The 31st International Technical Conference on Circuits/Systems,
Computers and Communications (ITC-CSCC 2016)

Design of Wireless Communication Modem for Internet-of-Things Applications

Hyunsu Hwang, Yongchul Jung and Yunho Jung
School of Electronics and Information Engineering, Korea Aerospace University
76 Hanggongdae-gil, Goyang-si, Gyeonggi-do 412-791, Korea
E-mail : {hshwang, ycjung, yjung}@kau.kr

Abstract: In this paper, wireless communication modem for internet-of-things (IoT) applications is proposed which can support various data rates from 31.25Kbps to 2Mbps, and its implementation results are presented. Repetition coding for 32-chip direct-sequence spread spectrum (DSSS) symbol is applied for low rates under 250Kbps to extend the coverage. Convolution coding, puncturing, and interleaving for non-DSSS symbol are performed for high rates from 500Kbps to 2Mbps for multi-media services. Simulation results show that the coverage increases at the rate of 51.8-77.3% for various environments compared with IEEE 802.15.4 ZigBee. The modem chip was implemented in $180nm$ CMOS process and total gate counts are 260K with the size of $5.8mm^2$.

Keywords—**Wireless communication, Modem, IoT, ZigBee**

1. Introduction

With the internet-of-things (IoT) technology, a domain shift for human life is expected towards connected devices and machines which are autonomously requesting and supplying information via wireless networks [1]-[3]. The information of everything such as identification and position with GPS/GNSS service will be available anywhere and at anytime through internet. As the connectivity solution for IoT, IEEE 802.15.4 ZigBee is being considered because of its low-power and low-cost property [4]-[6]. However, since ZigBee devices support only one data rate of 250Kbps at 2.4GHz frequency band, it is difficult to be applied to various applications [7]. Hence, to overcome the limit of existing ZigBee systems and to satisfy the requirements of various IoT applications, the modified wireless communication systems from ZigBee is needed.

This paper proposes a method of supporting variable data rates from low data rate of 31.25Kbps that has relatively long coverage to high data rate of 2Mbps that is capable of high-quality audio and video transmissions. Repetition coding for direct-sequence spread spectrum (DSSS) symbol is applied for low rates from 31.25Kbps to 125Kbps, which makes possible the coverage extension owing to the signal-to-noise power ratio (SNR) gain. On the other hand, convolution coding, puncturing, and interleaving for non-DSSS symbol are performed for high rates from 500Kbps to 2Mbps, which can be applied to multi-media services within small area.

The remainder of this paper is organized as follows: Section 2 explains the proposed wireless communication systems for IoT applications and Section 3 presents the performance evaluation results. Section 4 describes the hardware architecture design and implementation results for the proposed wireless communication modem. Finally, Section 5 concludes the paper.

2. Proposed Wireless Communication Systems

As shown in Figure 1, the packet structure of the existing IEEE 802.15.4 ZigBee is composed of synchronization header (SHR), PHY header (PHR) and PHY layer convergence protocol (PLCP) service data unit (PSDU). SHR consists of preamble which is 8x repeated index-0 symbols (S_0's) and start-of-frame delimiter (SFD) which is a field indicating the end-timing of preamble. PHR is 8-bit field which includes the frame length information, and PSDU is a data payload whose maximum length is 127 octets [7].

As illustrated in Figure 2, the preamble in the proposed systems is extended to maximum 32 octets for the time-synchronization in low SNR environment in order to increase the coverage. PHR is also extended to 2 octets for indicating the packet length increase for multi-media applications. Reserved bit in PHR of IEEE 802.15.4 standard is replaced by length-extension mode (LEM) field. That is, if LEM is 1, frame-length field is extended to 10 bits and therefore, PSDU of maximum 1022 octets is supported. If LEM is 0, packet structure is the same as that in IEEE 802.15.4 standard.

		1 Octet		**Variable : 0~127 Octets**
Preamble (4 Octets)	**SFD (1 Octets)**	**Frame Length (7bit)**	**Reserved (1bit)**	**PSDU**
SHR		**PHR**		**PHY Payload**

Figure 1. Packet structure of IEEE 802.15.4 ZigBee system.

