Mrs.Z: Improving ZigBee Throughput via Multi-Rate Transmission

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***Abstract*—ZigBee is a widely used wireless technology in low-power and short-range scenarios such as Internet of Things (IoT), sensor networks, and industrial wireless networks. However, the standard ZigBee supports only one data rate, 250Kbps, which thoroughly limits ZigBee's efficiency in dynamic wireless channels. In this paper, we propose Mrs.Z, a novel physical layer design to enable multi-rate selection in ZigBee. The key idea is to change the single spectrum spreading length to multiple ones. Correspondingly, to gracefully adapt to the channel variations, we propose a BER-based rate selection scheme, dividing bit errors into two categories: errors caused by the exceeding despreading threshold, which can be discovered in the physical layer, and caused by incorrect despreading, which is not visible until *cyclic redundancy check* (CRC) in the *media access control* (MAC) layer. Then, the receiver selects the rate based on the underlying negative impacts incurred by them and feedbacks to the transceiver. We implement Mrs.Z on USRPs and evaluate its performance in different scenarios. Results demonstrate that Mrs.Z achieves an improvement of 20% and 80% compared to the classic SoftRate and the standard ZigBee.**

I. Introduction

ZigBee, a low-cost, low-rate, and low-power communication technology based on the 802.15.4 standard [1], has been widely applied in various IoT platforms, such as smart home [2] and smart-grid systems [3]. Such wide deployments of ZigBee in IoTs are faced with three challenges: (i) requirements for the higher data rate in large-scale IoTs (ii) resistance to complex and dynamic channels, (iii) limited wireless link resources, all of which impose ever-increasing requirements on its throughput [4]. Traditionally, it is achieved via either collision avoidance [5] [6] or collision resolution [7] [8]. For example, ZigZag [9] reduces communication collisions by separating packets with time offsets, and mZig [10] recovers the transmitted information from collided packets by decomposing them chip-by-chip.

Rate adaptation — i.e, adaptively adjusting the communication data rate based on real-time link quality — is another orthogonal dimension to improve throughput, with proved effectiveness for WiFi-based communications, but is still defectively covered in Zigbee. Various rate selection schemes have been proposed to enhance WiFi's throughput against channel variations [11]–[13]. These designs are feasible because the 802.11 standard, the core of WiFi, is able to offer varying data rates of 6$\sim$600Mbps [14], by adjusting its modulation schemes (e.g., BPSK, QPSK, 16-QAM and 64-QAM in 802.11n) and coding rates (e.g., 1/2, 2/3, 3/4 and 5/6) at the transmitter. ZigBee, however, supports only one modulation scheme in the physical layer, leading to a single and fixed data rate, e.g., 250Kbps for ZigBee with the *Offset-Quadrature Phase Shift Keying* (O-QPSK) physical layer at 2.4GHz [1], impeding the deployment of rate adaptation techniques thereon. Note that adding new modulation schemes to ZigBee is clearly not desirable due to high rewriting cost.

To bridge the gap, we propose *multi-rate-selection in ZigBee* (Mrs.Z), a novel physical layer design that enables rate adaptation in ZigBee with little modification on commodity modules, improving its throughput while ensuring reliability and scalability. Mrs.Z is designed and implemented on top of the *direct-sequence-spread-spectrum* (DSSS), a widely used technique in ZigBee to reduce the negative impacts of interferences [1]. Specifically, DSSS improves communication reliability by encoding the original message to a longer chip sequence generated with the pseudo noise code. This, however, is at the cost of reduced throughput. Mrs.Z enhances DSSS by adaptively adjusting its coding rates (and thus the DSSS chip sequences) based on real-time link quality, with the objective to maximizing the communication throughput. Such adaptation, in turn, is determined based on a real-timely predicted *effective bit error rate* (BER_z) — a metric differentiating the bit errors contributed by difference causes and jointly describing their impacts on throughput degradation.

We implement and evaluate Mrs.Z on USRP N210s in a GNURadio testbed, with both static and mobile channels. The results show Mrs.Z improves the throughput by 10-20% when compared to SoftRate [15], the classic BER-based rate selection scheme originally developed for WiFi, and by 80% when compared to the standard ZigBee. Such throughput improvements of Mrs.Z are further increased to 30$\sim$40% over SoftRate and $\geq$90% over standard ZigBee, when smart retransmission scheme such as [16] is used.

This paper makes the following contributions:

- We propose Mrs.Z to enable multi-rate transmission in ZigBee, uncovering the limitation of the single and fixed data rate on ZigBee's throughput;
- We present a rate selection scheme in Mrs.Z, a physical layer enhancement of standard ZigBee, which is compatible to commodity ZigBee modules;

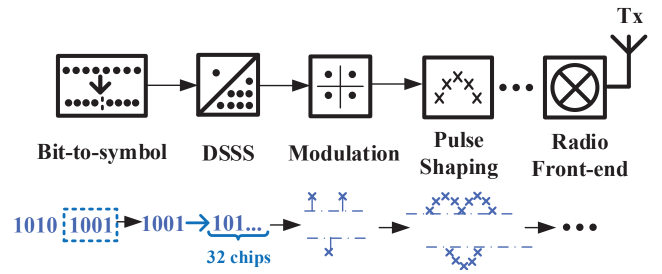


Fig. 1: The block diagram of ZigBee's transmitter in the physical layer.

- We implement and evaluate Mrs.Z on USRPs and GNU-radio, showing 20% and 80% improvements in throughput, when compared with SoftRate and standard ZigBee, respectively.

The paper is organized as follows. Section II introduces the background and our motivation. The design and implementation of Mrs.Z are presented in Section III and IV, respectively. Mrs.Z is evaluated in Section V. Section VI reviews the related works, and the paper concludes in Section VIII.

II. Preliminary

Here we briefly review the conventional design of ZigBee's physical layer and the potential opportunity to enable multi-rate transmission in ZigBee.

ZigBee operates in four different bands of 780MHz, 868MHz, 915MHz and 2.4GHz. In this paper, we mainly focus on ZigBee in the worldwide frequency band of 2.4GHz.

In ZigBee, the *physical layer* (PHY) first encapsulates data from the MAC layer to generate the *PHY protocol data unit* (PPDU), which contains (i) the *synchronization header* (SHR) field as a header, (ii) the *physical header* (PHR) field specifying the frame length, and (iii) the payload carrying the to-be-transmitted data. Then, the *transmitter* (TX) sends the PPDU to the receiver with the following steps: bit-to-symbol mapping, DSSS, O-QPSK modulation, and pulse shaping, as illustrated in Fig. 1.

