WiZig: Cross-Technology Energy Communication over a Noisy Channel

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***Abstract*—The proliferation of IoT applications drives the need of ubiquitous connections among heterogeneous wireless devices. Cross-Technology Communication (CTC) is a significant technique to directly exchange information among heterogeneous devices that follow different standards. By exploiting a side-channel like frequency, amplitude or temporal modulation, the existing works enable CTC but have limited performance under channel noise. In this paper, we propose WiZig, a novel CTC technique that employs modulation techniques in both the amplitude and temporal dimensions to optimize the throughput over a noisy channel. We establish a theoretical model of the energy communication channel to clearly understand the channel capacity. We then devise an online rate adaptation algorithm to adjust the modulation strategy according to the channel condition. Based on the theoretical model, WiZig can accurately control the number of encoded energy amplitudes and the length of a receiving window, so as to optimize the CTC throughput. We implement a prototype of WiZig on a software radio platform and a commercial ZigBee device. The evaluation show that WiZig achieves a throughput of 153.85 bps with less than 1 % symbol error rate in a real environment. The results demonstrate that WiZig realizes efficient and reliable CTC under varied channel conditions.**

I. Introduction

The ever-developing Internet of Things (IoT) brings the prosperity of wireless sensing and control applications [1] [2] [3]. In many scenarios, different IoT applications coexist and deploy heterogeneous devices in the shared medium as well as the physical space [4] [5] [6] [7]. Timely and efficient information exchange among those devices is therefore a fundamental requirement to ensure the usability, interoperability and dependability of the IoT [8] [9] [10] [11]. The major portion of those devices, however, operate on the same frequency band but follow different technologies, e.g. WiFi, ZigBee, and Bluetooth on the 2.4GHz ISM band. How to deliver data across different technologies remains an open problem.

Early works to address the above problem propose to build indirect connections among devices. Gathering data from the devices at the cloud is such an option but clearly lacks efficiency, due to the unpredictable transmission delay over the Internet. Another proposal is to connect the devices via a local gateway [12] [13]. Such a gateway is equipped with various radio interfaces, enabling it to communicate with devices of different wireless technologies. The need of extra hardware prevents such a proposal from pervasive uses, not to mention the potential traffic overhead induced by the gateway-oriented communications.

Direct communication among different technologies appears to be a more promising direction. Under this circumstance, Cross-Technology Communication (CTC) technique is proposed, which aims at directly exchanging mutually understandable information between two different technologies. This is a challenging task because a device cannot directly decode the standardized message from another technology. The existing proposals try to exploit free side-channels as information carriers. Regarding the wireless medium, a side channel typically exists in the following three dimensions: frequency, amplitude, and time [14]. For example, by intentionally control the absence or presence of data packets, the works in [15] and in [16] encode 0/1 bits in the amplitude dimension. Decoding of those modulated bits, however, is highly susceptible to channel noises. FreeBee [17] is a representative work in the temporal dimension. It enables direct unicast and cross-technology/channel broadcast among wireless technologies by embedding symbol into beacons and shifting their transmission timings. The achievable date rate of FreeBee, however, is bounded by the beacon rate (1/102.4ms) of commercial WiFi devices.

Based on the above facts, we realize that amplitude-modulation-based CTC is easy to implement but prone to packet corruptions over a noisy channel. Temporal modulation is relatively more robust to noise, while its throughput is generally restricted by various technological specifications. Can we achieve high-throughput CTC over a noisy channel? This is a crucial problem with great practical significance.

We explore the answer to the above question in this work and propose WiZig, a practical CTC protocol. By regulating the transmission power, a WiZig sender encodes one or more bits by means of multiple energy levels. A WiZig receiver detects the energy levels of the received signal sequences and then decodes a message. In the design of WiZig, we address both theoretical and practical challenges of CTC. The main contributions of this work are summarized as follows.

- We present a general framework of CTC, which jointly employs modulation techniques in both the amplitude and temporal dimensions. Based on this framework, we establish a theoretical model to clearly describe the relationship between BER (Bit Error Rate) and SNR (Signal to Noise Ratio), given the length of the receiving window.
- We devise the WiZig protocol, which mainly consists of two modulation techniques and an online rate adaptation

algorithm. The rate adaptation algorithm optimizes the throughput of CTC against dynamic noise, according to the theoretical foundation we build.

- We implement WiZig on a software radio platform and a commercial ZigBee device. We evaluate the performance of WiZig using different experimental settings. The throughput of WiZig is 153.85 bps with less than 1% symbol error rate in the real office environment. The results demonstrate WiZig can realize efficient and reliable CTC under varied channel noises.

The rest of this paper is organized as follows. Section II discusses the related work. Section III presents the design overview of WiZig. Section IV illuminates the theoretical fundamentals of this work. Section V presents the modulation of WiZig and an online rate adaptation algorithm. In Section VI, we evaluate the performance of WiZig. We conclude this work in Section VII.

II. Related work

In the era of IoT, realizing interconnection of all the smart things has become an inevitable trend. However, heterogeneous wireless devices are actually isolated from each other in the cyber space, because they cannot understand the messages from the other heterogeneous coexisting devices following different communication standards. Cloud is a choice to exchange the information among severs that store data from individual systems. But this method requires devices have access to the Internet [18] [19] [20]. Besides, the exchange has considerable sensor-to-server transmission delay. Some researchers propose to connect the coexisting devices through a local gateway [12] [13]. Equipped with multiple radio interfaces, a local gateway can translate data from different application systems. However, the relay traffic of the gateway will bring significant additional wireless traffic. Besides, the dedicated gateway will increase the deployment and maintenance cost.

