IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 1, 2018, accepted July 2, 2018, date of publication July 11, 2018, date of current version July 30, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2854794

A Novel Error Correction Mechanism for Energy-Efficient Cyber-Physical Systems in Smart Building

MING ZHAN[1], (Member, IEEE), JUN WU[2], (Member, IEEE), HONG WEN[3], (Member, IEEE), AND PENG ZHANG[4]

[1]Key Laboratory of Networks and Cloud Computing Security of University, College of Electronic and Information Engineering, Southwest University, Chongqing 400715, China
[2]School of Cyber Security, Shanghai Jiao Tong University, Shanghai 200240, China
[3]School of Aerospace, University of Electronic Science and Technology of China, Chengdu 611731, China
[4]Department of Science and Industry, Guangdong Mechanical and Electrical Polytechnic, Guangzhou 510550, China

Corresponding author: Jun Wu (junwuhn@sjtu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671390, Grant 61431008, and Grant 61572114, in part by the National Major Research and Development Program under Grant 2018YFB0904905, and in part by the Natural Science Foundation of Guangdong Province under Grant 2017A030313431.

ABSTRACT Smart building is an effective solution to address the issue of energy consumption in today's cyber-physical systems (CPSs) connected world. As an important tool to collect information from a fleet of electric appliance that installed in the building scope, a wireless sensor network is widely employed for this purpose. In this paper, we propose to incorporate forward error correction into the media access control layer of IEEE 802.15.4 standard for packets transmission, as the originally used automatic repeat request mechanism is a timing and energy consumed process that should be avoided in a noisy wireless channel of a smart building environment. Based on the developed CPS simulation platform, the bits error rate and packets error rate of convolutional codes (CCs), Reed-Solomon (RS) codes, and their concatenated codes are intensively investigated, on condition of been applied to different packet length and code rates. We show that the CCs are superior to other codes in most cases. However, the RS and CCs concatenated codes are good candidates, and the RS codes with larger symbol length are preferred for a longer packet. In this regard, future research will concentrated on non-line-of-sight wireless channel, and take the pulse interference from other devices into account.

INDEX TERMS Buildings, cyber-physical systems, IEEE 802.15.4, error correction, energy efficiency.

I. INTRODUCTION

Over the past decades, energy efficiency is increasingly become a hot topic as energy crisis and carbon emission have been seriously considered by the whole society [1]–[3]. According to recent statistical data regarding to energy consumption, more than 80% is accounted for fossil fuel, which may deteriorate energy deficiency and global warming to a much worse level [4]. To address this challenge, smart building has been emerged as a promising solution. By using cyber-physical systems (CPS) in industrial, commercial and domestic scenarios [5]–[10], power consumption and working state of a set of electricity-consumed equipment are monitored by a host controller, based on which energy efficient measures can be performed to reduce power wastage at real time. In case that smart grid is introduced, WSNs can combine different power systems, smart sensing, intelligent networks and embedded computing together, also with the purpose of improving energy utilization and reducing cost [11]–[14].

Among several wireless networks protocols in CPS-based control paradigm, which include Bluetooth, WiFi, and 6Lowpa, ZigBee is preferred in energy resource constrained scenarios due to a number of advantages [15]–[18], such as low power consumption, fast self-organization, more flexible for deployment, and easy for popularization in a large scale. As shown in Figure 1 of a CPS-based deployment in smart building, the wireless network is consisted of one coordinator, a fleet of routers and CPS nodes (end devices). After initialized by the coordinator, each end device can exchange information packets with the coordinator, the routers and