- In the bit-to-symbol mapping, the binary stream in PPDU is encoded to a symbol stream. For each octet in the binary stream, its four *least significant bits* (LSB) (b_0, b_1, b_2, b_3) are mapped to one 4-bit symbol, and four *most significant bits* (MSB) (b_4, b_5, b_6, b_7) are mapped to the next symbol. This mapping applies to the entire PPDU and the output symbol stream is fed into DSSS.
- In the DSSS phase, each data symbol is spread to a 32-chip pseudorandom noise sequence, where a chip is the smallest information-carrying unit in ZigBee. DSSS is used to enhance the transmission reliability against potential interferences.
- In the O-QPSK modulation phase, the chip sequence from DSSS module is modulated as follows: even-indexed chips are modulated onto the *in-phase* (I) carrier, and odd-indexed chips are modulated onto the *quadrature-phase* (Q) carrier. Q-phase chips are delayed by half-chip time with respect to I-phase chips to form an offset.
- In the pulse shaping phase, the chip sequence is shaped into half-sine pulse and then transmitted after Digital-Analog conversion.

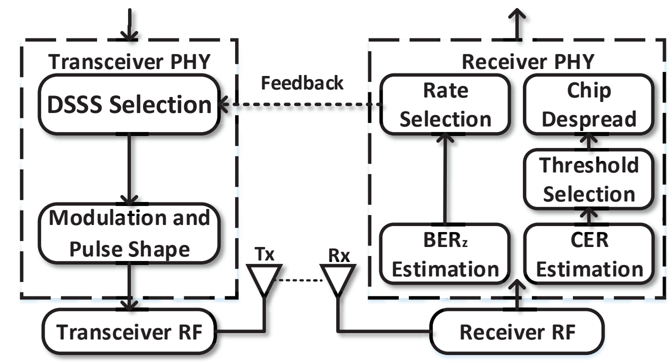


Fig. 2: An overview of the Mrs.Z design.

Reversed procedures are performed at the receiver. When decoding symbols from the received chip sequence, the receiver compares the chip sequence with each element in the symbol-chip mapping table, a table maintaining the corresponding chip sequence for each symbol. The receiver despreads the received chip sequence to the candidate symbol — the symbol with the least different chips when compared to the received chip sequence — if the number of such different chips is smaller than a pre-defined decoding threshold d_{th}; Otherwise, it concludes the transmission as failed and dumps the received chip sequence.

As specified in the standard, ZigBee has a bandwidth of 2MHz [1]. DSSS, however, spreads each 4-bit symbol to a 32-bit chip sequence, incurring redundancy in the transmitted chips and thus waste of available bandwidth. As a result, only a 250Kbps data rate, or one-eighth of the available bandwidth, is achieved in practice, implying the opportunities to improve the throughput by reducing transmission redundancy.

III. Design of Mrs.Z

We present the design of Mrs.Z in this section. Specifically, we first explain how to achieve the multi-rate transmission with current ZigBee modules, then we introduce the rate selection scheme to determine the optimal transmission rate online. Fig. 2 illustrates an overview of Mrs.Z.

A. Enabling Multi-rate Transmission in Mrs.Z

DSSS uses fixed-length redundant chips (e.g., 16 or 32 chips [1]) to ensure the reliable communications, at the cost of wasted bandwidth. Mrs.Z minimizes such wasted bandwidth by enabling variable-length DSSS chips and always trying to use the shortest possible chips while ensuring communication reliability. Specifically, Mrs.Z enables five symbol-chip spreading lengths for DSSS: 4-to-4 mapping (i.e., no spreading and thus redundancy in this way), 4-to-8 mapping, 4-to-16 mapping, 4-to-32 mapping, and 4-to-64 mapping. This way,

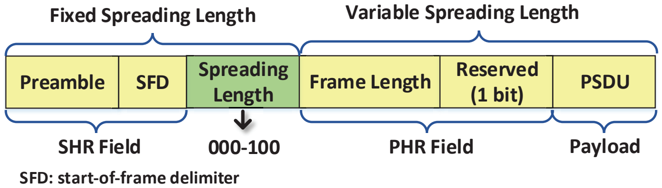


Fig. 3: The packet format in Mrs.Z.

the low-redundancy spreadings, e.g., 4-to-4, 4-to-8 and 4-to-16 mappings, can be used to achieve higher throughput when the channel condition is good, while the 4-to-32 and 4-to-64 mappings will be used in noisy channels to ensure reliability via higher redundancy. Mrs.Z accomplishes such rate adaptation by adaptively selecting the optimal spreading length via a feedback control loop between the transceiver and the receiver.

Transceiver Operations. With Mrs.Z, the transceiver uses three extra bits in its PPDU to inform the receiver about the spreading length, as shown in Fig. 3. Notice that the three extra bits incur little overhead compared to the packet length (>1000 bits). Specifically, the transceiver always spreads the SHR field and and the three extra bits to 64-chip sequences, ensuring their reliable delivery to the receiver; other bits, e.g., the PHR field and payload, are spread according to the receiver's feedback from previous transmission. The transceiver will receive a feedback to update its DSSS length from the receiver for each packet. A retransmission is triggered if no feedback for a packet comes in a given time.

Receiver Operations. Upon detecting a packet, the receiver uses 64-to-4 despreading to decode the spreading length, which is then used to recover the other fields from the chip sequences. The receiver then forms a per-frame feedback, informing the transceiver of the new spreading length and the reception state. The feedback takes the same PPDU format. To ensure its reliability, the feedback data is spread to 64 chips, which is tolerable because the reply frame is much shorter and incurs little overhead in throughput.

B. Rate Selection Scheme

Next we present the rate selection scheme of Mrs. Z.

Mrs. Z aims at throughput maximization. Improving throughput requires fast responsiveness to the channel variance, thus we focus on the PHY-layer based rate selection scheme. Generally, we separate the problem into two sub-problems: (i) selecting a physical metric to guide the rate selection adaptively; (ii) estimating the metric accurately.

