES

- [1] G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, and M. Welsh, "Fidelity and yield in a volcano monitoring sensor network," in *OSDI*. USENIX Association, 2006, pp. 381–396.
- [2] M. Maróti, B. Kusy, G. Simon, and Á. Lédeczi, "The flooding time synchronization protocol," in *SenSys*. ACM, 2004, pp. 39–49.
- [3] P. Levis, N. Patel, D. Culler, and S. Shenker, "Trickle: A self-regulating algorithm for code propagation and maintenance in wireless sensor networks," in *NSDI*. USENIX Association, 2004.
- [4] J. Lu and K. Whitehouse, "Flash flooding: Exploiting the capture effect for rapid flooding in wireless sensor networks," in *INFOCOM 2009, IEEE*, April 2009, pp. 2491–2499.
- [5] F. Ferrari, M. Zimmerling, L. Thiele, and O. Saukh, "Efficient network flooding and time synchronization with glossy," in *IPSN*. IEEE, 2011, pp. 73–84.
- [6] C. Noda, C. Pérez-Penichet, B. Seeber, M. Zennaro, M. Alves, and A. Moreira, "On the scalability of constructive interference in low-power wireless networks," in *WSN*, 2015.
- [7] Y. Wang, Y. He, D. Cheng, Y. Liu, and X.-Y. Li, "Triggercast: Enabling wireless constructive collisions," in *INFOCOM, 2013 Proceedings IEEE*, April 2013, pp. 480–484.
- [8] IEEE Standard, *IEEE 802.15.4 specification*, 2011.
- [9] Y. Wang, Y. He, X. Mao, Y. Liu, and X.-Y. Li, "Exploiting constructive interference for scalable flooding in wireless networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 21, no. 6, pp. 1880–1889, 2013.
- [10] D. Yuan and M. Hollick, "Let's talk together: Understanding concurrent transmission in wireless sensor networks," in *Local Computer Networks (LCN)*, IEEE. IEEE, 2013, pp. 219–227.
- [11] J. Park, J. Jeong, H. Jeong, C.-J. Liang, and J. Ko, "Improving the packet delivery performance for concurrent packet transmissions in wsns," *Communications Letters, IEEE*, vol. 18, no. 1, pp. 58–61, 2014.
- [12] D. Wu, C. Dong, S. Tang, H. Dai, and G. Chen, "Fast and fine-grained counting and identification via constructive interference in wsns," in *IPSN*. IEEE Press, 2014, pp. 191–202.
- [13] M. Doddavenkatappa, M. C. Chan, and B. Leong, "Splash: Fast data dissemination with constructive interference in wireless sensor networks," in *NSDI*, 2013, pp. 269–282.
- [14] F. Ferrari, M. Zimmerling, L. Mottola, and L. Thiele, "Low-power wireless bus," in *SenSys*. ACM, 2012, pp. 1–14.
- [15] M. Suzuki, Y. Yamashita, and H. Morikawa, "Low-power, end-to-end reliable collection using glossy for wireless sensor networks," in *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*. IEEE, 2013, pp. 1–5.
- [16] D. Carlson, M. Chang, A. Terzis, Y. Chen, and O. Gnawali, "Forwarder selection in multi-transmitter networks," in *IEEE DCOSS*. IEEE, 2013.
- [17] "Texas Instruments CC2530," <http://www.ti.com/product/cc2530>.
- [18] B. Bloessl, C. Leitner, F. Dressler, and C. Sommer, "A GNU Radio-based IEEE 802.15.4 Testbed," in *12. GI/ITG KuVS Fachgespräch Drahtlose Sensornetze (FGSN 2013)*, Sep. 2013, pp. 37–40.
- [19] "iMinds technical testing: iLab.t," <http://ilab.t.iminds.be/>.