		2 Octets					**Variable : 0~1022 Octets**
Preamble (4~32 Octets)	**SFD (1 Octets)**	**Frame Length (7bit)**	**LEM (1bit)**	**TM (4bit)**	**Ext. Length (3bit)**	**Reserved (1bit)**	**PSDU**
SHR		**PHR**					**PHY Payload**

Figure 2. Packet structure of the proposed systems.

The transmission mode (TM) field in PHR of the proposed systems indicates 9 types of transmission modes as shown in Table 1. In case of TM0-3, repetition coding for 32-chip DSSS symbol is applied for coverage extension with low data rates such as 32.15Kbps, 62.5Kbps and 125Kbps. TM4 is the IEEE 802.15.4 standard-compatible with the data rate of 250Kbps. In case of TM5-7, scrambling, convolutional coding, puncturing and interleaving for non-DSSS symbol are applied for multi-media applications with high data rates such as 500Kbps, 1Mbps and 1.33Mbps. TM8 supports maximum data rate of 2Mbps and there is no encoding and spreading. For all TMs, minimum shift keying (MSK) modulation is also applied.

Table 1. Transmission mode (TM) of the proposed systems.

TM	Data Rate	Spreading and Error Correction Coding
0	32.15Kbps	8x RC for 32-chip DSSS symbol
1	62.5Kbps	4x RC for 32-chip DSSS symbol
2	125Kbps	2x RC for 32-chip DSSS symbol
3	250Kbps	32-chip DSSS (standard-compatible)
4	500Kbps	2x RC and CC-1/2 for non-DSSS symbol
5	1Mbps	CC-1/2 for non-DSSS symbol
6	1.33Mbps	CC-2/3 for non-DSSS symbol
7	1.5Mbps	CC-3/4 for non-DSSS symbol
8	2Mbps	Unspread and Uncoded

In order to perform time-synchronization in the receiver, the correlation property for preamble is utilized as shown in Figure 3. Correlation peak is detected at the location where the received preamble and the correlation window precisely coincide. To enhance the performance of time synchronization, preamble length needs to be extended for the superior correlation property. New long preamble such as gold code can be applied. However, new preamble requires additional complexity because it needs extra correlator and preamble storage memory. Therefore, the extension of preamble length using repetition coding is better than that using new gold code. However, when doubling the length of preamble by repeating the identical indix-0 symbol S_0, correlation peak may appear when the correlation window is located at the middle point of the first and second symbol as depicted in Figure 4, which makes the accurate time synchronization hard. Hence, a novel preamble transmission structure is required that can improve the performance of time synchronization by increasing the length of preamble, instead of transmission by simply repeating the identical preamble symbol.

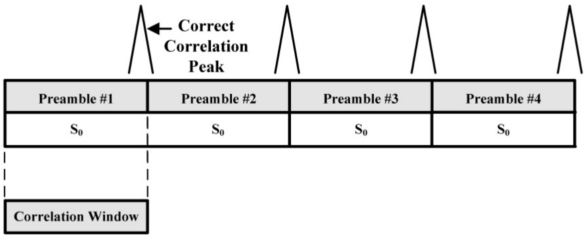

Figure 3. Correlation property for preamble specified in IEEE 802.15.4 standard.

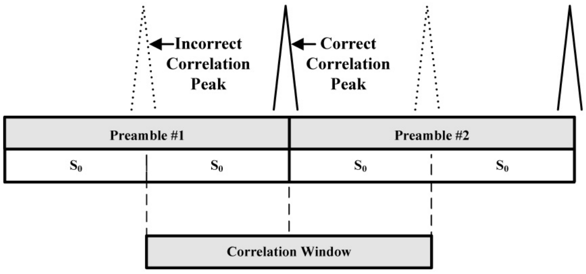

Figure 4. Correlation property for the repeated preamble.