Existing PHY-layer based rate selection schemes use either *signal-to-noise ratio* (SNR) (e.g., as in CHARM [17]) or BER (e.g., as in SoftRate [15]) as the metric. However, SNR is known to be ineffective to accurately reflect the *packet loss rate* (PLR) in varying channels [18], and BER is not a good metric in ZigBee neither due to the following reasons. Examination of receiver's despreading scheme reveals that the bit errors in ZigBee are resultant from two cases: (i) exceeding errors, when the chip error number in the received

Symbol	Chip Sequence
...	...
0001	0100111110001001
...	...
1111	1010110111000001

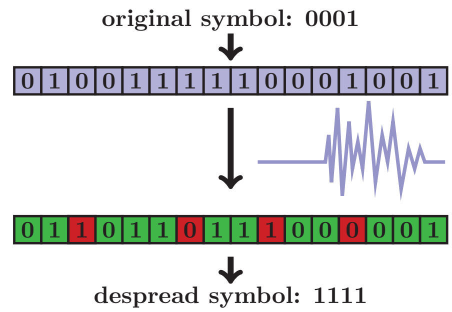


Fig. 4: In this case, the receiver incorrectly despread the chip sequence of 0001 to another symbol 1111.

DSSS sequence is larger than the given threshold d_{th}, or (ii)mis-despreading errors, the DSSS sequence is decoded into a symbol different from the original one, as shown in Fig. 4. Typically, mis-despreading errors cause more penalty on throughput, as the receiver cannot detect such errors before the MAC layer's CRC validation, and cannot decide which symbol is wrong from a packet failing the CRC validation. In contrast, exceeding errors can be dumped directly in the physical layer. The penalty difference is even clearer when some error recovery schemes are used (e.g., retransmit wrong bits only instead of the whole packet) because it is hard to determine the to-be-retransmitted wrong symbols with incorrectly despread symbols in the packet. As a mitigation, we are motivated to divide BER into BER_{ee}, the ratio of exceeding errors, and BER_{id}, the ratio of mis-despreading errors. We define BER_{z}, an abstract metric for rate selection, to represent the potential effect of BER_{ee} and BER_{id}:

$$\text{BER}_{\text{z}} = \text{BER}_{\text{ee}} + \alpha \text{BER}_{\text{id}}, \quad (1)$$

where α represents the effect of bit errors caused by incorrect despreading incur to the throughput. The value of α varies according to the physical design in ZigBee and the scenarios, generally, $\alpha \geq 1$. In Section V, experiments are conducted for the optimal α selection in different scenarios when smart retransmission [16] is applied. The advantages of using BER_{z} to indicate channel conditions include: (i) it covers the time penalty of crossing layers; (ii) it is more adaptive to error recovery mechanism where bit errors of different types can be handled differently; (iii) it envelopes traditional BER, i.e., When $\alpha = 1$, BER_{z} reverts to traditional BER.

Mrs.Z achieves rate selection based on the above-defined BER_{z}. Specifically, to maximize the throughput, rate selection in Mrs.Z is divided into four procedures:

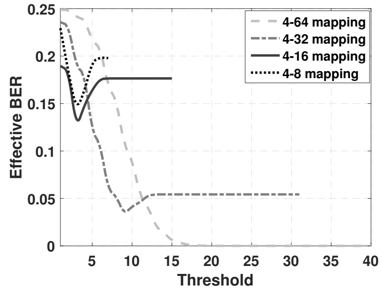


Fig. 5: Threshold affects BER_z dramatically. This figure describes the relation between BER_z and despreading threshold when CER=10%, where $\alpha = 3$.

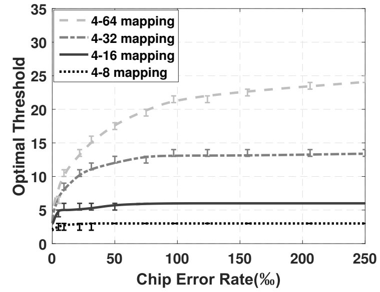


Fig. 6: The relationship between the optimal threshold and CER.

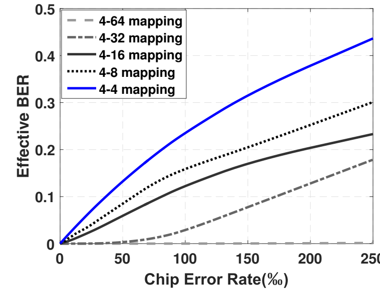


Fig. 7: BER_z when Mrs.Z selects the optimal threshold for each spreading length.

- Using physical hints to estimate the *chip error rate* (CER);
- Using CER to select a good decoding threshold d_{th} for each DSSS length;
- Using physical hints to estimate BER_z;
- Selecting the rate with BER_z.

Next we explain each step in detail.

Estimate CER. CER estimation is used for the threshold selection. When the receiver despreads a chip sequence, it traverses the symbol-chip mapping table to find a symbol whose mapping chip sequence has the least differences compared with the received chip sequence. If the number of differences is smaller than the despreading threshold d_{th}, it despreads the chip sequence to that symbol. If a packet is correctly received, using the chip difference number to estimate chip errors is highly accurate. However, it is possible that the chip differences exceed the threshold or a symbol is incorrectly despread to another symbol in a poor-quality channel. Using chip differences, limited with an upper bound of d_{th}, in these cases as chip errors causes an underestimation.

To avoid the effect of underestimation, Mrs.Z exploits CER in the SHR field to make calibration. Since the header is decoded to 64-chip sequences, CER in the SHR field can be assumed accurate. The calibration is implemented by making a weighted average of CER in the SHR filed and in the body. The calibration factors are emprically set to 0.3 and 0.7 respectively. When CER computed in the SHR field is low, calibration is not required. When the computed value is high, Mrs.Z will average CER computed in the SHR field and CER across the packet body in case of heavy error deviation from the correct CER.

Select the Optimal d_{th}. Appropriate threshold selection can maximize throughput. The traditional fixed threshold degrades the performance: an over-small threshold incurs extra packet loss, while an over-large threshold allows more bit errors caused by incorrect spreading, further increasing BER_z. Fig. 5 describes the BER_z for each spreading length when CER is about 10% and α is set to 3. Mrs.Z adaptively decides the threshold d_{th} based on the estimated CER, with the objective to minimize BER_z. The potential thresholds meeting such requirement could be in a range, and Mrs.Z selects the smallest one in such cases.