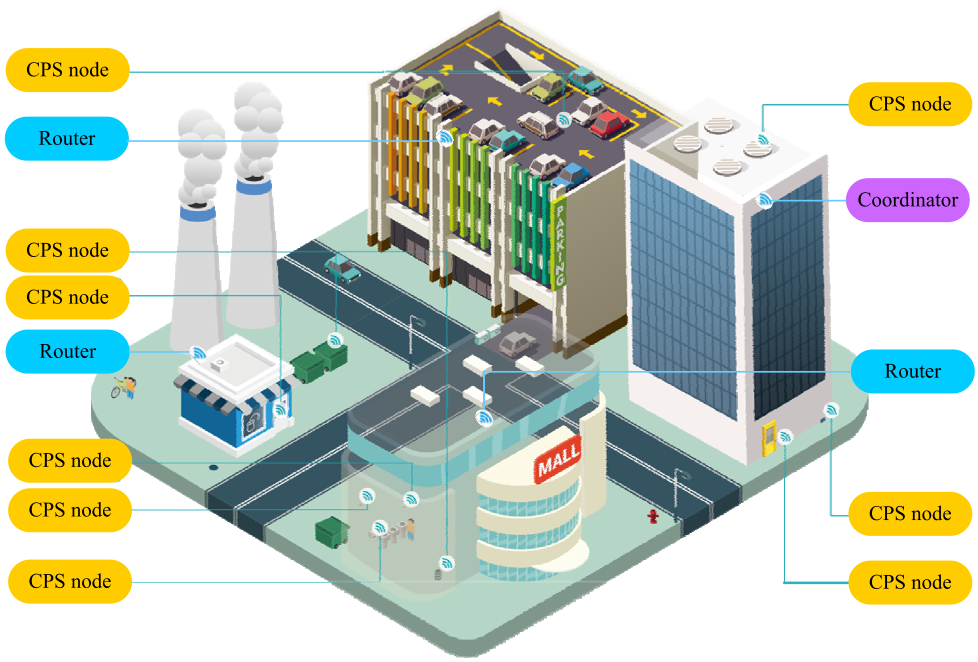


FIGURE 1. Wireless physical and MAC layers of the CPS-based smart building.

other end devices. Although this wireless networks can be directly used in smart building and industrial control applications, frequent retransmission of error corrupted packets is a serious defect that should be highlighted, because the retransmission strategy not only reduces energy efficiency of the embedded battery resource, but also prolongs the average transmission latency [19]–[22], [24], [26]. Aiming to reduce the probability of packets retransmission, the forward error correction (FEC) technique is adopted in some existing researches. While most of these works were performed for industrial scenarios [25]–[28], the achieved superiorities may not applicable for smart building. Moreover, packet length in industrial control applications is short, usually in the order of 100 bits [29], [30]. As compared with the scenarios in smart building, the packet length can up to the maximum size of IEEE 802.15.4 physical layer, i.e., 102 bytes (816 bits) for the media access control (MAC) layer payload. Presently, these factors are not considered in smart building scenarios.

Building on our developed MAC layer simulation platform, this paper gives comprehensive bits error rate (BER) and packets error rate (PER) analysis of several classic coding schemes. On condition of additive white Gaussian noise (AWGN) wireless channel, Reed-Solomon (RS) codes, convolutional codes (CCs) and their concatenated codes are tested for different code rates. As a first contribution of this research, we present an intensive comparison and analysis of the error correction capability of classic codes when applied in smart building. Secondly, we show the relationship between BER and PER, which may shade a light on modeling the error pattern for future research. Thirdly, we propose RS and CCs concatenated codes are promising coding schemes that should be employed in practical implementation, if the involved RS encoding/decoding latency can be tolerated.

The rest of this paper is organized as follows. Section II gives background knowledge of the CPS-based physical and MAC layers, and show how to integrate the FEC technique with MAC layer format for backward compatibility. Section III details why RS, CCs and their concatenated codes are selected in this research, the simulation setup and processes are also proposed in this Section. In Section IV, the BER and PER performance are investigated in AWGN wireless channel of smart building. As a further research, performance comparison and analysis of the adopted codes with the same signal to noise ratio (SNR) is performed. At last, conclusion, limitation and future works are presented in Section V.

II. BACKGROUND KNOWLEDGE OF THE ADOPTED PHYSICAL AND MAC LAYER

ZigBee is a kind of self-organized wireless network that that defined over IEEE 802.15.4 standard, and works at the license-freed industrial, scientific and medical (ISM) bands. At central frequency of 868 MHz, 915 MHz and 2.4 GHz, the theoretical data rates can up to 20 kbps, 40 kbps and 250 kbps, respectively. To improve robustness of the signal in the heavy employed ISM bands that co-existed with other wireless devices, IEEE 802.15.4 physical layer uses direct Sequence Spread Spectrum (DSSS). For purpose of fast extension in practical implementation, IEEE 802.15.4 physical and MAC layers adopt the protocols of

IEEE 802.15.4 standard, whose data packet composition of the physical/MAC layer is represented in Figure 2. Theoretically, using FEC in the physical layer can bring performance improvement in terms of reliability and latency. But the cost accounted for hardware overhead will increase, while it is also not flexible to use different coding schemes and decoding algorithms in the MAC layer by software implementation. For this reason, this paper proposes to apply FEC in the MAC layer. Similar strategy can also be founded in [31]–[33], but these research have used error correction codes for industrial control applications.

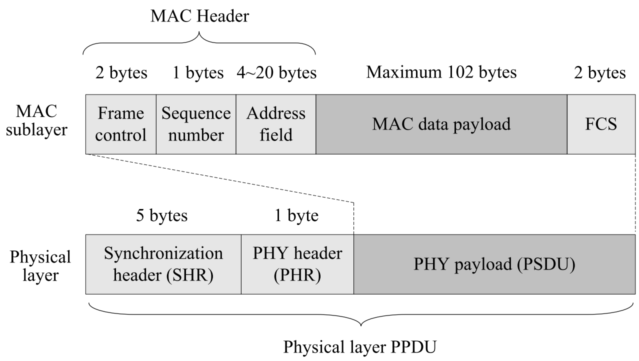


FIGURE 2. Packet composition of IEEE 802.15.4 physical and MAC layers.

