Maximum Throughput and Minimum Delay in IEEE 802.15.4

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Abstract. This paper investigates the maximum throughput and minimum delay of the new IEEE 802.15.4-standard. This standard was designed as a highly reliable and low-power protocol working at a low data rate and offers a beaconed and unbeaconed version. We will give the exact formulae for a transmission between one sender and one receiver for the unbeaconed version as this one has the least overhead. Further, the influence of the different address schemes, i.e. no addresses or the use of long and short addresses, is investigated. It is shown that the maximum throughput is not higher than 163 kbps when no addresses are used and that the maximum throughput drops when the other address schemes are used. Finally, we will measure the throughput experimentally in order to validate our theoretical analysis.

1 Introduction

The market of wireless devices has experienced a significant boost in the last few years and new applications are emerging rapidly. Several new protocols have been proposed such as IEEE 802.11g and IEEE 802.16. However, these protocols focus on achieving higher data rates in order to support high bit rate applications for as much users as possible. On the other hand, there is a growing need for low data rate solutions which provide high reliability for activities such as controlling and monitoring. Furthermore, these applications often use simple devices which are not capable of handling complex protocols. In order to cope with this problem, a new standard was defined in the end of 2003: IEEE 802.15.4 [1].

The goal of the IEEE 802.15.4 standard is to provide a low-cost, highly reliable and low-power protocol for wireless connectivity among inexpensive, fixed and portable devices such as sensor networks and home networks [2, 3]. This last type of networks is commonly referred to as Wireless Personal Area Networks (WPAN). The standard works in the 2.4 GHz range -the same range as 802.11b/g

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and Bluetooth- and defines a physical layer and a MAC sub layer. The standard is used by the Zigbee Alliance [4] to build a reliable, cost-effective and low-power network.

In this paper, we will investigate the maximum throughput and minimum delay of 802.15.4. We will do this both analytically and experimentally. All the information needed for obtaining these results can be found in the standard [1]. This paper will offer the exact formulae for these calculations in order to give an overview and an easy way to calculate the maximum throughput without the need to completely understand the standard.

The paper is organized as follows. Section 2 will give a brief technical overview of 802.15.4. In section 3, the maximum throughput is calculated. The analysis of the results is given in section 4 and experimental validation is done in section 5. Finally, section 6 concludes the paper.

2 Technical Overview

The new IEEE 802.15.4 defines 16 channels in the 2.4 GHz band, 10 channels at 915 MHz and 1 channel at 868 MHz. The 2.4 GHz band is available worldwide and operates at a raw data rate of 250 kbps. The channel of 868 MHz is specified for operation in Europe with a raw data rate of 20 kbps and for North America the 915 MHz band is used at a raw data rate of 40 kbps. All of these channels use DSSS. The standard specifies further that each device shall be capable of transmitting at least 1 mW (0 dBm), but actual transmit power may be lower or higher. Typical devices are expected to cover a 10–20 m range.

The MAC sub layer supports different topologies: a *star topology* with a central network coordinator, a *peer to peer* topology (i.e. a tree topology) and a *combined topology* with interconnected stars (clustered stars). Both topologies use CSMA/CA to control access to the shared medium. All devices have 64-bit IEEE addresses, but short 16-bit addresses can be assigned.

In order to achieve low latencies, the IEEE 802.15.4 can operate in an optional superframe mode. In this mode, beacons are sent by a dedicated device, called a PAN-coordinator at predetermined intervals (PAN = Personal Area Network). These intervals can vary from 15 ms to 245 seconds. The time between these beacons is split in 16 slots of equal size and is divided in two groups: the contention access period (CAP) and the contention free period (CFP) in order to provide the data with quality of service (QoS). The time slots in the CFP are called guaranteed time slots (GTS) and are assigned by the PAN-coordinator. The channel access in the CAP is contention based (CSMA/CA). When a device wishes to transmit data, the device waits for a random number of back off periods. Subsequently, it checks if the medium is idle. If so, the data is transmitted, if not, the device backs off once again and so on.