Specifically, Mrs.Z estimates the optimal threshold for each DSSS spreading length based on the relation between the optimal threshold and BER. This relationship is built based on the following two assumptions:

- Stochastic channel: With fixed CER, a chip error can occur anywhere in a short time duration. This is reasonable because interferences can occur at any time in the industrial scenario.
- Independency between CER and spreading length: CER will not be affected by the way symbols are spread. For example, if the chip error number in 4-to-64 spreading is c, the chip error number in 4-to-32 spreading will be about $\frac{c}{2}$.

Mrs. Z achieves the mapping between the optimal d_{th} and CER from extensive experiments, as shown in Fig. 6. The difference between the real optimal d_{th}^{*} and d_{th} which Mrs.Z has selected is no large than one. This demonstrates the effectiveness of the threshold selection. Fig. 7 presents the average BER_z when the optimal d_{th} is selected in each spreading length.

Estimate BER_z. We show how receivers compute the BER_z from chip sequences in this part. If there exists an explicit relationship between BER and CER together with the optimal decoding threshold, the problem of predicting BER_z using CER across different DSSS length would be easy. Unfortunately, such a relationship is not reliable because similar CER can lead to quite different BER_z.

Inspired by AccuRate [12], Mrs.Z uses constellation to estimate BER_z accurately. For a chip sequence, Mrs.Z first computes each chip's possibility to be 0 or 1. Then, it uses this one-chip possibility to determine the probability of receiving a correctly despread symbol and uses it to estimate BER_z. The receiver decodes these points in the diagram according to their positions. For example, a point in the first quadrant will be decoded into $(1, 1)$. The interferences and channel fading cause points to be deviated from the correct positions, and

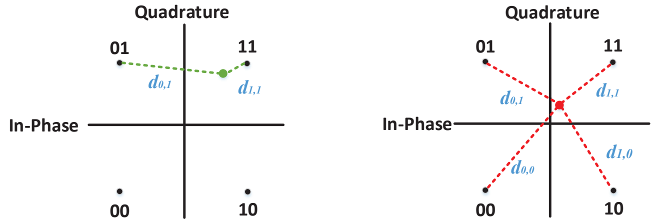


Fig. 8: A point with little dispersion can be assumed correct with high confidence. However, for the points far away from the standard position, it is highly likely to be corrupted.

chip error occurs if the point falls outside its original quadrant. Define $d_{i,j}^{(k)}$ as the distance to the correct position (i,j) and $p_{i,j}^{(k)}(i=0,1,j=0,1,k=0,1,...,l/2)$ as the possibility of kth point in each decoding case, where

$$p_{i,j}^{(k)} = \frac{\frac{1}{d_{i,j}^{(k)}}}{\sum\limits_{r=0,1,t=0,1} \frac{1}{d_{r,t}^{(k)}}}. \quad (2)$$

We use P_s to represent the possibility of sending symbol s. For instance, the possibility of sending symbol 0100 is $P_4 = p_{0,1}^{(0)} p_{0,0}^{(1)}$. The possibility of sending other symbols can also be acquired similarly. Thus we get $P_i^{(n)}$ $(i=0,1,...,15)$ for the nth symbol. We normalize the $P_i^{(n)}$ into $\mathcal{P}_i^{(n)}$, which represents the possibility that transceiver has sent a symbol i.

In the receiver, let c_n $(n = 1,...,N)$ denote the observed chip errors in chip sequence n and d_{th} denote the threshold selected in the last transmission. If $d_{th} < c_n$, the incurred bit errors are caused by exceeding errors, thus $\mathrm{BE}_{\mathrm{ee},n} = 4, \mathrm{BE}_{\mathrm{id},n} = 0$ (the coefficient 4 represents each symbol consists of 4 bits). If $d_{th} \geq c$, the potential bit errors incurred in the chip sequence n is defined as

$$\begin{cases} \mathrm{BE}_{\mathrm{id},n} = 4(1-\mathcal{P}_s^{(n)}); \\ \mathrm{BE}_{\mathrm{ee},n} = 0, \end{cases} \quad (3)$$

where s is the despread symbol in the receiver. Combining (3) with (1), $\mathrm{BER_z}$ across the frame with length L can be calculated as

$$\mathrm{BER_z} = \frac{\sum\limits_{n=1}^{N}(\mathrm{BE}_{\mathrm{ee},n} + \alpha \mathrm{BE}_{\mathrm{id},n})}{L}. \quad (4)$$

Select the Rate. Before rate selection, Mrs.Z first computes a tuple of the $\mathrm{BER_z}$ threshold $(b_{1,l}, b_{2,l}, b_{3,l}, b_{4,l})$ for each spreading length. Given the predicted $\mathrm{BER_z}$, Mrs.Z checks which interval it belongs to and selects the corresponding rate. For example, given $b_{1,l} < \mathrm{BER_z} < b_{2,l}$, Mrs.Z selects the 4-to-8 spreading length at the transmitter. The determination of $(b_{1,l}, b_{2,l}, b_{3,l}, b_{4,l})$ depends on retransmission cost and data rate difference between different spread lengths. Mrs.Z allows jumping over multiple rates from a higher to a lower rate, e.g., from 4-to-4 to 4-to-64 spreading. The reverse case, however, is prohibited. Switching to a higher rate is more gradual to avoid retransmission caused by accidental inaccurate estimation.

C. Further Improvement

We further improve Mrs.Z by attaching a postamble [19] to each packet, enhancing its robustness in diverse environments. Such postambles also help detect collisions. A trade-off is made in determining the length of the postamble to avoid incurring heavy overhead. Typically, the length of postamble can be set equal to the preamble in the SHR field.

Time-varying Channels. The accuracy of CER estimation decreases in time-varying channels. To mitigate this problem, Mrs.Z uses a short postamble to mark the end of a packet. The postamble is spread to the fixed 64-chip length as in the SHR field, and is also considered when Mrs.Z estimates the overall CER based on the CER in the SHR field.

For extremely fast-varying channels, channel varies in a per-frame transmission duration. It is difficult to select the optimal rate. In such cases, Mrs.Z priorities reliability over data rate by using 4-to-32 or 4-to-64 mapping to reduce packet loss.

Collision Detection. Bit errors can be caused by poor link quality and collisions. Since collisions only influence the throughput temporarily, rate lowering due to collisions should be avoided. This requires the transceiver to distinguish the collisions from the poor channel quality when bit errors increase. Existing approaches have been able to detecting collisions in an accurate level. Mrs.Z takes the idea in [19], which uses the postamble, to detect whether an increasing in $\mathrm{BER_z}$ is incurred by collisions.