Figure 5 shows the structure of the proposed preamble. The preamble length increases according to transmission mode so that the performance of time synchronization can be improved and no correlation peak is detected in false location. Each of preamble symbol S_p, S_q, S_r is set at one of the 16 data symbols specified in IEEE 802.15.4 standard. Since these DSSS symbols are used for the transmission of information data, extra memory to store the preamble is not needed. The proposed preamble structure is composed such that the required number of preamble symbol is minimized, while maintaining the correlation property. Moreover, to minimize the number of correlator, each first preamble symbol is set to the symbol S_0 so that the correlator for S_0 can be shared for low-complexity implementation. Also, the correlators for S_p, S_q, S_r can be shared as the transmission mode.

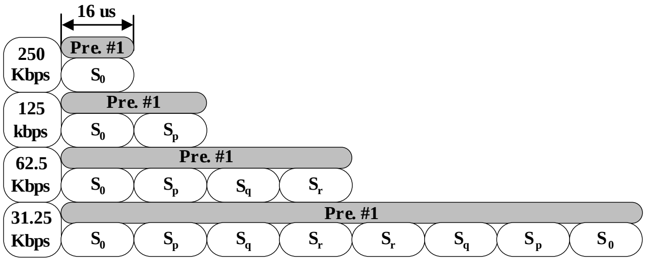

Figure 5. Structure of the proposed preamble.

3. Simulation Results

Figure 6 shows the packet error rate (PER) performance for the proposed wireless communication systems. The frequency offset of $\pm 40ppm$ specified in IEEE 802.15.4 standard and additive white Gaussian noise (AWGN) were considered. As the data rate decreases, the required SNR also decreases, which means the coverage can be extended.

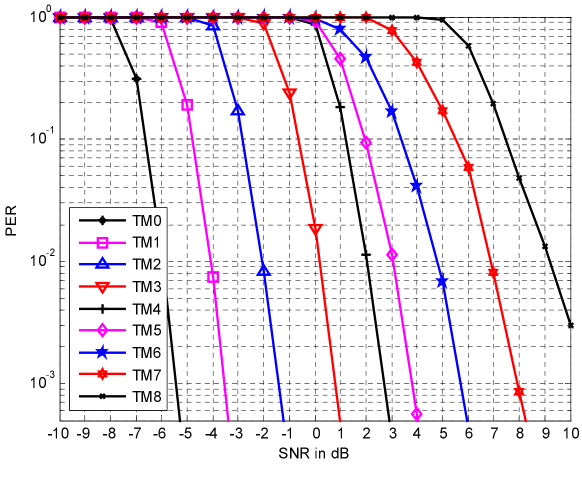

Figure 6. PER performance of the proposed systems.

By using the following equation in [8], the coverage performance of the proposed systems were evaluated:

$$Coverage = 10^{\frac{G_{tx}+G_{rx}+27.6-20\log(F)+G_{ad}+P_{tx}-S_{rx}}{N}} \quad (1)$$

G_{tx} and G_{rx} denote the antenna gains of transmitter and receiver, respectively. F denotes the operating frequency of 2.4GHz. G_{ad} is the additional path loss that depends on the object causing the path loss such as wall and floor. N denotes the path loss factor that depends on the field such as open field, open office and dense office. P_{tx} is the transmitter output power and is set to 9dB. S_{rx} is the receiver sensitivity and is calculated from the PER performance.

Figure 7 shows the coverage performance for various fields such as open field, open office and dense office. G_{tx} and G_{rx} were set to 0dB, respectively. G_{ad} was also assumed to be 0dB. The path loss factor N for open field, open office and dense office were set to 25dB, 30dB and 40dB, respectively. In case of open field, the coverage of the standard-compatible TM3 is $743m$, while that of TM0 is extended to 1,317m which is increased by 77.3%. Even in case of dense office, the coverage of TM3 is $112m$, while that of TM0 is elongated to about $169m$ which is increased by 51.8%.