Recently, Cross-Technology Communication (CTC) technique is proposed to enable direct communication between heterogeneous wireless device [21]. FreeBee [17] embeds symbols into beacons by shifting their transmission timings. However, the date rate of FreeBee is limited by the beacon rate which is usually 102.4ms/beacon for commercial WiFi devices. Other works propose energy profile as a new information carrier to exchange the data without gateway. Esense [15] is the first work that uses energy sampling realizing information transmission from WiFi to ZigBee devices. It aims at building an alphabet of implicit messages using the packet duration information. HoWiEs [22] improves the Esense mechanism and uses the combination of predefined packets sizes form the alphabet to realize delivery. Gap Sense [23] prepends legacy packets with a customized preamble and constructs sequences of energy pulses. Then the receiver senses the gaps between the energy pulses to convey information to decode the message. The absence or presence of packets is used to transmit messages for interconnection between heterogeneous wireless devices[16].

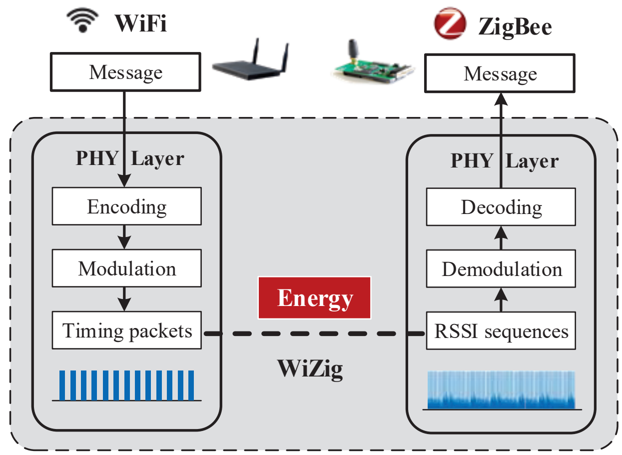


Fig. 1. The Framework of WiZig

Since the communication channel is intrinsically noisy, it is non-trivial to reduce the harmful impact of noise and realize lower error rate. Without theoretical model, existing energy-profile based CTC only heuristically resists noise. Moreover, communication channel is dynamic and it is challenging to improve the data rate without increasing the bit error rate. The impact of noise on throughput is analyzed in [17] but how to anti random and uncontrolled noise is not clear. In [15] [16] [22] [23], it has been revealed that energy profile is promising as a new channel to realize direct communication between heterogeneous wireless devices. However, those works only shed the light of exchanging information via energy channel without clear design to apply in the the practical noisy environments.

Different from existing methods, WiZig adjusts the amplitude and temporal modulation to conquer the negative effects of noise. Based on our theoretical model of energy channel, we devise a novel online rate adaption algorithm to realize efficient and reliable cross-technology communication.

III. Overview of WiZig Framework

In this section, we first present the design framework of WiZig, a novel CTC technique that enables direct communication among wireless devices with different PHY/MAC standards. WiZig leverages the overhearing of transmissions between different technologies to encode and decode information. Based on this framework, we derive a theoretical model to describe the relationship between BER and SNR, which can be used to optimize the throughput under noise.

Fig. 1 depicts the overall Framework of WiZig that includes two parts, WiZig sender and WiZig receiver. Without losing generality, we take the transmission from WiFi to ZigBee as an example. The sender modulates messages as the presence and absence of WiFi packets (two energy levels) to represent symbol "1" and "0". After encoding and modulation, the sender transmits these WiFi packets without modifying the PHY layer. On the receiver side, the WiZig receiver detects

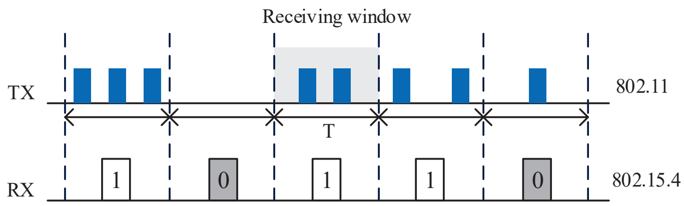


Fig. 2. The basic schematic diagram of WiZig

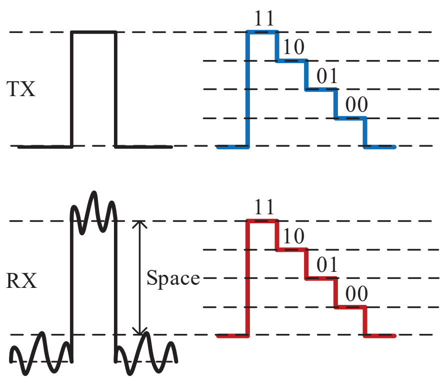


Fig. 3. The schematic diagram of communication with multiple energy levels (four energy levels in the example)

the Received Signal Strength Indicator (RSSI) sequences in the overlapping communication channel that is saturated with WiFi packets from WiZig sender. Then the receiver decodes the message as "1" when the accumulative RSSI values within a receiving window reach a threshold. Otherwise, the receiver decodes the message as "0". The basic communication process of WiZig is shown in Fig. 2. It is obvious that the channel resource is not fully exploited if only transmitting one bit in one fixed receiving window. The sender can increase the number of energy levels to encode multiple bits at once and shorten the receiving window length to realize higher data rate.