Collisions occur in two cases:

- The transceiver synchronizes with the receiver first and then the interferer's packet comes. The receiver can detect the header of a packet but cannot receive the whole packet correctly.
- The interferer synchronizes with the receiver first and then the transceivers packet comes. The receiver cannot detect the header of a packet in this case.

For collisions starting after the receiver synchronizes with the transceiver, the receiver will detect a sharp spike in bit errors, which is much steeper than the rise due to poor-quality channels. The receiver won't give a feedback to lower the rate in this case. For collisions where transceiver's signal starts later than synchronization of the receiver and the interferer, a packet loss occurs. It would be hard for the receiver to distinguish the collision from poor-quality channels directly. The postamble we have added can help to detect such a collision. Unless the transceivers packet overlaps the interferer in the postamble field, the receiver can detect if a packet loss happens with high possibility. If consecutive packet loss is detected by the receiver, implying the poor channel quality, the receiver will give a feedback to lower the rate.

IV. Implementation

We have implemented Mrs.Z on two GNURadio-based USRP N210s. The implementation is on top of the work in [20], which implements the traditional 802.15.4 framework. Mrs.Z further improves ZigBee's PHY layer.

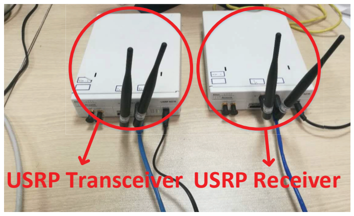


Fig. 9: Testbed

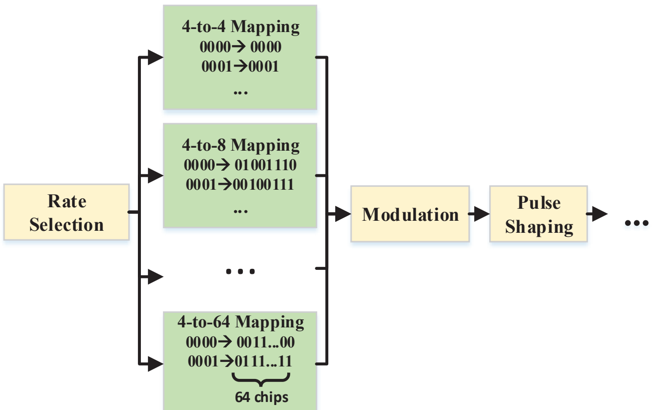


Fig. 10: Rate selection in the transmitter.

Physical Layer. Mrs.Z makes lightweight modification on the traditional ZigBee framework at the transceiver. The design is based on the fixed physical bandwidth (2MHz) and variable spreading lengths, i.e., the data rate will be 500Kbps if the transceiver uses 4-to-16 spreading ($\frac{2M}{16/4} = 500$Kbps).

In spite of the lightweight modification on the DSSS module, the other parts remain the same as the traditional ZigBee in the transceiver. The output of bit-to-symbol module is fed to the DSSS selector, where Mrs.Z reads the advertised spreading length in the last feedback received from the receiver, as shown in Fig. 10. Then the packet goes through modulation and pulse shaping in sequence to be transmitted.

At the receiver, Mrs.Z keeps detecting the packet header. Once a packet is detected, Mrs.Z estimates the CER, selects the optimal threshold d_{th}, estimates the BER_z, and at last determines the transmission rate. No matter whether the packet is dumped or accepted, the receiver feedbacks a tiny packet (ACK or NAC) with the selected rate.

Interference Emulator. Fine-grained interference control in real links is challenging. Instead, we emulate interferences by mixing the source signal with a Gaussian noise source in the GNURadio. We adjust the amplitude of noise from -12 to 14dB to validate Mrs.Z's robustness to noisy environments.

V. Experiments

Based on our testbed, we conduct extensive experiments to evaluate the performance of Mrs.Z in a general office scenario.

A. BER-SNR Relation

We first demonstrate that enabling multi-rate transmission in ZigBee results in different levels of resistance to noise

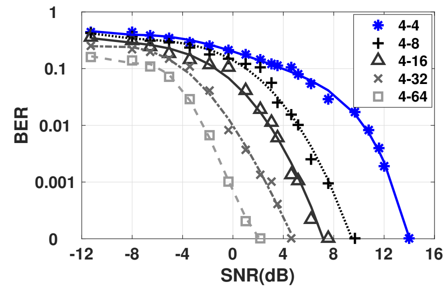


Fig. 11: The BER-SNR relationship when symbols are spread to different lengths.

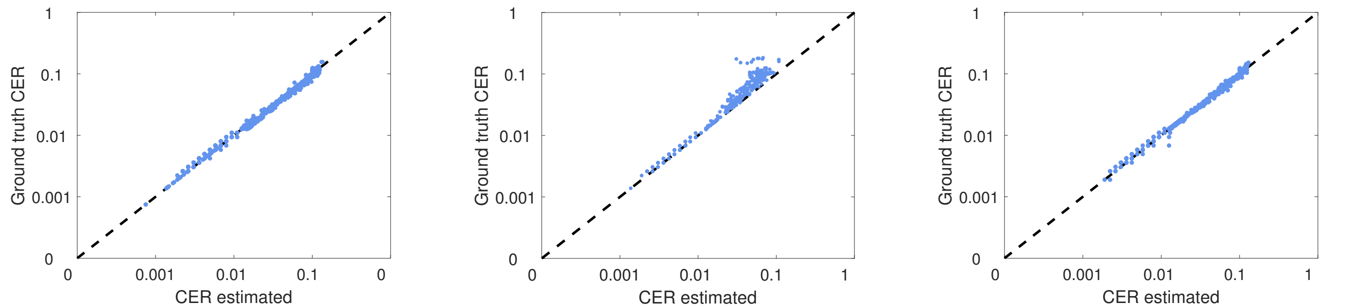
when using different spreading lengths. In this part, we give an evaluation on the BER-SNR relation to show the capability of resisting to noise of each spreading length. In the experiments, the transmitting gain is set to 0.75. We vary the SNR from -12dB to 14dB. Note that when SNR is smaller than -12dB, the receiver can hardly detect the preamble of the packet. Since BER is influenced by the channel quality and the despreading threshold in ZigBee, we fix the threshold to 1, 2, 5, 11, 25 for 4-to-4, 4-to-8, 4-to-16, 4-to-32, 4-to-64 spreading lengths. Results have shown in Fig.11.