As the MAC sub layer needs a finite amount of time to process data received from the PHY, the transmitted frames are followed by an Inter Frame Space (IFS) period. The length of the IFS depends on the size of the frame that has just been transmitted. Long frames will be followed by a Long IFS (LIFS) and

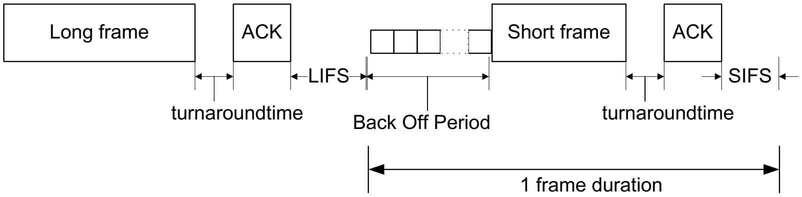


Fig. 1. Frame sequence in 802.15.4. We notice the back off period and that long frames are followed by a long inter frame space and short frames by a short inter frame space.

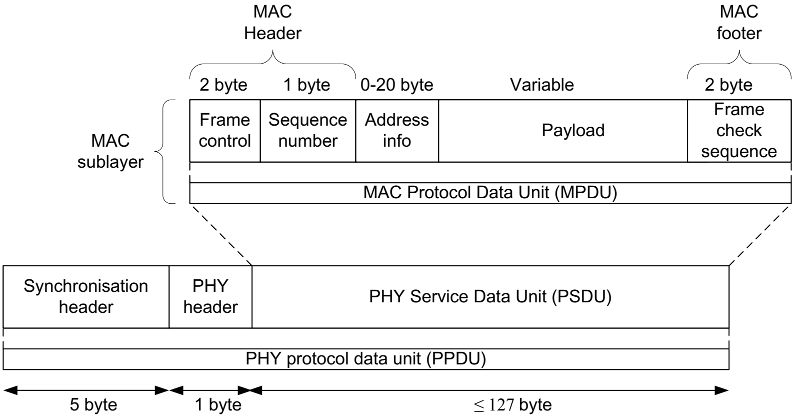


Fig. 2. Frame structure of IEEE 802.15.4

short frames by a Short IFS (SIFS). An example of a frame sequence, using acknowledgments (ACKs), is given in figure 1. If no ACKS are used, the IFS follows the frame immediately.

The packet structure of IEEE 802.15.4 is shown in figure 2. The size of the address info can vary between 0 and 20 bytes as both short and long addresses can be used and as a return acknowledgment frame does not contain any address information at all. Additionally, the address info field can contain the 16-bit PAN identifier, both from the sender and from the receiver. These identifiers can only be omitted when no addresses are sent. The payload of the MAC Protocol Data Unit is variable with the limitation that a complete MAC-frame (MPDU or PSDU) may not exceed 127 bytes.

3 Theoretical Calculations

3.1 Assumptions

The maximum throughput of IEEE 802.15.4 is determined as the number of data bits coming from the upper layer (i.e. the network layer) that can be transmitted.

Hence, we are only interested in the throughput of the MAC-layer according the OSI-protocol stack.

In this paper, only the unslotted version of the protocol (i.e. without the super frames) in the 2.4 GHz band is examined. Indeed, the 2.4 GHz band provides the most channels at the highest data rate and the unslotted version has the least overhead. Hence, CSMA with a back off scheme is used.

The maximum throughput is calculated between only 1 sender and only 1 receiver which are located close to each other. Therefore, we assume that there are no losses due to collisions, no packets are lost due to buffer overflow at either sender or receiver, the sending node has always sufficient packets to send and the BER is zero (i.e. we assume a perfect channel).

3.2 Calculations

The maximum throughput (TP) is calculated as follows. First the delay of a packet is determined. This overall delay accounts on the one hand for the delay of the data being sent and on the other hand for the delay caused by all the elements of the frame sequence, as is depicted in figure 1, i.e. back off scheme, sending of an acknowledgement, ... In other words, the overall delay is the time needed to transmit 1 packet. Subsequently, this overall delay is used to determine the throughput:

$$TP = \frac{8 \cdot x}{delay(x)} \tag{1}$$

In this formula, x represents the number of bytes that has been received from the upper layer, i.e. the payload bytes from figure 1. The delay each packet experiences can be formulated as:

$$delay(x) = T_{BO} + T_{frame}(x) + T_{TA} + T_{ACK} + T_{IFS}(x) \tag{2}$$

The following notations were used:

T_{BO} = Back off period
$T_{frame}(x)$ = Transmission time for a payload of x byte
T_{TA} = Turn around time (192 μs)
T_{ACK} = Transmission time for an ACK
T_{IFS} = IFS time