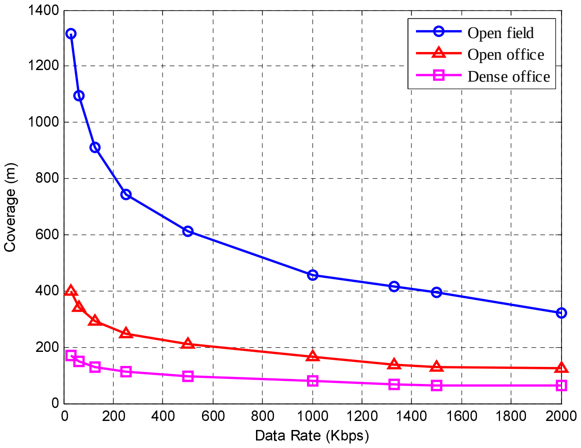

Figure 7. Coverage performance of the proposed systems.

4. Design of Proposed Wireless Communication Modem

Figure 8 shows the hardware architecture of the proposed wireless communication modem which can support variable data rates of 32.15Kbps, 62.5Kbps, 125Kbps, 250Kbps, 500Kbps, 1Mbps, 1.3Mbps, 1.33Mbps and 2Mbps. The transmitter is composed of TX low rate unit (TLRU), TX high rate unit (THRU) and MSK modulator. TLRU supports low data rate under 250Kbps and consists of a bit-to-symbol mapper, DSSS spreader and repetition encoder unit. THRU supports high data rate over 500Kbps and consists of scrambler, convolutional encoder, puncturer and block interleaver.

The receiver is composed of automatic gain controller (AGC), time synchronizer, demodulator and RX high rate unit (RHRU). The AGC controls the gain of the amplifier in the RF transceiver to provide a constant amplitude for the received signal. Time synchronizer finds the DSSS symbol boundary by using the matched filter with DSSS symbol size and demodulator detects the transmitted symbol. RHRU performs an inverse process to THRU and is composed of de-interleaver, de-puncturer, Viterbi decoder and descrambler. One-point scheme is applied to Viterbi decoder for low-complexity implementation, which can perform the write operation 4x faster than the read operation on trace-back memory [9].

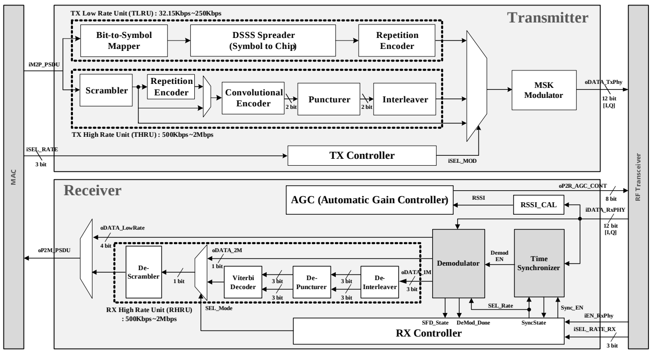

Figure 8. Hardware architecture of the proposed modem.

The proposed modem was designed in HDL and implemented using a 180nm 1-poly 6-metal (1P6M) 1.8V CMOS standard cell library. Table 2 depicts the logic synthesis results for the operating clock frequency of 8MHz. As shown in this Table, the proposed modem includes about 260K logic gates.

Table 2. Synthesis results of the proposed modem chip

Block	Gate Count (K)	Proportion(%)
TX	6.97	2.67
AGC	10.84	4.16
Time Synchronizer	192.19	73.67
Demodulator	13.80	5.29
Deinterleaver	8.11	3.11
Viterbi Decoder	23.75	9.10
Descrambler	0.60	0.23
ETC	4.62	1.77
Total	260.88	100

Figure 9 shows the layout view of the proposed modem chip which includes RF transceiver, analog front-end (AFE), and baseband processor. Total chip size is $14mm^2$ and the core size is 12.6mm^2 including RF transceiver and AFE such as analog-to-digital converter (ADC) and digital-to-analog converter (DAC). The size of the digital baseband processor is 5.8mm^2 including two dual-port memories for the verification. Power consumption of the modem chip was measured using verification platform. The power consumption of transmitter was $18mW$, while that of receiver was $16mW$. The real-time operation of the proposed modem was successfully evaluated. The key features of the fabricated modem chip are summarized in Table 3.