B. CER Estimation Accuracy

Next we validate Mrs.Z's accuracy in CER estimation in both static and mobile channels, testifying its responsiveness to channel dynamics.

Static Channel. We first measure the performance of CER estimation in static channels. The transceiver transmits data every 500 milliseconds. We measure Mrs.Z's performance across different transmission power, transceiver positions, SNRs (i.e, by mixing a noise source to the signal source), and spreading lengths, including 4-to-8, 4-to-16, 4-to-32 and 4-to-64. We do not explore the case of 4-to-4 spreading because the despreading threshold will always be 1 in this case — predicting CER will not be needed. In a transmission, the receiver computes CER in the SHR field and the postamble of each packet as a rough channel estimation for each frame. If this CER is higher than a threshold, which we set from 10^{-2} to 10^{-1}, the CER in the preamble and postamble will be averaged into the CER in the packet body.

We also compute the ground truth CER by comparing the received sequence with the transmitted data. Fig. 12a compares the estimated CERs with their ground truth in static channels. If chip errors can hardly be observed in a single packet, chip errors in several consecutive packets are aggregated to estimate their overall CER. Results in Fig. 12a validate Mrs.Z's reliability in CER estimation. In the low-CER area, CER estimation is highly accurate because bit errors rarely occur. Errors in a chip sequence can be definitely achieved by comparing the received chip sequence with the ground-truth sequence. In the high-CER area, CER estimation deviates a little around the baseline, but is still acceptable for the threshold selection.

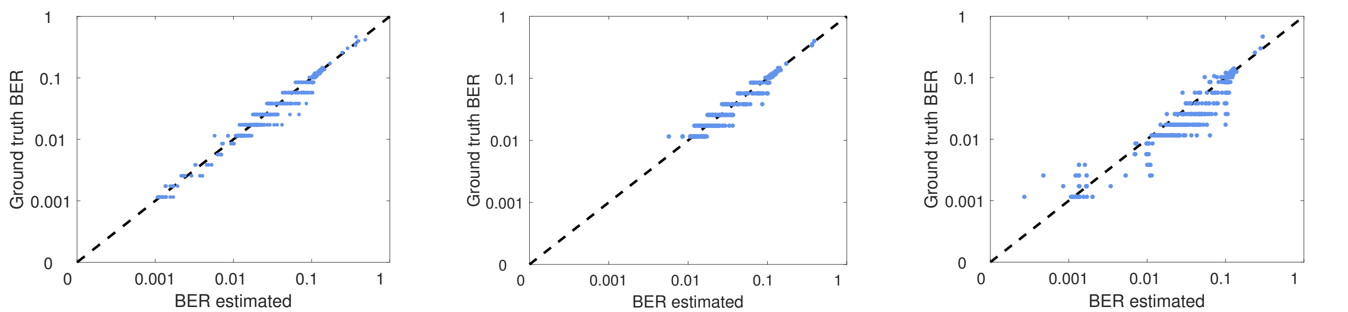


(a) In static channels, the estimation of CER is accurate.

(b) The CER observed directly from physical hints is not reliable when it gets larger.

(c) In mobile channels, the estimation of CER is accurate.

Fig. 12: CER prediction



(a) In static channels, Mrs.Z reliably estimates BER.

(b) In mobile channels, Mrs.Z reliably estimates BER.

(c) SoftRate cannot reliably estimate BER because the relation between CER and BER is complicated.

Fig. 13: BER prediction

We also conducted a contrast experiment to show the necessity of Mrs.Z, where we keep using the detected chip differences at the receiver as the estimated chip errors even with strong interferences. When the chip differences in a chip sequence exceed the threshold, we simply use the threshold, d_{th}, as the chip errors in this sequence. With this method, CER is underestimated in the high-CER on the whole from Fig. 12b. Such an underestimation is caused by two parts: (i) when the chip differences exceed the threshold, we use the threshold d_{th} as the estimated chip errors, which is strictly smaller than the actual chip errors; (ii) when there is an incorrectly despread symbol, the observed chip errors c are no more than the actual chip errors c^*.

Mobile Channel. We further evaluate the accuracy of CER estimation in different cases, via (i) moving transceivers away from the receiver with a speed of 0.1-0.5m/s, and (ii) making a plastic card/book/human moving between the transceiver and the receiver periodically. Fig. 12c plots the accuracy of CER estimation in such mobile channels.

Results show the CER estimation of Mrs.Z is robust in low-mobility channels. When moving at a high speed, the points aggregates in the region larger than 10^{-2}, the average ground truth gets larger but the estimation accuracy is similar to the performance in low-mobility channels, showing Mrs.Z's resistance to channel mobility .

C. BER Estimation Accuracy

We test Mrs.Z's performance in predicting BER_z in both static and mobile channels. For the ease of experiments, we let α=1, thus BER is BER_z we want.

The transceiver generates and transmits packet every 500 milliseconds, which is mixed with a noise source, where SNR ranges from -12dB to 14dB. In the both static and mobile channels, the transceiver transmits about 200 packets with 32 bytes. For extremely low BER, we aggregate the results of 5 packets. Similarly, we collect the ground truth BER by comparing the transmitted and the received frames.

With Mrs.Z, the receiver counts the chip errors, c, in each chip sequence. If $c < d_{th}$, the chip sequence will be despread to some symbol s. Mrs.Z then uses $(1-\mathcal{P}_s)$ to compensate for the underlying BER underestimation when the chip sequence is incorrectly despread. Fig. 13a and 13b show Mrs.Z predicts BER reliably in both static and mobile channels.

In contrast, we make benchmark experiments of BER estimation in static channels based on SoftRate. Notice that SoftRate can only achieve chip errors using *Log Likelyhood Ratio* (LLR). To get BER, it requires an empirical mapping accumulated from experience. Fig. 13c shows that such a prediction is not reliable in ZigBee. Although SoftRate predicts CER accurately [15], it performs poorly in BER estimation

TABLE I: List of the throughput in different SNRs.

Spreading length	>13dB	10-13dB	7-10dB	3-7dB	-4-3dB
4-to-4	151.6kb/s	67.5kb/s	18.4kb/s	0	0
4-to-8	101.7kb/s	103.4kb/s	49.8kb/s	10.9kb/s	0
4-to-16	66.4kb/s	64.1kb/s	63.9kb/s	19.1kb/s	5.1kb/s
4-to-32	34.2kb/s	34.4kb/s	33.9kb/s	33.6kb/s	11.2kb/s
4-to-64	19.1kb/s	18.7kb/s	18.9kb/s	18.5kb/s	18.3kb/s

because the CER and the BER are loosely related. Even if two packets have the same CER, their BER can be totally different if one's chip errors concentrate in some sequences and the other's chip errors are distributed uniformly.