At the MAC layer level, there are four kinds of data units that defined by IEEE 802.15.4 standard. In this research, we only use the data frame for encoding/decoding transmission. As shown in Figure 2, the MAC header is composed of one 2-bytes frame control, one 1-byte sequence number and one (4 20)-bytes address field. Followed by a MAC payload field with the length ranges from 1 byte to 102 bytes. The FCS field is a special 2-bytes cyclic redundancy check (CRC) code that generate by using International Telecommunication Union-Telecommunication sector (ITU-T) standard over MAC header and payload, based on which the receiver side can calculate the consistency of the received packet. If there are errors, the automatic repeat request (ARQ) mechanism is enabled to require for retransmission. In general, this error control strategy can guarantee very high reliability, the implicit long latency may result in traffic congestion in the wireless channel, and is definitely consume much energy resource.

Targeted to improve energy efficiency by reducing the probability of packet retransmission, and not to modify the MAC layer structure for backward compatibility, the FEC technique is applied to the packet as shown in Figure 3. At first, the FCS field only contains the CRC bits generated for the MAC header, and the MAC header is not encoded. In this way, more bits in the payload field are used for the redundant bits to achieve better error correction capability. For receiver not aware of the FEC technique, the packets with corrupted MAC header is simply discarded. In the second step, the MAC payload and the corresponded CRC bits (also 2 bytes by using the ITU-T standard) are encoded.

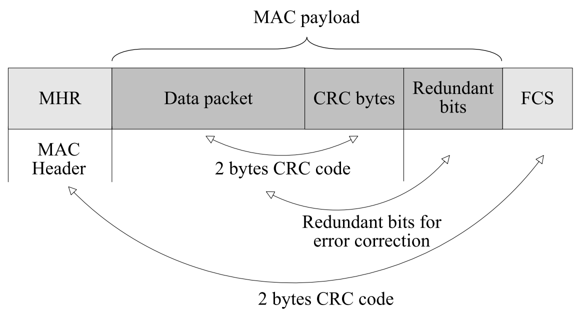


FIGURE 3. Proposed MAC layer frame format using FEC technique.

On considering the adopted codes in this research are systematic codes, the receiver side can check if the MAC payload is correctly received. In case there are errors, the payload and the redundant bits are input to a decoder for error correction, and to calculate if the decoded packet has remove the errors by CRC checking. When the packet is received/decoded without error bits, the packet will be accepted or relayed according to the information in the address field. Otherwise, the packet is discarded, and starts the ARQ procedures to ask for retransmission.

III. SELECTION OF CODING SCHEMES AND SIMULATION ENVIRONMENT SETUP

A. PRINCIPLE OF FEC AND CODES SELECTION

Different from the ARQ strategy, where the noise corrupted packet is discarded and its copy is retransmitted until the packet is error-free received. FEC technique processes the packet before transmission as shown in Figure 4. At the transmitter side, the to be transmitted packet is first input into a encoder, in which some redundant bits are added to the packet according to certain encoding rules. At the receiver side, the decoder corrects the error bits by employing a suitable decoding algorithm, as the redundant bits contain additional information of the transmitted bits that can be used to calculate consistency of these bits. However, this does not mean all errors can be recovered, the error correction capability is limited by the decoding scheme, code rate and decoding algorithm.

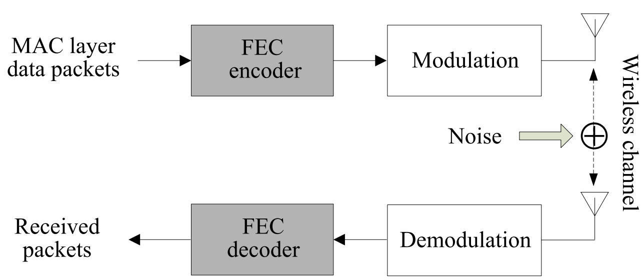


FIGURE 4. Block of FEC encoding/decoding transmission.

Grouped by the error correction capability, current coding schemes can be classified as modern codes and classic codes. Modern codes include Turbo codes, density parity check (LDPC) codes, fountain codes and polar codes, whose error correction capability can approach the Shannon Limit when used for long packet encoding transmission. For example, a packet more than 10^4 bits. Unfortunately, these codes will suffer from serious error floor in medium to high SNR region when applied to short packet [34], [35]. Moreover, iterative decoding algorithms, such as the maximum a posteriori probability decoding algorithm in logarithmic domain (Log-MAP) and belief propagation (BP) algorithm, are usually adopted in practical implementation to get near optimal decoding performance, but with the penalty of increased latency and power dissipation. As a result, classic codes, include Bose-Choudhary-Hocquenhem (BCH) codes, RS codes, repeated codes and CCs, are preferred in energy resource constrained applications. Especially, RS codes are the non-binary BCH codes that defined over high order Galois Field, this makes RS codes superior to BCH codes in correcting burst error bits. With the convolutional coding structure, CCs can encoding/decoding bits while it is receiving packet. The implicit low latency and simple encoding/decoding advantages are very useful in WSNs for smart building. Consequently, RS codes, CCs and their concatenated codes are employed in this research, and to investigate their BER/PER performance under AWGN wireless channel in smart building.