However, the energy communication channel is intrinsically noisy as shown in Fig. 3. It is important to reduce the harmful impact of noise to improve the throughput without increasing the error rate. Hence we model the energy channel and theoretically analyze the relationship among the bit error rate (BER), symbol error rate (SER), signal to noise ratio (SNR) and the number of energy levels. SER is the error rate that the receiver incorrectly decodes the symbol within a receiving window. Based on the theoretical model, we carefully design our modulation/demodulation rules and parameters to reduce the bit error rate under a noisy channel. In addition, the wireless channel is dynamic. It is challenging to fully explore the channel resources without increasing the error rate under the intrinsically dynamic channel. Hence, an accurate rate adaption mechanism is proposed in WiZig to optimize the throughput with the error rate satisfying the requirement. The online rate adaption mechanism can increase throughput safely when channel is good and reduce the error rate when channel

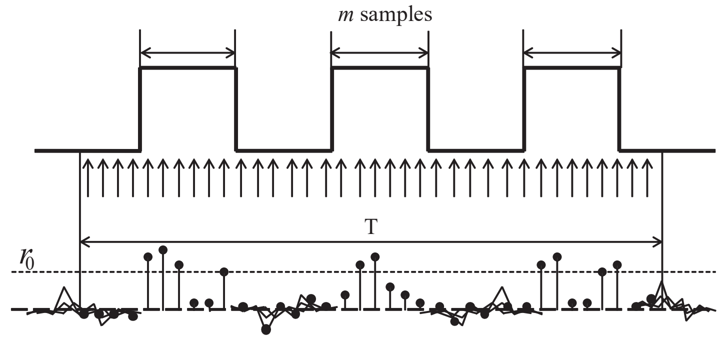


Fig. 4. Energy communication when channel is noisy

is poor.

IV. Theoretical Analysis

The intrinsic noise on wireless channel will corrupt the RSSI samples that the receiver received, as shown in Fig. 4. To understand the potential of energy communication channel and improve its ability of anti-interference, we first model the energy communication channel to describe the constraint relationship among the BER and SNR for one sample point. Then we consider the whole samples in a receiving window to describe the relationship of SER and SNR.

First, we bulid a model that describes the relationship between BER and SNR for one sample. Assuming the channel is an additive white Gaussian noise channel (AWGN), with the mean of 0 and the variance of σ_{n}^2, Its one-dimensional probability density is defined as

$$f_0(x) = \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{x^2}{2\sigma_n^2}} \quad (1)$$

Suppose the transmission power of the sender is a. Then the signal at the receiver is the superposition of sending signal and channel noise. Its one-dimensional probability density is defined as

$$f_1(x) = \frac{1}{\sqrt{2\pi\sigma_n^2}} e^{-\frac{(x-a)^2}{2\sigma_n^2}} \quad (2)$$

The curves of $f_0(x)$ and $f_1(x)$ are as shown in Fig. 5(a).

If we take the decoding threshold as b, the decision rule is as follows:

(1) $x > b$, decode as 1.

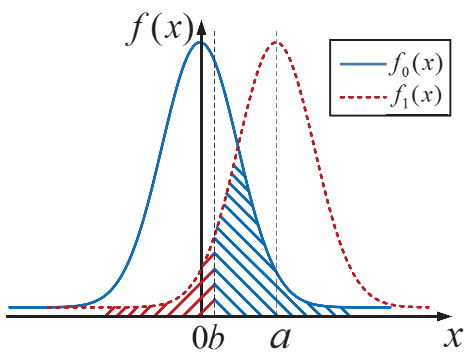
(2) $x \leq b$, decode as 0.

The probabilities that the receiver decode 1/0 incorrectly as 0/1 are $P(0|1)$ and $P(1|0)$, respectively.

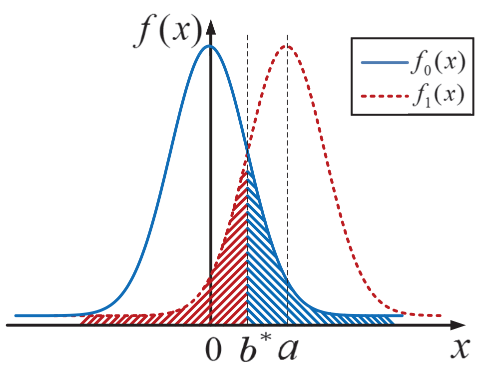
$$P(0|1) = P(x \leq b) = \int_{-\infty}^{b} f_1(x)dx = 1 - \frac{1}{2} erfc(\frac{b-a}{\sqrt{2}\sigma_n}) \quad (3)$$

$$P(1|0) = P(x > b) = \int_{b}^{+\infty} f_0(x)dx = 1 - \frac{1}{2} erfc(\frac{b}{\sqrt{2}\sigma_n}) \quad (4)$$

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{+\infty} e^{-u^2} du \quad (5)$$



(a) $0 < b < a$



(b) $b^* = \frac{a}{2}$

Fig. 5. The curves of one-dimensional probability density of sending signal and channel noise