For the IFS, SIFS is used when the MPDU is smaller than or equal to 18 bytes. Otherwise, LIFS is used. (SIFS = 192 μs, LIFS = 640 μs). The different times are expressed as follows:

Back off period

$$T_{BO} = BO_{slots} \cdot T_{BO\,slot} \tag{3}$$

BO_{slots} = Number of back off slots
$T_{BO\,slot}$ = Time for a back off slot (320 μs)

The number of back off slots is a random number uniformly in the interval (0, 2^{BE}-1) with BE the *back off exponent* which has a minimum of 3. As we only assume one sender and a BER of zero, the BE will not change. Hence, the number of back off slots can be represented as the mean of the interval: $\frac{2^3-1}{2}$ or 3.5.

Transmission time of a frame with a payload of x bytes

$$T_{frame}(x) = 8 \cdot \frac{L_{PHY} + L_{MAC\_HDR} + L_{address} + x + L_{MAC\_FTR}}{R_{data}} \tag{4}$$

L_{PHY} = Length of the PHY and synchronization header in bytes (6)
L_{MAC_HDR} = Length of the MAC header in bytes (3)
$L_{address}$ = Length of the MAC address info field
L_{MAC_FTR} = Length of the MAC footer in bytes (2)
R_{data} = Raw data rate (250 kbps)

$L_{address}$ incorporates the total length of the MAC address info field, thus including the PAN-identifier for both the sender as the destination if addresses are used. The length of one PAN-identifier is 2 bytes.

Transmission time for an acknowledgement

$$T_{ACK} = \frac{L_{PHY} + L_{MAC\_HDR} + L_{MAC\_FTR}}{R_{data}} \tag{5}$$

If no acknowledgements are used, T_{TA} and T_{ACK} are omitted in (2).

Summarizing, we can express the throughput using the following formula:

$$TP = \frac{8 \cdot x}{a \cdot x + b} \tag{6}$$

$$delay = a \cdot x + b \tag{7}$$

In this equations, a and b depends on the length of the data bytes (SIFS or LIFS) and the length of the address used (64 bit, 16 bit or no addresses). The parameter a expresses the delay needed for sending 1 data byte, parameter b is the time needed for the protocol overhead for sending 1 packet. The different values for a and b can be found in table 1.

Table 1. Overview of the parameters for equation 5

nr of address bits		a	b
0 bits	ACK	0.000032	0.002656
	no ACK	0.000032	0.002112
16 bits	ACK	0.000032	0.002912
	no ACK	0.000032	0.002368
64 bits	ACK	0.000032	0.003296
	no ACK	0.000032	0.002752

4 Analysis

In this section, we will analyze the throughput and bandwidth efficiency of IEEE 802.15.4 and we will discuss the lower delay limit. Several scenarios are considered: an address length of 64 bit address, of 16 bit address or without any address info and in all cases with or without the use of ACKs. The bandwidth efficiency is expressed as