B. SIMULATION ENVIRONMENT SETUP AND TESTING PROCEDURES

In this subsection, we first detail the methodology to pad zero bits for packet length and code rates compatibility purpose, then we propose the procedure on how to construct the simulation environment. Considering the maximum payload length of MAC layer is 816 bits, packet with three kinds of length, i.e., 104 bits, 240 bits and 360 bits, are used for BER/PER performance analysis under AWGN wireless channel.

In the testing, the packet length may not compatible with the code rates. For example, when a 104-bits packet is encoded by using CCs with the code rate of 5/6, packet length of the encoded sequence is 124.8 bits, theoretically. However, such kind of result is not allowed as the unit "bit" is defined over integer field. To deal with this unsuitability, traditional adopted method is to add some zero bits to the tail of a packet. After decoding at the receiver side, the padded zero bits are removed. For a more complicated case that the RS and CCs concatenated codes are used in this research, Figure 5 illustrates how zero bits are padded/removed in the corresponded encoding/decoding procedure. It should be noted that, in the simulation, we use Chase algorithm and soft Viterbi algorithm for RS and CCs decoding, respectively.

Figure 6 presents procedures of our simulation, based on which we have construct a Matlab simulation platform for purpose of BER/PER testing: i) parameters such as packet length, code rates, coding scheme and the maximum number of packets for simulation N_{mnp} are set for simulation; ii) generates random data packets for transmission; iii) inputs data packets into the encoder to get encoded data packets; iv) the encoded data packets are binary phase shift keying (BPSK) modulated before transmission; v) the encoded data packets are passed through an AWGN wireless channel with predefined value of noise (E_b/N_0 or SNR); vi) the received packets are demodulated; vii) the demodulated packets are input into a decoder for error correction; and viii) calculates BER and PER. When enough number of packets have been processed, for example, 10^5 data packets for BER of 10^{-4}, the testing is finished while BER/PER results are output.

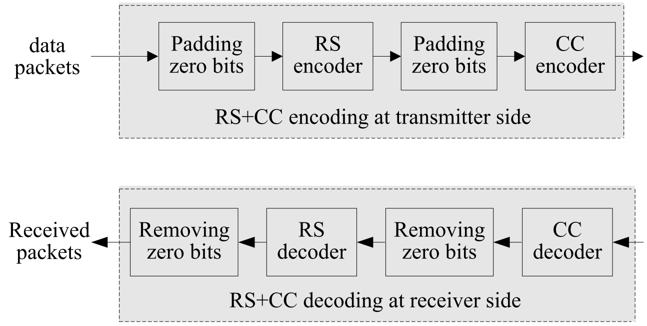


FIGURE 5. Padding/removing zero bits for encoding/decoding.

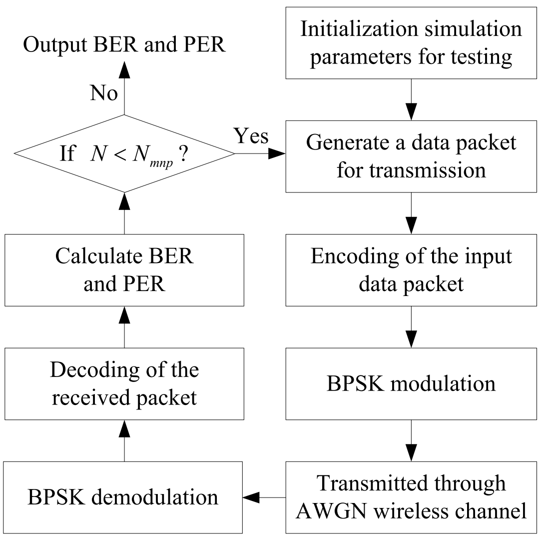
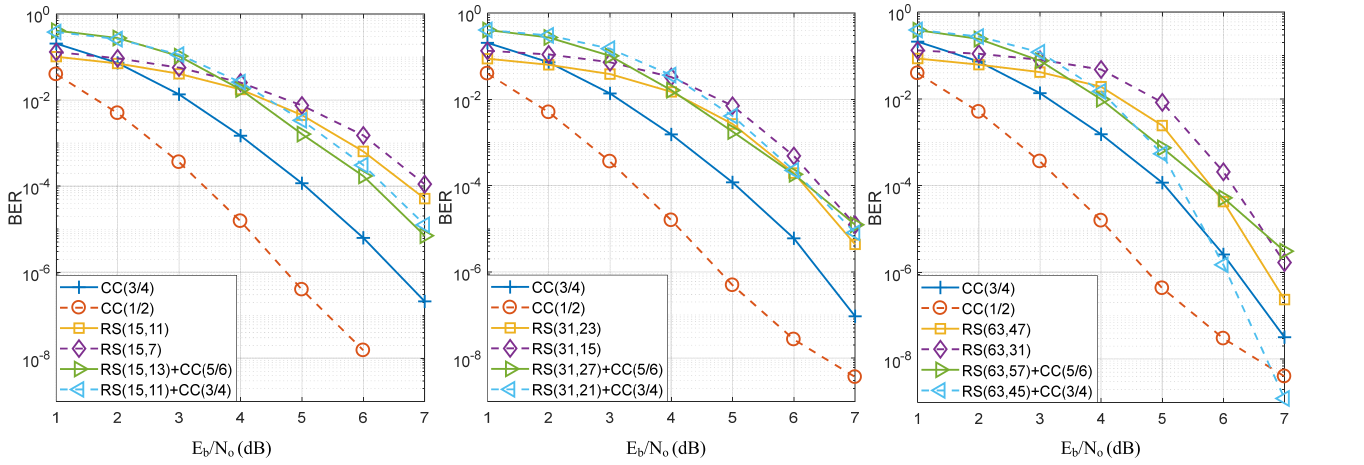