D. Throughput

In this section, we evaluate the throughput of Mrs.Z against the traditional ZigBee and SoftRate [15], a rate-adaptive design shown to perform well in 802.11. The experiments in this section are done in a laboratory environment, thus we emulate noise and interferences using a noise source in GNURadio. Again, we measure their performance in both static and mobile channels. Mobile channels are emulated by separating two USRPs periodically with a mobile iron board. We also evaluate the impact of retransmission strategy on Mrs.Z, and compare it with the traditional ZigBee and SoftRate.

Throughput in Different SNRs. We evaluate the throughputs with different spreading lengths in different SNRs in this part. We divide SNR into five intervals and make evaluation for each spreading length respectively. Results in Table I show that each spreading length outperforms others in the certain SNR interval. When SNR is smaller than -4dB, the throughput is extremely low even if using 4-to-64 spreading. Meanwhile, between two adjacent spreading lengths, the shorter one cannot achieve a theoretical 2x improvement over the longer one due to retransmission or some environmental factors.

Methodology. We first present the methodology of performance comparison. The XCVR2450 board used in our experiments does not support full-duplex communication. As a result, we implement the send-feedback mechanism as follows: once the transceiver transmits a packet, it enters the waiting state. The receiver feedbacks a short packet to the transceiver after receiving a packet. When the transceiver is in a waiting state, it changes its role to a receiver waiting for the reception of a reply. If a feedback with an ACK is received, it triggers a new transmission. On the other hand, if a feedback with a NAK is received or the waiting time exceed, it triggers a retransmission. The timeout threshold here is set to 2x of the time to transmit a packet spread in a 4-to-64 way.

Next we compare the performance of Mrs.Z to traditional ZigBee and SoftRate. Traditional ZigBee only supports the 4-to-32 spreading, thus limiting its overall throughput. We use SoftRate as another benchmark because it can be implemented in ZigBee with little modification. SoftRate is a well verified rate selection scheme in 802.11, with the key idea to select the optimal transmitting rate based on BER prediction. It uses LLRs to predict BER accurately. However, directly applying SoftRate in ZigBee cannot achieve as high throughput as it has achieved in 802.11. BER in ZigBee cannot be achieved directly due to DSSS. Using LLR in ZigBee means SoftRate has to compute CER first, and then transfer CER to BER, which degrades BER prediction.

We collect traces with SNR increasing from -12dB to 14dB. Time of collecting data of each SNR value is set to about 20 seconds. The frame length is 32 bytes.

Without Smart Retransmission. We first evaluate the achieved throughputs when no smart retransmission scheme is used, as plotted in Fig. 14.

Mrs.Z achieves the highest throughput in static channels, showing 80% and 15% improvements over traditional ZigBee and SoftRate, respectively. We further examine the spreading length used in each method as shown in Fig. 15. The 4-to-4 spreading is rarely used in our experiments even with SNR as high as 12dB, in which case Mrs.Z cannot further improve the throughput over traditional ZigBee. For traditional ZigBee, the improvements lie in two respects. On the one hand, Mrs.Z can select a higher rate in a good-quality channel. On the other hand, the fixed-spreading-length of traditional ZigBee will likely cause retransmissions when the noise is large, while Mrs.Z can select a lower rate to avoid retransmission, improving the throughput. Mrs.Z outperforms SoftRate because SoftRate cannot predict BER_z as accurately as in 802.11 — the LLR it used predicts CER well but is not capable to transfer CER into BER directly.

The throughputs achieved with all the three methods decrease significantly in mobile channels, as the iron board blocked many packets. The three methods have similar throughputs because the 4-to-16, 4-to-8 or 4-to-4 spreading is rarely used in these cases — the differences among them are mainly contributed by the retransmission frequency when the 4-to-32 or 4-to-64 spreading is used.

In industrial application, transmission can be blocked by mobile workers, robots or interferences from other transceivers. Mrs.Z increases the ZigBees adaptivity to such scenarios. In high-quality channels, Mrs.Z selects the smaller length for higher throughput while in low-quality channels, Mrs.Z selects the larger length for reliable transmission.

With Smart Retransmission. Smart retransmission [16] supports partial transmission in 802.11, by identifying the error-prone bits and retransmitting only these bits instead of the entire packet. In ZigBee, a chip sequence with the minimal chip differences larger than d_{th} is concluded as a bit error, which needs retransmission. For bit errors caused by incorrect despreading, however, we can hardly locate them in the physical layer, and thus the whole packet should be retransmitted. Next we evaluate the performance of Mrs.Z, SoftRate and ZigBee when such smart retransmission scheme is used.

We emulate the smart retransmission scheme by sending frames with predetermined contents. During each transmission, the receiver compares the received frame with the predetermined contents to judge if it needs to retransmit the

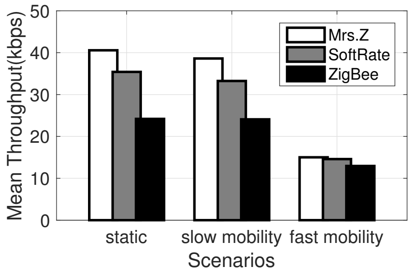


Fig. 14: Median throughput without smart retransmission.

Fig. 15: Distribution of selected spreading lengths in static channel.

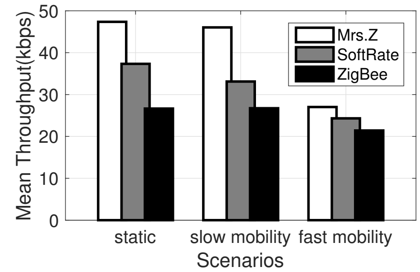


Fig. 16: Median throughput with smart retransmission.