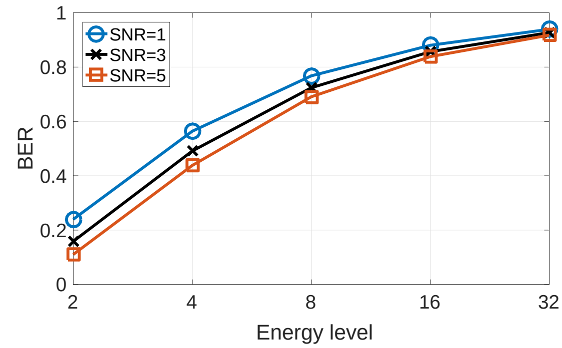


Fig. 6. The relationship between BER and energy level

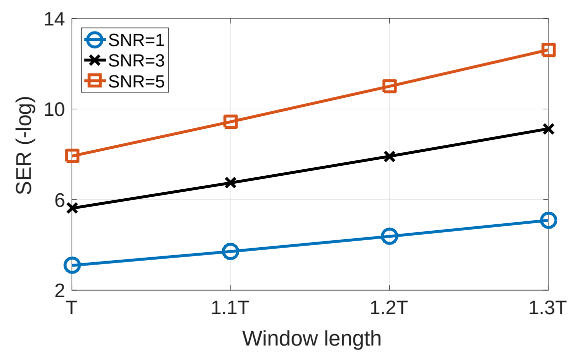


Fig. 7. The relationship between SER and window length

If assuming that the probability that sender sends 1 and 0, denoted as $P(1)$ and $P(0)$ are equal, then the total error rate of receiver p can be calculated as follows.

$$p = P(1)P(0|1) + P(0)P(1|0) = \frac{1}{2}P(0|1) + \frac{1}{2}P(0|1) \quad (6)$$

From Eq. (6), we can find that p is related with decision threshold b and signal strength a. We can obtain the optimal decision threshold $b^* = \frac{a}{2}$ to minimize the total error rate p by letting $\frac{\partial p}{\partial b} = 0$. When we choose $b^* = \frac{a}{2}$, p can be calculated as follows and shown in the shaded area in Fig. 5(b).

$$p = \frac{1}{2}erfc(\sqrt{\frac{r}{4}}), r = \frac{a^2}{2\sigma_n^2} \quad (7)$$

Eq. (7) revels the relationship of BER and SNR for one RSSI sample. Assuming the receiver samples m values in a receiving window, if the number of samples that are decided as 0/1 by the receiver but the sender actually transmits 1/0 is less than a threshold $m - m_0$, the receiver can decode message correctly within a receiving window. Then the SER is as Eq. (8).

$$P_e = \sum_{q=0}^{m_0} C_m^q (1-p)^q p^{m-q} \quad (8)$$

If M energy levels are used, BER and SER can be represented as Eq. Eq. (9) and Eq. Eq. (10), respectively.

$$p_m = (1 - \frac{1}{M})erfc(\sqrt{(\frac{3}{M^2-1})\frac{r}{4}}), r = \frac{a^2}{2\sigma_n^2} \quad (9)$$

$$P_{em} = \sum_{q=0}^{m_0} C_m^q (1-p_m)^q {p_m}^{m-q} \quad (10)$$

We can observe the relationship among BER (p), SNR (r) and the number of energy levels (M) in Fig. 6. BER will increase with the increase of r when same number of energy levels is used. For example, when the number of energy levels is 2, the BER are 0.0569 and 0.2398 when the SNR are 5dB and 1dB, respectively.

We can also find that the BER will sharply increase when the number of used energy levels increases. For example, when SNR is 3dB, the BER is 0.1103 when the number of energy levels is 2. The BER will increase to 0.6906 if we use eight energy levels and up to 0.9175 if we use 32 energy levels.

The BER will be much higher when using more energy levels. So in this case, it is essential to adjust the length of receiving window to reduce error rate. How long the length of receiving window we need to increase during each process of decoding? We extend the receiving window as $K = T + n * \frac{T}{10}$ and the SER will decrease with extending the length