FIGURE 6. Procedures of the simulation (where N is the number of processed packets, N_{mnp} is the predefined maximum number of packets for simulation).

IV. PERFORMANCE COMPARISON AND ANALYSIS

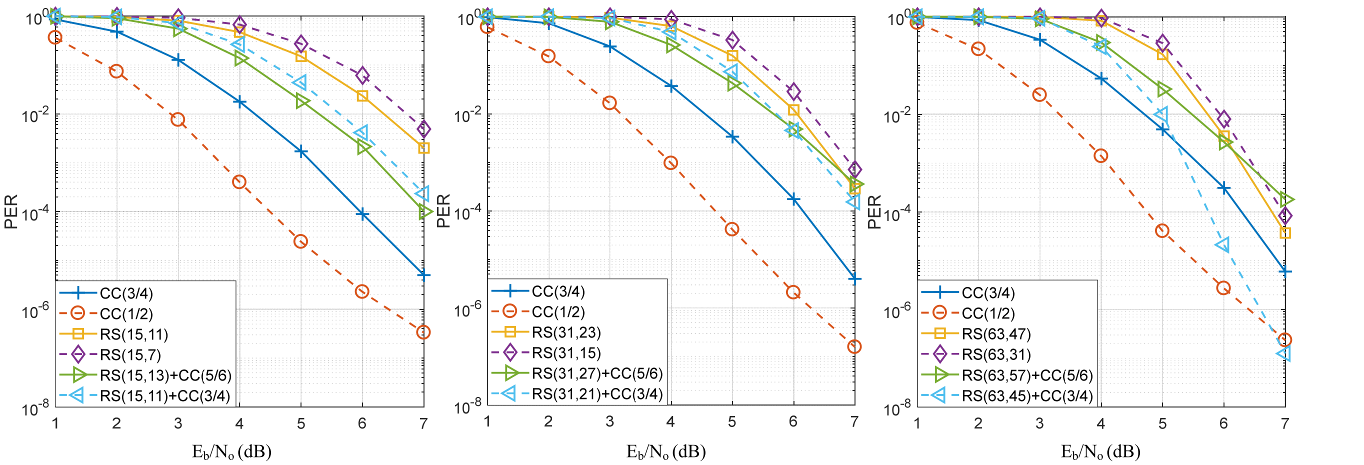
A. PERFORMANCE COMPARISON WITH THE SAME E_B/N_0

As mentioned in Section III, RS codes, CCs and their concatenated codes are adopted in this research. For convenience of comparison, two code rates, i.e., 0.75 and 0.5 are used by the corresponded encoders to generate packets with different error correction capability. Figure 7 and Figure 8 present the BER and PER performance for three kinds of packet length, respectively. We can see the BER and the PER metrics are



(a) (b) (c)

FIGURE 7. BER performance comparison of RS code, CCs and their concatenated codes (for RS(n,k) that defined over GF(2^m), where m is the symbol length in bits, $n = 2^m - 1$ is the codeword length in symbols, k is the information sequence length in symbols; for $CC(R)$, R is the code rate). (a) Packet length 104 bits. (b) Packet length 240 bits. (c) Packet length 360 bits.