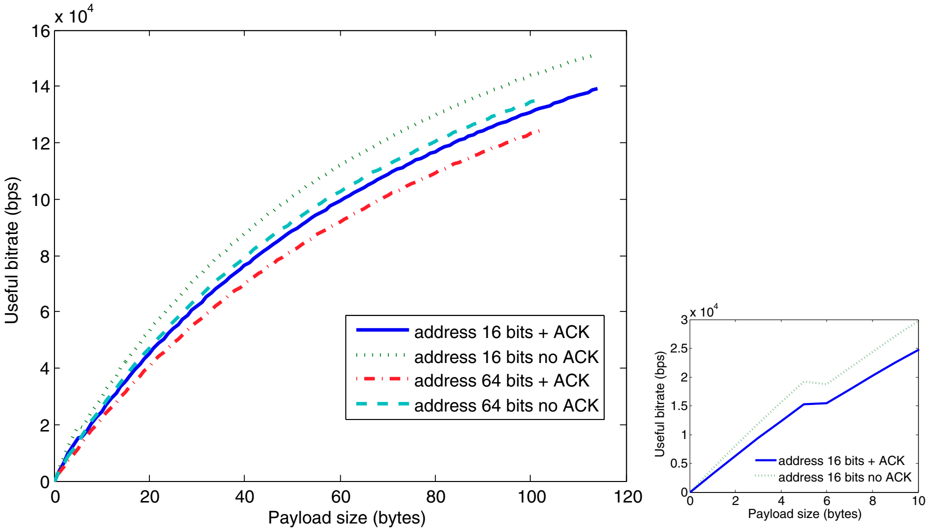
$$\eta = \frac{TP}{R_{data}}. \tag{8}$$

The results can be found in figures 3 and 4 where figure 3 gives the useful bitrate and figure 4 the bandwidth efficiency. In the figures, the payload size represents the number of bits that are received from the upper layer. In section 2 it was mentioned that the maximum size of the MPDU is 127 bytes. Consequently, the number of data bytes that can be sent in one packet is limited. This can be seen in the figures: when the address length is set to 2 bytes (or 16 bits), the maximum payload size is 114 bytes. This can be calculated as follows: $MPDU = L_{MAC\_HDR} + L_{address} + L_{MAC\_FTR} + payload$, where $L_{address}$ equals to $2 \cdot 2$ bytes + $2 \cdot 2$ bytes for the PAN-identifiers and the short addresses respectively. Putting the correct values into the formula for MPDU, gives us 114 bytes as maximum payload length. When the long address structure is used (64 bits), 102 data bytes can be put into 1 packet. If no addresses are used, the PAN-identifiers can be omitted, which means that $L_{address}$ is zero. The maximum payload is now set to 122 bytes.

In general, we see that the number of useful bits or the bandwidth efficiency grows when the number of payload bits increases. The same remark was made when investigating the throughput of IEEE 802.11 [5] and is to be expected as all the packets have the same overhead irrespective of the length of the packet. Further, the small bump in the graph when the address length is 16 bits at 6 bytes, figure 3(b), is caused by the transition of the use of SIFS to LIFS: at that moment the MPDU will be larger than 18 bytes. In all cases, the bandwidth efficiency increases when no ACK is used, which is to be expected as less control traffic is being sent. In figure 3 and 4 we have only shown the graphs for short and long addresses. The graphs for the scenario without addresses are similar to the previous ones with the understanding that the maximum throughput is higher when no addresses are used. The graphs were omitted for reasons of clarity.

A summary can be found in table 2 where the maximum bit rate and bandwidth efficiency of the several scenarios are given.

We can see that we under optimal circumstances, i.e. using no addresses and with-out ACK, an efficiency of 64.9% can be reached. If acknowledgements are used, an efficiency of merely 59.5 % is obtained. Using the short address further lowers the maximum bit rate by about 4%. The worst result is an efficiency of only 49.8% which is reached when the long address is used with acknowledgements. The main reason for these low results is that the length of the MPDU is limited to 127 bytes. Indeed, the number of overhead bytes is relatively large compared to the number of useful bits (MPDU payload). This short packet



(a) **(b)**

Fig. 3. Useful bitrate in function of the number of payload bytes for the different address schemes. The graph on the right (b) shows a snapshot of the left graph for an address size of 16 bits. The transition from SIFS to DIFS can be seen clearly.

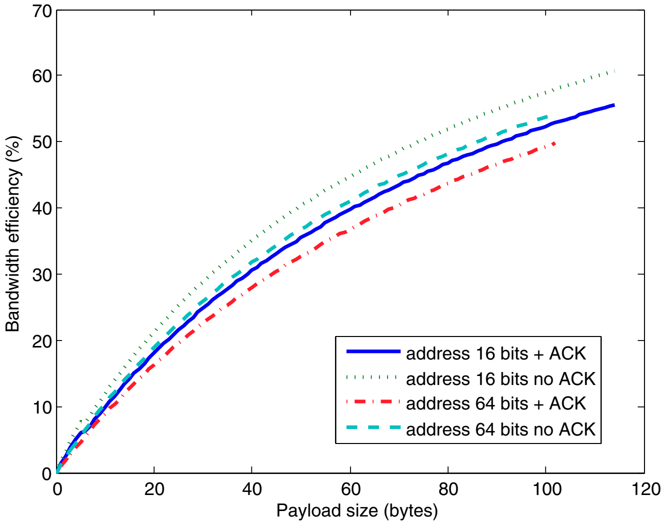


Fig. 4. Bandwidth efficiency of IEEE 802.15.4

length was chosen in order to limit the number of collisions (small packets are used) and to improve fair use of the medium. Further, the main application area

Table 2. Maximum bitrate and maximum efficiency of IEEE 802.15.4 for different address lengths

nr of address bits		maximum bitrate (bps)	maximum efficiency (%)
0 bits	ACK	147,780	59.5
	no ACK	162,234	64.9
16 bits	ACK	139,024	55.6
	no ACK	151,596	60.6
64 bits	ACK	124,390	49.8
	no ACK	135,638	54.8