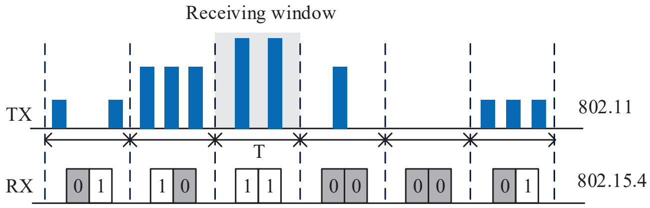


Fig. 8. The schematic diagram of amplitude modulation

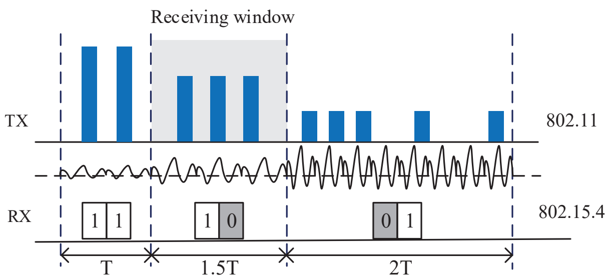


Fig. 9. The schematic diagram of temporal modulation

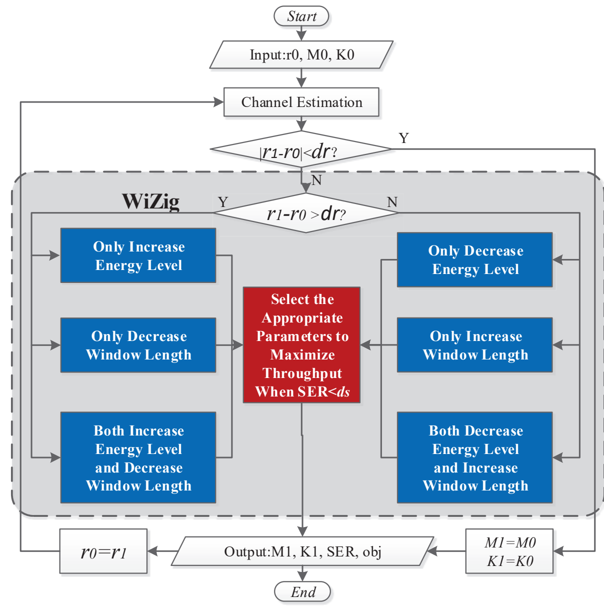


Fig. 10. The flow chart of online rate adaptation algorithm

of receiving window as shown in Fig. 7 ($-log(SER)$ will increase monotonically). For example, when SNR is 1dB, the SER can be reduced from 0.0453 when $n = 0$ to 0.0014 when $n = 5$. In addition, The SER will also decrease sharply with the increase of SNR.

V. Modulation and Demodulation

A. Amplitude Modulation

We propose amplitude modulation that increases the number of used energy levels to encode more bits at once for improving throughput. With amplitude modulation, WiZig is able to increase the data rate when channel is good by increasing the number of used energy levels to encode multiple bits in a receiving window. To satisfy required error rate, WiZig is also able to decrease the number of used energy levels when channel is poor. Without losing generality, we take the modulation of four energy levels as an example, as shown in Fig. 8. The WiZig sender transmits packets with three different powers to provide three energy levels that can be encoded as 01, 10, 11. And the absence of packet is encoded as 00. The WiZig receiver samples the RSSI on channel and can detect four different energy levels. Then the receiver can decode 2 bits data at once.

There are packet samples $(s_1, s_2, ..., s_m)$ in receiving window T. The amplitude modulation/demodulation rules are as follows. (1) The WiZig sender transmits packets with three different powers W_0, W_1 and W_2. Without losing generality, we assume $W_2 > W_1 > W_0$. Then the sender encodes the packets with power of W_2 as bit “11”, the packets with power of W_1 as “10”, the packets with power of W_0 as “01”. The absence of packet is encoded into “00”. (2) The receiver detects signal strength on the overlapping channel and obtains the RSSI sequences. Based on the number of used energy levels, the receiver sets three deciding thresholds th_{e0}, th_{e1} and th_{e2} which satisfy $th_{e2} > th_{e1} > th_{e0}$. For each packet sample, its logic value will be decided as “11” if the sampling value $RSSI \geq th_{e2}$, “10” if the sampling value $th_{e1} \leq RSSI < th_{e2}$, “01” if the sampling value $th_{e0} \leq RSSI < th_{e1}$, “00” otherwise. (3) For each receiving window, its decoding value will be “11”, “10”, “01” and “00” if more than th_m samples have the logic value “11”, “10”, “01” and “00”, respectively.

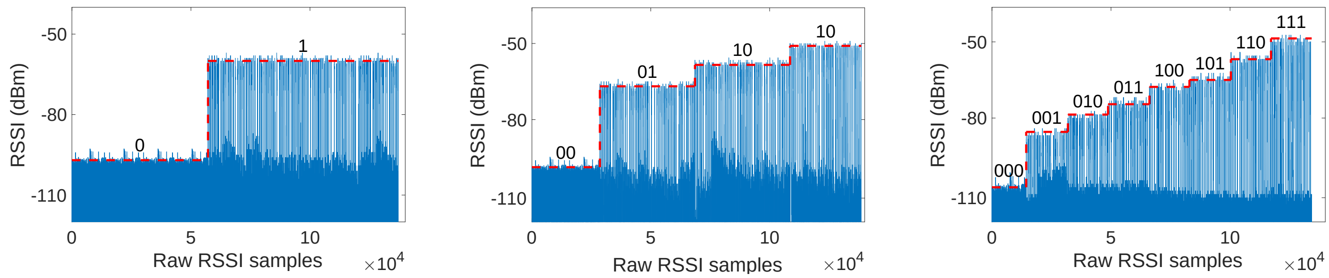
B. Temporal Modulation

We propose temporal modulation to be more resilient to the dynamic noise on wireless channel. WiZig extends the length of window to decrease the error rate when the channel quality is poor and shorten the length of time window to improve the date rate when the channel quality is good. Without losing generality, we also take the modulation of four energy levels as an example as shown in Fig. 9.

The modulation/demodulation rules are as follows. (1) The WiZig receiver samples the signal strength on channel and estimates the channel noise. If current SNR is becoming larger, then WiZig will shorten the receiving window length to improve the data rate. On the contrary, if current SNR is getting lower, then WiZig extends the receiving window length to tolerate the bursty sample errors. We extend and shorten the receiving window by adjusting $K = T \pm n * \frac{T}{10}, n = 0, 1, 2, 3...$. (2) After determining the length of receiving window, the sender modulate the data and the receiver decode the energy symbols by the rules in amplitude modulation.