5. Conclusions

The wireless communication modem for IoT applications was proposed and its implementation results were presented. The proposed system can support variable data rates from 32.15Kbps to 2Mbps, and can be applied to various applications such as sensor networks in wide area and multi-media

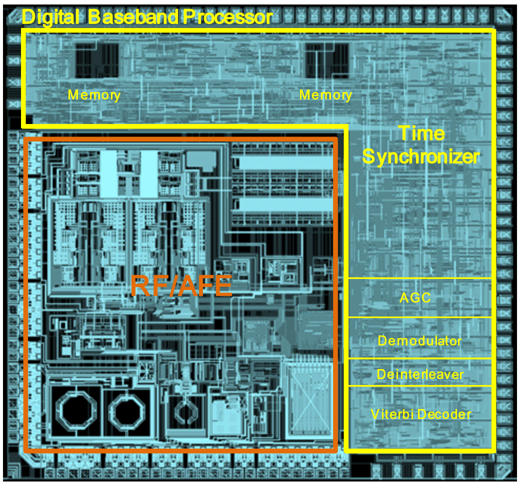

Figure 9. Layout view of the proposed modem.

Table 3. Key features of the fabricated modem chip.

Technology	180nm 1P6M CMOS
Package Type	128 pin QFP
Supply Voltage	I/O : $3.3V$, Core : $1.8V$
Clock Frequency	8MHz
Internal Memory	32KB
Area (mm^2)	Chip : $14mm^2$, Core : $12.6mm^2$
Power Consumption (mW)	TX : $18mW$, RX : $16mW$

services in small area. The proposed modem was fabricated using 180nm CMOS process with RF transceiver and AFE, and was successfully tested with verification platform.

Acknowledgments

This work was supported by the Technology Innovation Program, 10049009, funded by the Ministry of Knowledge Economy (MKE, Korea) and the first and second authors were supported by Expert Education Program of Maritime Transportation Technology (GNSS Area), Ministry of Oceans and Fisheries (MOF, Korea).

References

[1] B. Xu, L. Xu, H. Cai, C. Xie, J. Hu, and F. Bu, “Ubiquitous data accessing method in IoT-based information systems for emergency medical services,” *IEEE Trans. on Industrial Informatics*, vol. 10, no. 2, pp.1578-1586, May 2014.

[2] A. Gluhak, S. Krco, M. Nati, D. Pfisterer, N. Mitton, and T. Razafindralambo, “A survey on facilities for experimental internet of things research,” *IEEE Communications Magazine*, vol. 49, no. 11, pp.58-67, Nov. 2011.

[3] C. Perera, C. Liu, S. Jayawardena, and M. Chen, “A survey on internet of things from industrial market perspective,” *IEEE Access*, vol. 2, pp.1660-1679, Jan. 2015.

[4] G. Vivek and M. sunil, “Enabling IoT services using WiFi-ZigBee gateway for a home automation system,” *IEEE International Conference on Research in Computational Intelligence and Communication Networks (ICRCICN)*, pp.77-80, Nov. 2015.

[5] T. Elarabi, V. Deep, and C. Rai, “Design and simulation of state-of-art ZigBee transmitter for IoT wireless devices,” *IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, pp.297-300, Dec. 2015.

[6] Z. Lin, P.I. Mak, and R.P. Martins, “A sub-GHz multi-ISM-band ZigBee receiver using function-reuse and gain-boosted N-path techniques for IoT applications,” *IEEE Journal of Solid-State Circuits*, vol. 49, no. 12, pp.2990-3004, Dec. 2014.

[7] IEEE 802.15.4, “Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LRWPANs),” 2003.

[8] Application Note AN2611, “System consideration for short range RF devices,” NXP semiconductors

[9] G. feygin and P. G. Gulak, “Survivor sequence memory management in Viterbi decoders,” *IEEE International Symposium on Circuits and Systems*, pp.2967-2970, Jun. 1991.