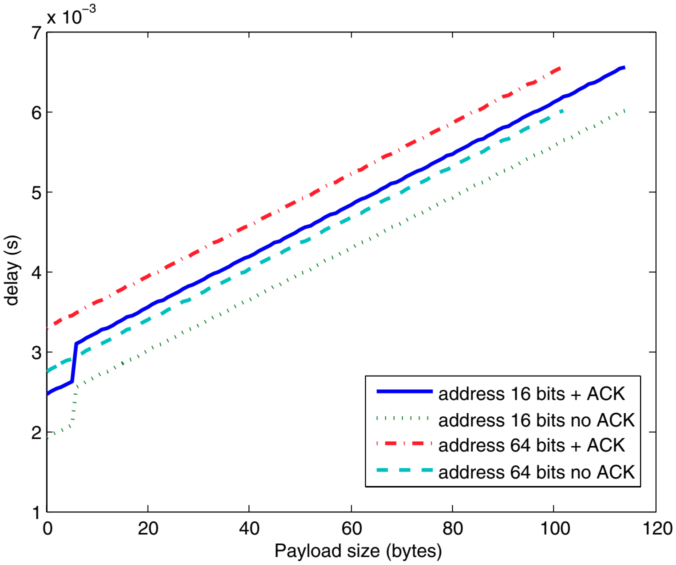


Fig. 5. Minimum delay for varying payload sizes for the short and long address

of this standard focuses on the transmission of small quantities of data, hence the small data packets.

Figure 5 gives the minimum delay each packet experiences. We immediately notice that the delay is a linear function of the number of payload bytes, as long as we assume a payload of more than 6 bytes for the short address scheme. The jump in the graph for the short address length is caused by the IFS-mechanism. In table 3, the minimum delay is given for the different scenarios. For the maximum payload, the minimum delay is the same for all the scenarios. Indeed, the MPDU is set to the maximum of 127 bytes. However, as can be seen in figure 5, the maximum number of payload bits differs when the short or long address is used.

5 Experimental Results

In order to validate our theoretically obtained maximum throughput, we will measure experimentally the throughput between 2 radios using the IEEE 802.15.4

Table 3. Minimum delay in ms for a payload of zero bits and a payload of a maximum number of bits

nr of address bits		delay (ms)	
		payload = 0 bits	payload = maximum
0 bits	ACK	2.21	6.56
	no ACK	1.66	6.02
16 bits	ACK	2.46	6.56
	no ACK	1.92	6.02
64 bits	ACK	3.30	6.56
	no ACK	2.75	6.02

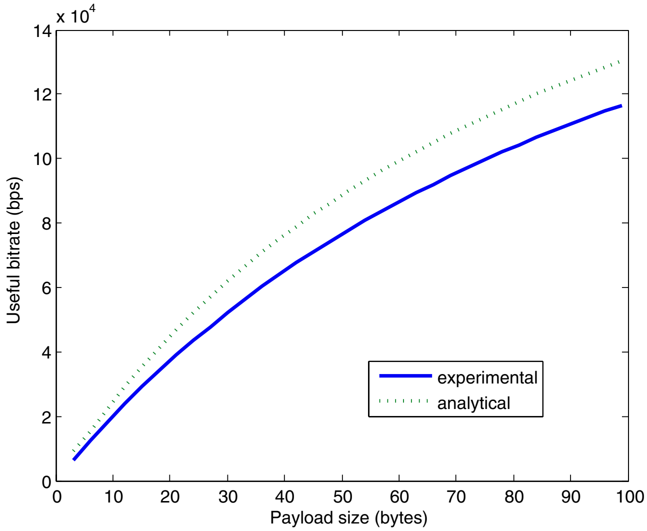


Fig. 6. Comparison between analytical and experimental results when short addressing and acknowledgments are used

specification. For our assays, we have used the 13192 DSK (Developer's Starter Kit) of Freescale Inc. This kit uses the MC13192 radio chip of Freescale Inc. [9]. This radio works at 2.4 GHz and software is included which implements the IEEE 802.15.4–standard. In order to minimize interference caused by other habitants of the 2.4 GHz-band, we have used channel 16 (highest channel) as this channel does not overlap with any of the channels of IEEE 802.11 [6]. Figure 6 gives a comparison between the theoretically and experimentally obtained results when a short address and an acknowledgment is used. We see that the experimental curve is lower than the one obtained analytically. The relative difference between the two curves is steady at about 11 %. However, we notice that the 2 graphs have the same curve. We have fitted the experimental curve with (7) and we obtained the following values for a and b respectively: 0.0000324 and 0.00359. The analytical values can be found in table 1 (16 bit address and ACK used):