C. Online Rate Adaptation

Energy communication channel is intrinsically dynamic. It is challenging to improve the data rate without increasing BER



(a) Two energy levels (b) Four energy levels (c) Eight energy levels

Fig. 11. Raw RSSI sequences with different number of energy levels

Fig. 12. The experiment platform: a prototype of WiZig, one USRP acts as WiFi sender, another USRP generates Gaussian noise and TelosB mote is used as ZigBee device

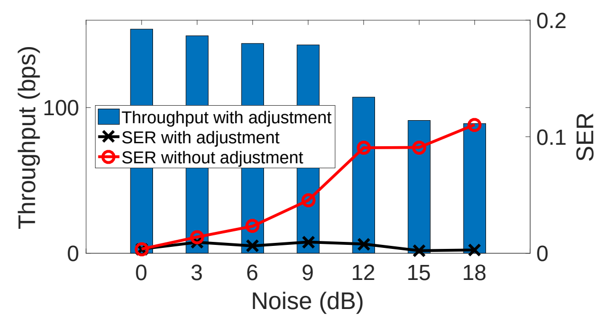


Fig. 13. Throughput and SER with and without adaptation algorithm

under the dynamic channel. Therefore, it is important to adjust the energy levels and receiving window length adaptively according to current channel conditions. WiZig integrates an online rate adaptation algorithm to make a balance between S-ER and date rate to optimize the throughput without increasing the error rate. The optimization goal is defined as

$$obj = \frac{\log_2 M}{K} * (1 - P_{em}) \tag{11}$$

where $\log_2 M$ is the number of data bits that can be decoded within each receiving window, K is the length of receiving window and P_{em} is the SER. When SNR varies from r_0 to r_1, parameters can be adjusted from (M_0, K_0) to (M_1, K_1) to adjust to the channel condition changes.

The flow chart of our online rate adaptation algorithm is illustrated in Fig. 10. The working flow is as follows. (1) The WiZig receiver samples the energy on the channel and estimates the new SNR r_1. (2) If the difference between r_1 and r_0 is less than the threshold d_r, then the original parameters will be used without any modification. (3) If the new SNR r_1 is higher than r_0, it means communication channel is better. Then WiZig has three methods to adjust parameters. The first one is to only increase the number of energy level and then we can obtain a new parameter M_1. The second method is to only decrease the window length and then we can obtain a new parameter K_1. The third method is to both increase the energy level and decrease the window length, then we can obtain new parameters M_1 and K_1. If new SNR r_1 is lower than r_0 it means communication channel is worse. Then WiZig will also has three method to adjust parameters which is similar when SNR r_1 is higher than r_0. (4) The WiZig selects the appropriate parameters which can maximize the throughput when $SER < d_s$. (5) The receiver obtains the new parameters (M_1, K_1) and deliveries them to the sender. Then the sender modulates/encodes messages with the updated parameters and the receiver demodulates/decodes the message with new parameters.

VI. Evaluation

A. Evaluation Settings

We implement a prototype of WiZig on TelosB, a commercial ZigBee platform, and USRP platform as shown in Fig. 12. Our prototype uses an USRP N210/GNURadio to generate WiFi packets following IEEE 802.11 standards. Spectrum overlap is the prerequisite of energy communication. In our implementation, we choose 802.11 channel 6 and 802.15.4 channel 17 to construct the energy communication channel. USRP/N210 sender transmits 3000 packets with length of 250 bytes per second to act as WiZig sender. We control the transmission power to generate different energy levels and the difference between two adjacent levels of transmission gain is 5 dB because the corresponding RSSI values are enough to be distinguished. We use another USRP/N210 to generate

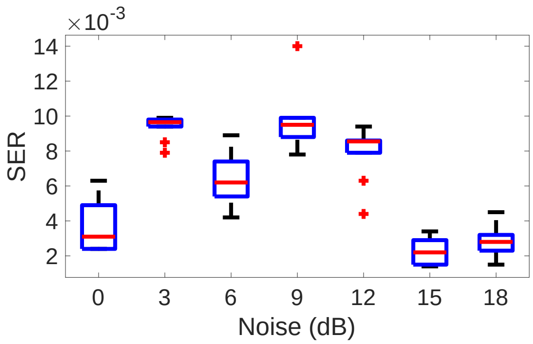


Fig. 14. SER under different noise intensities

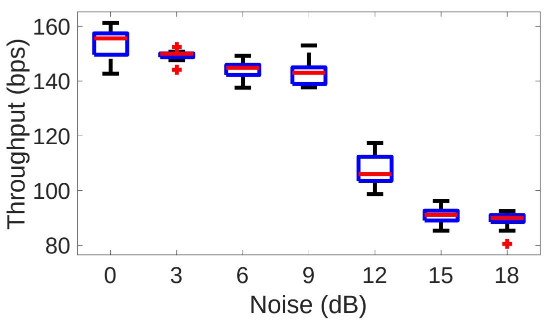


Fig. 15. Throughput under different noise intensities

Gaussian noise with different power. The decoding threshold th_m is decided by the difference of the received RSSI values between the noise and particular energy levels. The RSSI sampling rate of TelosB node is 36 KHz. The initial unit receiving window of one symbol is 5 ms and the decision threshold th_m is 7, half of the total packet samples in a receiving window.

B. SER and Throughput

First, the transmission gain of USRP is 20 dB and TelosB receiver detects RSSI sequences with sampling rate is 36 kHz and time window length 5 ms. The threshold th_e is -70 dBm. Fig. 11(a) shows the raw RSSI values sampled by a TelosB mote and the spikes are caused by the transmission of WiFi packets. The sender modulates the presence or absence of packets as 1 or 0. The SER is 0 and throughput is 102.93 bps. We can find that the difference between spikes and noise base is still large, which means that the encoding space is enough and we can divide multiple energy levels to improve the throughput.