(a) (b) (c)

FIGURE 8. PER performance comparison of RS code, CCs and their concatenated codes. (a) Packet length 104 bits. (b) Packet length 240 bits. (c) Packet length 360 bits.

closely related to each other, a coding scheme with better BER also outperforms its counterpart in term of PER. Seen Figure 7 and Figure 8, we can get the following conclusions:

1) For RS codes that defined over high order $GF(2^m)$, where m is the number of bits in one symbol, the RS codes with larger m have better BER/PER performance than the RS codes with smaller m. However, when RS codes with the same symbol length but with different code rates are compared, we find lower rated RS code can not outperform the higher rated RS codes. A clear instance can be seen in Figure 7-(c) and Figure 8-(c). For packet length of 360 bits and at E_b/N_0 of 6 dB. The BER performance of RS(63,47) is about 4.3×10^{-5}, superior to the PER of 2.1×10^{-4} of RS(63,31). The rationale behind this case is that E_b/N_0 is used as the horizontal coordinate. Considering SNR is computed by $\text{SNR} = E_b/N_0 + 10 \times log(R)$, where R is the code rate of RS codes, lower code rate denotes smaller SNR for the same E_b/N_0, and thus stronger noise will be introduced when the encoded packets are transmitted through an AWGN wireless channel. However, we also noticed that when E_b/N_0 is set to a very high level, such as 15 dB, RS(63,31) can overtake RS(63,47) in terms of BER and PER, as the noise in AWGN wireless channel is weak enough that the maximum burst error correction capability becomes the dominant factor.

2) In case that ultra-high reliability (on the order of 10^{-7} for PER) is not pursued, CCs have the best BER/PER performance than RS codes and RS+CC concatenated codes, on condition of the similar code rates. For example at packet length of 104 bits, the BER and PER of CC(1/2) at E_b/N_0 equals to 5 dB is 3.9×10^{-7} and 1.4×10^{-5}, respectively, far much better than the corresponded 7.5×10^{-3} and 0.27 of RS(15,7), and the corresponded 3.4×10^{-3} and

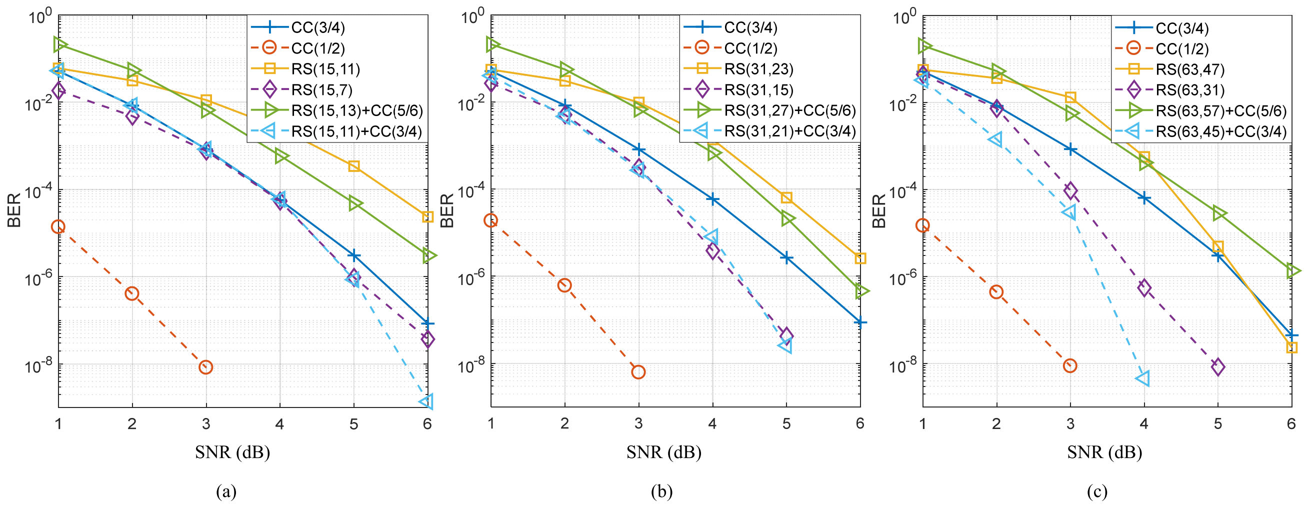


FIGURE 9. BER performance comparison of RS code, CCs and their concatenated codes with the same SNR. (a) Packet length 104 bits. (b) Packet length 240 bits. (c) Packet length 360 bits.

4.4×10^{-2} of RS(15,11)+CC(3/4). Similar results also can be found for packet length of 240 bits and 360 bits, except that at E_b/N_0 of 7 dB, RS(63,45)+CC(3/4) reaches the PER of approximately 1.2×10^{-7} level, which is only slightly exceeded the PER of about 2.3×10^{-7} of CC(1/2). This phenomenon shows CCs are superior to RS codes and RS+CC concatenated codes in AWGN wireless channel where error bits are randomly emerged. Although RS+CC concatenated codes can correct some random error bits since CCs act as the inner codes, the higher rated inner CCs can not correct some error bits whose relative distance may exceed the maximum burst error correction capability of the outer RS codes. Such cases can only improved when RS codes with larger symbol length are used as the outer codes. For example, RS(31,21)+CC(3/4) and RS(63,45)+CC(3/4) have similar overall code rates, but the symbol length of RS(31,21) code is 5 bits and the burst error correction capability is 25 bits, versus to RS(63,45) with the symbol length of 6 and the burst error correction capability of 54 bits. Therefore, when RS(63,45) is used as the outer code, the BER and PER performance will drastically improved.