0.000032 and 0.00291. We see that the main difference is in the part that is independent of the number of bytes sent. This is an indication that an extra delay or processing time needs to be added to each packet. The duration of this extra delay is about 680 μs (b is expressed in seconds: 0.00359-0.00291 = 0.00068 seconds). Another experiment was done where the long address was used without an ACK. Again a lower throughput than theoretically expected is achieved. Now we have a difference of about 9 %. The fitted values for a and b are 0.00003201 and 0.003271 respectively. As in the previous situation, the extra delay is independent of the number of bits sent and is about 520 μs. The time difference in the two situations is comparable. The extra delay is probably caused by processing the software on the devices.

6 Conclusion

The maximum throughput and minimum delay are determined under the condition that there is only 1 radio sending and 1 radio receiving. The next step in analyzing the performance of IEEE 802.15.4 would be introducing more transmitters and receivers which can hear each other. It is assumed that the maximum overall throughput, i.e. the throughput of all the radios achieved together, will fall as the different radios have to access the same medium. Indeed, this will result in collisions and longer back off periods. This also will cause lower throughput and larger delays. Another issue is the performance of the slotted version of IEEE 802.15.4 and the use of varying duty cycles. This study was done in [7]. As was mentioned in section 2 and 4, IEEE 802.15.4 works in the 2.4 GHz-band, the same band as WiFi (IEEE 802.11) and Bluetooth (IEEE 802.15.1). Consequently, these technologies will cause interference when used simultaneously. The interference between WiFi and 802.15.4 was investigated in [6] and [8]. It was concluded that WiFi interference is detrimental to a WPAN using 802.15.4. However, if the distance between the IEEE 802.15.4 and IEEE 802.11b radio exceeds 8 meter, the interference of IEEE 802.11b is almost negligible.

In this paper, we have presented the exact formulae for determining the maximum theoretical throughput of the unbeaconed version of IEEE 802.15.4. It was concluded this throughput varies according to the number of data bits in the packet and that a maximum throughput of 163 kbps can be achieved. Generally, the bandwidth efficiency is rather low due to the small packet size imposed in the standard.

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References

1. IEEE Std. 802.15.4: IEEE Standard for Wireless Medium Access Control and Physical Layer specifications for Low-Rate Wireless Personal Area Networks, 2003
2. Ed Callaway et al.,"Home Networking with IEEE 802.15.4: A developing Standard for Low-Rate Wireless Personal Area Networks", IEEE Communications Magazine, Vol 40 No. 8, pp 70-77, Aug. 2002
3. José A. Gutierrez, Marco Naeve, Ed Callaway, Monique Bourgeois, Vinay Mitter, Bob Heile, "IEEE 802. 15.4: A developing standard for low-power low-cost wireless personal area networks", IEEE Network, vol. 15, no. 5, September/October 2001 pp. 12-19
4. ZigBee Alliance, www.zigbee.org
5. Xiao Y. and Rosdahl J., "Throughput and delay limits of 802.11", IEEE Communications Letter, Vol. 6, No. 8, August 2002, pp. 355-357
6. Soo Young Shin, Sunghyun Choi, Hong Seong Park, Wook Hyun Kwon, "Packet Error Rate Analysis of IEEE 802.15.4 under IEEE 802.11b Interference", Wired/Wireless Internet Communications 2005, LCNS 3510, May 2005, pp.279-288
7. Jianliang Zheng and Myung J. Lee "Will IEEE 802.15.4 make Ubiquitous networking a reality?: A discussion on a potential low power, low bit rate standard", IEEE Communica-tions Magazine, Vol. 42, No. 6, Jun 2004, pp. 140 - 146
8. N. Golmie, D. Cypher, and O. Rebala, "Performance Evaluation of Low Rate WPANs for Sensors and Medical Applications", Proceedings of Military Communications Conference (MILCOM 2004), Oct. 31 - Nov. 3, 2004
9. Freescale Inc. http://www.freescale.com/ZigBee