Second, the transmission gain is set as 15 dB, 20 dB and 25 dB, the raw RSSI values sampled by a TelosB mote are shown in Fig. 11(b). The threshold th_{e0}, th_{e1}, th_{e2} are -80dBm, -70 dBm, -60 dBm. Obviously, we can find that there are three different types of spikes which can be encode as 01, 10 and 11. The SER is also 0 and the throughput is 140.27 bps.

Third, the transmission power is set as 0 dB, 5 dB, 10 dB, 15 dB, 20 dB, 25 dB, and 30 dB, the raw RSSI values sampled by a TelosB mote are shown in Fig. 11(c). The threshold th_{e0}, th_{e1}, th_{e2}, th_{e3}, th_{e4}, th_{e5}, th_{e6} are -86 dBm, -80 dBm, -74 dBm, -68 dBm, -62 dBm, -56 dBm, -50 dBm. Obviously, we can find that there are seven different types of spikes which can be encode as 001, 010, 011, 100, 101, 110, 111. The SER is 0.0036 and the throughput is 153.85 bps.

C. Benefit of online rate adaptation

WiZig includes amplitude modulation and temporal modulation. Amplitude modulation can increase the number of energy levels to improve the data transmission rate and temporal modulation can extend the length of receiving window to reduce the SER. It is important for WiZig to make a balance between throughput and SER by adjusting the number of energy levels and the length of receiving window to realize a better optimization according to the rate adaptation algorithm when the channel noise is increasing.

First, we increase the channel noise and keep the original setting with fixed parameters (energy level=8 and receiving window=T). The gain of jamming USRP is set as 0dB, 3dB, 6dB, 9dB, 12dB, 15dB, 18dB. The distance between TelosB node and this noise source is twenty centimeters. We can find that SER will increase sharply as shown in Fig. 13. When noise is 0dB and the SER is 0.0036. However, when the noise is 3dB, the SER is 0.0139 and larger than 0.01. Furthermore, when noise is 18dB, the SER will be up to 0.1103 which is more than ten times of 0.01. In this condition, there is little sense to record throughput due to that it is difficult for the ZigBee receiver to decode message correctly with higher SER. our adaptation algorithm can reduce SER and increase the throughput by reducing the number of energy levels and extending the length of receiving window. when noise is 3dB, the SER with rate adaptation algorithm is 0.0094, which is lower than 0.01. The throughput correspondingly is 149.3 bps, which is a little lower than original 153.85. The SER is always lower than 0.01 and the throughput will decreases with the increasing of noise amplitude. When the noise is 18dB, the SER is 0.0028, which decreases by near 40 times than the SER without adaption algorithm. In addition, the throughput is about 89 bps, which is lower than 153.85 bps due to that the energy level is changed to 2 from 8 and the length of receiving window is extended to 1.1T to guarantee the SER is lower than 0.01.

For each noise condition, we conduct 10 experiments and the results of SER and throughput are shown as Fig. 14 and Fig. 15. We can find that the values of SER are always lower than 0.01, except 0.014 when noise is 9dB. The throughput will decrease with the increase of noise. It is also stable and the fluctuation of throughput is smallest when noise is 3dB.

Our rate adaptation algorithm can find optimal parameters of energy level and receiving window length (M, K) when channel is noisy. We select several combination parameters (energy level and receiving window length) and observe corresponding throughput and SER under three different kinds of noise. There