3) RS+CC concatenated codes are preferred when ultra-high reliability is definitely needed for long packet transmission (360 bits in this research). In Figure 7 and Figure 8, we can see that the BER and PER performance of RS+CC concatenated codes are very close to that of RS codes at the lower E_b/N_0 region for similar code rate. However, RS(63,45)+CC(3/4) outperform CC(1/2) when E_b/N_0 is set to a higher level (as discussed in 2) of this subsection). Considering the code rate of RS(63,45)+CC(3/4) is 0.54 while the code rate of CC(1/2) is 0.5, RS+CC concatenated codes have advantage to achieve better error correction capability than CCs at the higher E_b/N_0 region. Unfortunately, this advantage can not be extended to the cases of short packet transmission. As discussed in Section II-B, when RS codes with long symbol length is adopted to encode a short packet, more zero bits should be padded, and thus reducing the data transmission efficiency that may not feasible in practical implementation.

B. PERFORMANCE COMPARISON WITH THE SAME SNR

In the previous subsection, E_b/N_0 is used as the horizontal coordinate, which means the transmission power for each bit is the same. For a packet with a smaller code rate, more redundant bits are added to the original packet, and thus can be used to correct more error bits. Considering the transmission power for the encoded packet is the same as that of the original data packet, the transmission power assigned to each bit in the encoded packet is reduced. For this reason, E_b/N_0 is a metric to evaluate the error correction capability of a coding scheme from the perspective of energy efficiency. As there are scenarios where the transmission power is the same for all packets regardless of the code rates, it is necessary to investigate the BER and PER performance of different coding schemes but with the same SNR, which is the purpose of this subsection as presented in Figure 9 and Figure 10, respectively.

1) CCs still have the best BER and PER performance, as compared with RS codes and RS+CC concatenated codes on condition of similar code rates. Since we use AWGN to model the wireless channel in this research, it shows CCs are effective codes to address the randomly emerged errors. Moreover, the low encoding/decoding latency is also an important characteristic that emphasized in practical applications. In this regard, CCs are preferred coding scheme for short packets transmission in smart building scenarios.

2) RS codes with larger symbol length can improve the error correction capability as the packet length increases. For example, at SNR of 5 dB, the BER of RS(15,7) is about 9.6×10^{-7} for packet length of 104 bits. With similar code rate of RS(31,15) for a longer packet length of 240 bits, the BER is about 4.2×10^{-8}, and is further reduced to approximately

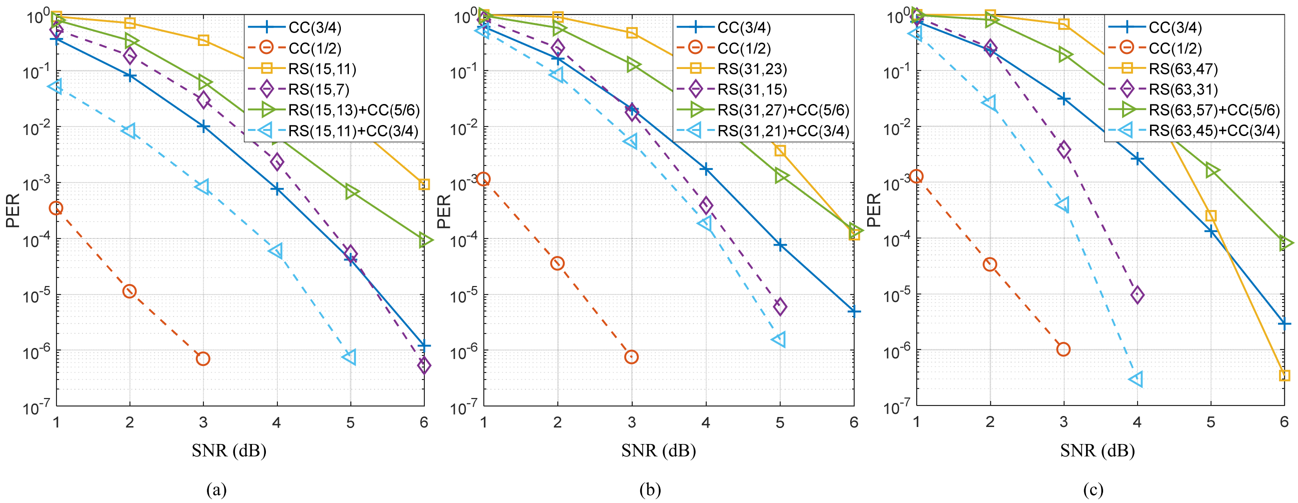


FIGURE 10. PER performance comparison of RS code, CCs and their concatenated codes with the same SNR. (a) Packet length 104 bits. (b) Packet length 240 bits. (c) Packet length 360 bits.