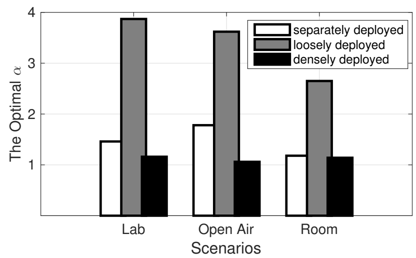


Fig. 17: The optimal α producing the highest throughput in various scenarios.

whole packet or just a few bits, and attach the information to the feedback. Fig. 16 plots the resultant throughputs. Mrs.Z achieves even larger improvement when smart retransmission is used, specifically, an improvement of 30% over SoftRate and almost 90% over traditional ZigBee. Such pronounced improvements hold even in mobile channels. This is mainly because Mrs.Z assigns an impact coefficient $\alpha > 1$ to bit errors caused by incorrect despreading. Since $\alpha > 1$, Mrs.Z is more likely than SoftRate to select a lower rate to avoid retransmitting the whole packet. Similarly, it is more likely for Mrs.Z to select a higher rate when bit errors are all caused by exceeding errors, which only need to be partially retransmitted.

E. Select α

The value of α should be carefully selected to maximize the transmission throughput. Without any optimization, the value of α can be simply set to 1 if we neglect the resource consumption in the MAC layer, and thus Mrs.Z reverts to the traditional ZigBee. When smart retransmisson is applied, the selection of α becomes complicated for the potential impact of mis-despreading errors on the to-be-retransmitted part is unknown. We conduct experiments in different scenarios to seek for the optimal solution of α. The power gain at both USRPs are set to 0.75.

Under the given fixed rate selection thresholds, we evaluate the Mrs.Z's performance in three scenarios:

- **Laboratory**: In the laboratory environment, ZigBee transmission can be influenced by electromagnetic interference, which will also have an impact on α selection.
- **Open Air**: The open air features less electromagnetic interference and more mobile barriers.
- **Room**: The room provides the least interference. The channel is relatively static.

In each scenario, we experimentally identify the optimal α when USRPs are separately deployed (only one transeiver and one receiver), loosely deployed (four USRPs deployed in an area) and densely deployed (more than ten USRPs deployed in an area). Since the optimal value α fluctuates in a range, we achieve an average result with several experiments in one scenario. The results are shown in Fig. 17.

From the results, α is close to 1 when separately deployed or densely deployed. When deployed separately from other transceivers, bit errors rarely occur, among which the optimal α in the open air is higher relatively for the environment noise. In contrast, when USRPs are densely deployed, most of the symbols are spread to 32 or 64 chips because of the severe interference, where mis-despreading bit errors hardly occur. Actually, the value of α can be selected in a large range in this case and we plot the smallest one among them. The optimal α achieves the highest value when loosely deployed. It is because when loosely deployed, many symbols are spread to 8 or 16 chips, where mis-despreading symbols are common, and the smart retransmission scheme makes mis-despreading errors have higher negative impackets over exceeding errors.

VI. Related Works

Rate adaptation has been a well-addressed problem in the 802.11 standard in the past years. According to the processing layer, rate adaptation algorithms can be divided into two categories, MAC-layer based rate selection and PHY-layer based rate selection.

MAC-layer based rate selection schemes, including RRAA, WOOF [21], SampleRate and so on, make rate selection with PLR. RRAA uses frame loss information gathered over tens of frames to adapt the rate. To distinguish collisions from noise, RRAA compares frame loss statistics both with and without RTS/CTS. WOOF reduces the overhead of RTS/CTS by using the channel busy time to monitor the network load. With higher channel busy time, a transmission failure is more likely to be caused by a collision. SampleRate, which is deployed on Atheros cards, takes a different method. It makes a prediction on transmission time by frequently sampling with different transmission rates and tries to minimize the average transmission time. SampleRate does not give a distinction between collision and noise. Generally, MAC-layer based rate selection schemes responds slowly because the receiver usually needs multiple receptions for one rate selection.

PHY-layer based rate selection uses physical hints to pick a proper rate. SGRA [11] predicts frame delivery ratio directly from SNR. However, the SNR-BER relation can vary over real wireless channels. Similarly, CHARM is a scheme leveraging reciprocity of wireless channel to estimate average SNR at the receiver, thereby picks a rate based on SNR. The problem lies in that the reciprocity is not always reliable in testbeds, leading to a sub-optimal rate selection. To improve the performance, SoftRate predicts BER with LLR for rate selection. With physical layer hints, it estimates per-frame BER as a feedback to the transceiver, where a new rate can be picked for the next transmission. To accurately distinguish collisions from channel fading, it adds a postamble in the end of each frame to detect a collision with high likelihood. AccuRate shows the improvement room SoftRate. AccuRate [12] judges the channel condition by observing the dispersion between the received symbol positions and their proper positions. Then, it can select the highest rate whose dispersion is below the permissible dispersion. To increase the throughput further, H-RCA [13] employs Bayesian analysis for each rate-increase trial, ensuring the rate increase won't lead to a poorer performance. Meanwhile, TXOP [22] technique is applied to accurately distinguish collision loss. SmartPilot [23] calibrates the channel state information using decoded bits with high confidence level, improving the accuracy of obtaining the optimal rate.

In the recent years, new metrics are considered into rate selection schemes, making it more complicated. TurboRate [24] enables rate selection for multi-user LANs. TurboRate picks the rate based on the SNR in single-in-single-out scenarios and the direction of the transceiver's signal received by the access point. EERA [25] considers energy consumption in rate selection. It achieves a trade-off between the energy efficiency and higher throughput.

Mrs.Z is a physical-layer based rate selection scheme. It leverages the underlying impact of different bit errors to give an accurate prediction on throughput.

VII. Acknowledgement

This research is supported in part by NSFC No. 61672349, 61373155, 61672353, 61472252, National Key Research and Development Program No. 2016YFE0100600, 973 Project 2014CB340303, and Shanghai Key Laboratory of Scalable Computing and Systems at Shanghai Jiao Tong University.

VIII. Conclusion

In this paper, we have proposed Mrs.Z, a physical design enabling multi-rate transmission and rate selection in ZigBee. We first leverage the inherent DSSS module in ZigBee to make ZigBee able to select different rates for transmission, which only needs lightweight modifications. Then, a rate adaptation scheme feasible on ZigBee is proposed in Mrs.Z. Mrs.Z divides bit errors into two categories, errors caused by exceeding chip errors and incorrect despreading, to predict the potential impact of bit errors on throughput. We implement Mrs.Z and verify its effectiveness on USRPs and GNURadio platform. Results show that Mrs.Z achieves an improvement of 20% and 80% over SoftRate and nave ZigBee in throughput without smart retransmission. With smart retransmission, the throughput gain achieves up to 30% and 90%.

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