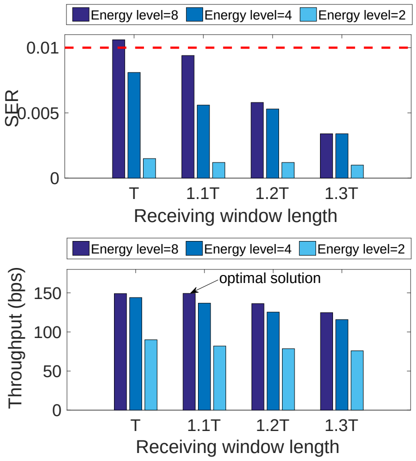


Fig. 16. SER and throughput with different parameters when noise is 3 dB

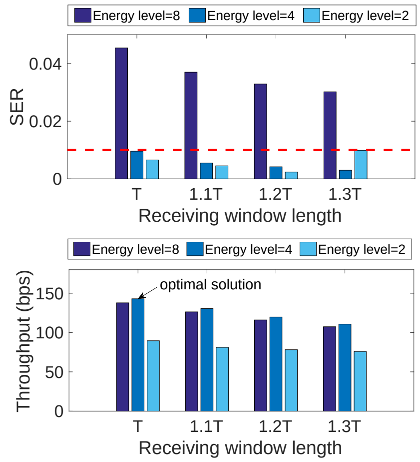


Fig. 17. SER and throughput with different parameters when noise is 9 dB

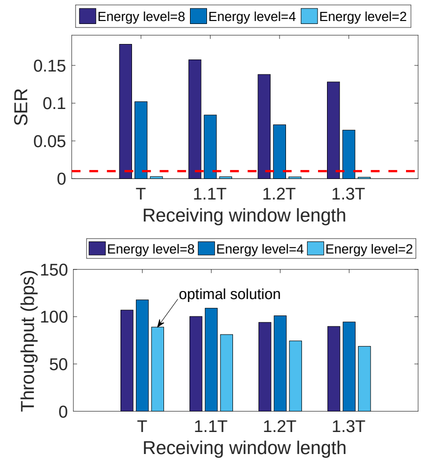


Fig. 18. SER and throughput with different parameters when noise is 18 dB

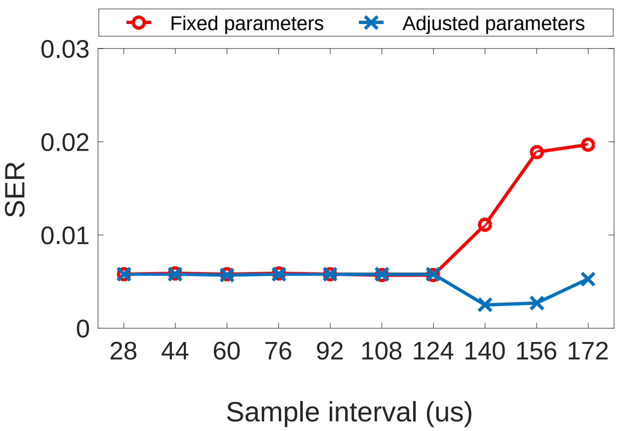


Fig. 19. SER under different RSSI sampling rates

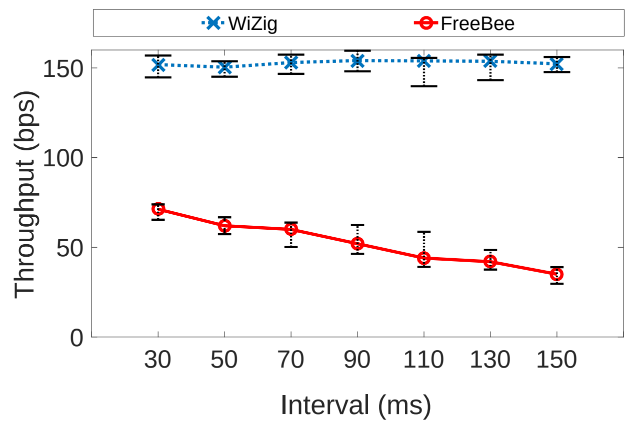


Fig. 20. Throughput under different WiFi beacon intervals

are 12 parameter combinations. Energy level varies from 8 to 2 and receiving window length increases from T (5 ms) to 1.3T. We take that the noise is 3dB, 9dB and 18dB as examples to show that adjusting the parameters of energy level and window length can obtain optimal throughput under the condition of guaranteeing the SER is lower than 0.01. When noise is 3dB, the SER is lower than 0.01 except when energy level is 8 and window length is T. In this condition, we can choose other parameter combinations to make the throughput maximization as shown in Fig. 16. If we choose the energy level is 8 and window length is 1.1T, then the SER will be 0.0094 and the throughput is 149.3 bps. When noise is 9dB, the SER is larger than 0.01 when the energy level is 8. So it is necessary to decrease the energy level. In this condition, the SER will be 0.0096 and the throughput is 141.0176 bps if the energy level is 4 and window length is T as shown in Fig. 17. When noise is 18dB, the SER is larger than 0.01 when the energy level is 8 and 4. In this condition, we choose the energy level is 2 and window length is T to obtain the optimal throughput of 89.0167 bps and at the same time that the SER is 0.0028 as shown in Fig. 18.

D. Robustness of SER Model

Several other parameters, for example, the sample rate of the receiver can also influence the SER. WiZig can adjust the number of energy levels and the length of receiving window to reduce SER according to the theoretical support of SER Model. The fixed parameters are that the energy levels is two and the receiving window length is 5 ms which are also the original parameter settings for the receiver. The parameters are adjusted by the receiver when the SER is higher than 0.01.

We check the robustness of WiZig with considering the sampling rate of ZigBee devices. USRP/N210 sender transmits packets modulated by BPSK1/2 with length of 250 bytes. We change the sample interval of ZigBee receiver and observe the variation of SER as shown in Fig. 19. We can find that the relationship of SER and sample interval is not an absolutely monotonic relation. SER is relatively small and stable when sampling interval is less than 140 us. The sample rate of the receiver have a great influence on SER and WiZig can choose the optimal parameters to reduce SER with theoretical support of SER Model.

In addition, we demonstrate the effectiveness of our design by comparing the throughput between WiZig and FreeBee, a state-of-art cross-technology communication scheme. FreeBee modulates symbol messages by shifting the timing of period beacon frames and demodulates the message by RSSI values based on the method of folding [24]. We set the number of beacon repetitions for statistic demodulation is $\rho = 2$ and observed the throughput variation of FreeBee and WiZig when the beacon interval changes from 30 ms to 150 ms as shown in Fig. 20. Enlarging the beacon interval has two effects. On the one hand, it will offer more space for timing shift and yield more bits per symbol. On the other hand, it require more time to reach the same ρ. The throughput of FreeBee will decrease with the enlarging of beacon interval. The throughput of WiZig is stable and higher than FreeBee.

VII. Conclusion

We propose WiZig, a novel mechanism that enable wireless devices with different PHY/MAC standards realize direct communication. We model the energy channel and analyze the relationship among the BER, SER, SNR and the energy levels in theory. Based on the theoretical model, we carefully design our amplitude/temporal modulation/demodulation rules to reduce the SER and increase throughput under noisy channel. In addition, an online rate adaptation algorithm is proposed to dynamically adjust the number of energy levels and the length of receiving window to realize higher data rate. We implement a prototype of WiZig on a software radio platform and a commercial ZigBee device. The evaluation show that WiZig achieves a throughput of 153.85 bps with less than 1% symbol error rate. The results demonstrate WiZig can realize efficient and reliable CTC under varied channel noises.

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