8.3×10^{-9} for RS(63,31) with the packet length of 360 bits. In case of the same symbol length, RS codes with smaller code rates outperform their counterparts whose code rates are higher, as the SNR is the same while lower code rates mean increased burst error correction capability. On the other hand, when the code rates are high, RS codes are inferior to RS+CC concatenated codes at low to medium SNR region. But this disadvantage is reversed in the high SNR region. As can be seen in Figure 10-(c), RS(63,47) also outperforms CC(3/4) when SNR is more than 5 dB in term of PER.

3) Compared with CCs and RS codes that with higher code rates, RS+CC concatenated codes achieve the worst BER and PER performance. As the inner codes, CCs can only correct few error bits, while RS codes act as the outer codes also provide limited burst error correction capability. When the overall code rates of RS+CC concatenated codes are reduced to a lower lever, for example about 0.5 in this test, the BER and PER performance will greatly improved. Especially, the BER and PER performance are closely related with the burst error correction capability of the adopted RS outer codes. Therefore, burst error is the crucial factor that impedes performance improvement. Such kind of error pattern should be highlighted in short packet transmission, and RS+CC concatenated codes are a promising candidate in this context.

V. CONCLUSIONS

CPS-based smart building represents an effective solution to deal with the topic of energy crisis by the research community. To collect information about energy consumption from all devices installed in the monitored scope, wireless sensor network is adopted in this research, and aimed to reduce the probability of packets retransmission by incorporating error correction codes in the MAC layer, as power consumption is a bottleneck issue for energy resource constrained IEEE 802.15.4 applications. Building on analysis of the frame format of IEEE 802.15.4 physical and MAC layers, we propose to encode the MAC layer payload while the frame structure is retained without modification. By employing RS codes, CCs and their concatenated codes in our developed simulation platform, the BER and PER performance are intensively investigated in a typical AWGN wireless channel. It has been shown that CCs outperform RS codes and RS+CC concatenated codes in most cases where ultra-high reliability is not highly required. Otherwise, RS+CC concatenated codes are preferred on condition of a lower code rate at high E_b/N_0 (SNR) region for longer packets transmission (more than 360 bits in this research). Furthermore, when RS+CC concatenated codes are adopted to achieve ultra-high reliability, the RS codes with larger symbol length should be employed. Additionally, there are some issues needs much research in the future. These include to investigate the BER and PER performance of the adopted codes in Rayleigh wireless channel, and to address the pulse interference from other devices that co-located in the same building.

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MING ZHAN (M'16) received the Ph.D. degree from the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, Chengdu, China, in 2013. From 2016 to 2017, he was a Visiting Scholar with the Royal Institute of Technology, Stockholm, and ABB Corporate Research Center, Västerås, Sweden. He is currently an Associate Professor with the College of Electronic and Information Engineering, Southwest University, Chongqing, China. His research interests include low-complexity and energy-efficient error correction decoder, wireless sensor networks, and high-performance communications in industrial automation.

JUN WU (M'12) received the Ph.D. degree in information and telecommunication from Waseda University, Japan, in 2011. He was a Post-Doctoral Researcher with the Research Institute for Secure Systems, National Institute of Advanced Industrial Science and Technology, Japan, from 2011 to 2012. He was also a Researcher with the Global Information and Telecommunication Institute, Waseda University, from 2011 to 2013. He is currently an Associate Professor with the School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, China. He is also the Vice Director of the National Engineering Laboratory for Information Content Analysis Technology, Shanghai Jiao Tong University. He has hosted and participated in a lot of research projects, including the National Natural Science Foundation of China, the National 863 Plan and 973 Plan of China, the Japan Society of the Promotion of Science Projects, and so on. His research interests include advanced computing, communications and security techniques of software-defined networks, information-centric networks smart grids, and Internet of Things. He has published over 100 refereed papers in the above-mentioned fields. He has been a TPC Member of over ten international conferences, including ICC, GLOBECOM, WINCON, and so on. He has been a Guest Editor of the IEEE Sensors Journal. He is an Associate Editor of the IEEE Access. He is the Chair of the IEEE P21451-1-5 Standard Working Group.

HONG WEN received the Ph.D. degree from the Communication and Computer Engineering Department, Southwest Jiaotong University, in 2004. From 2008 to 2009, she was a Visiting Scholar and a Post-Doctoral Fellow with the ECE Department, University of Waterloo. She is currently a Professor with the National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China, China. Her current main interests lie in wireless communication.

PENG ZHANG received the M.S. degree from Hunan Normal University, China. He is currently a Lecture with the Department of Science and Industry, Guangdong Mechanical and Electrical Polytechnic, Guangzhou, China. He has published over 20 papers in related journals and conferences. His interests include wireless communication technologies and industry studies.