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Throughput and Delay Analysis of Unslotted IEEE 802.15.4

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***Abstract*—The IEEE 802.15.4 standard is designed as a low power and low data rate protocol offering high reliability. It defines a beaconed and unbeaconed version. In this work, we analyze the maximum throughput and minimum delay of the unbeaconed or unslotted version of the protocol. First, the most important features are described. Then the exact formula for the throughput and delay of a direct transmission between one sender and one receiver is given. This is done for the different frequency ranges and address structures used in IEEE 802.15.4. The analysis is limited to the unslotted version as this one experiences the lowest overhead. It is shown that the maximum throughput depends on the packet size. In the 2.4 GHz band, a bandwidth efficiency of 64.9% is reached when the maximum packet size is used. Further we describe the influence of the back off interval. A significant gain is found when the backs off parameters are altered. We have measured the throughput experimentally in order to compare the theoretical analysis with real-life examples.**

***Index Terms*— IEEE 802.15.4, multiple access control, performance, throughput**

I. INTRODUCTION

In the last few years, new applications using different kinds of wireless technology are rapidly emerging. These applications all have their proprietary requirements with regard to the required data rate, power consumption, reliability and much more. Hence, several new protocols have been proposed such as IEEE 802.11g, IEEE 802.16 and IEEE 802.15.4. Whereas the first two focus on achieving higher data rates in order to support high bit rate applications, the latter is designed for low data rate and provides high reliability for activities such as controlling and monitoring. These applications generally use simple devices, such as sensors, which are not capable of handling complex protocols as they have limited processing capacities and limited power available. An interesting application is building automation. The building is equipped with wireless devices such as temperature sensors and light switches. These devices are battery operated and consequently require a low power protocol. In addition, the data that needs to be sent over the network is limited to a few kilo bits per second. More application scenarios are defined by the ZigBee Alliance [2] that defines the routing and application layers above the IEEE 802.15.4 standard.

The goal of the IEEE 802.15.4 standard is to provide a low-power, low-cost and highly reliable protocol for wireless connectivity among inexpensive, fixed and portable devices [3][4][5]. These devices can form a sensor network or a Wireless Personal Area Network (WPAN). This last type of network is used for communication among devices (including telephones and personal digital assistants) close to one person. The standard defines a physical layer and a MAC sub layer.

Three different frequency ranges are offered. The most important one is the 2.4 GHz range. This is the same range as 802.11b/g and Bluetooth. Consequently, the issue of interference and thus coexistence between the different wireless technologies will be a significant one, especially as reliability is an important requirement.

The main contribution of this paper is that we analyze the throughput and delay of IEEE 802.15.4, both analytically and experimentally, for various scenarios such as different addresses and frequency bands. The exact formula for direct communication is drawn up. This gives an overview and an easy way to calculate the maximum throughput without the need to completely analyze the standard. All the information needed for obtaining these results can be found in the standard [6]. The paper is an extension of [1] where only the 2.4 GHz range was considered. In this paper, we will also look into the other frequency bands and offer a more thorough analysis, including the influence of the back off window.

Section II of this paper offers a technical overview of the IEEE 802.15.4 standard. An overview of related work, such as other performance studies and interference issues, is given in section III. In section IV, the exact formula for the maximum throughput and minimum delay

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Based on "Maximum Throughput and Minimum Delay in IEEE 802.15.4" by B. Latré, P. De Mil, I. Moerman, N. Van Dierdonck, B. Dhoedt and P. Demeester which appeared in the Proceedings of the International Conference on Mobile Ad-hoc and Sensor Network (MSN'05), Wuhan, China, December 2005 © 2005 LNCS.

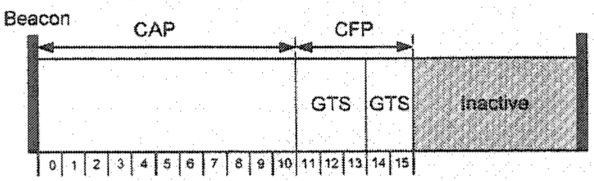

Figure 1. An example of a superframe structure

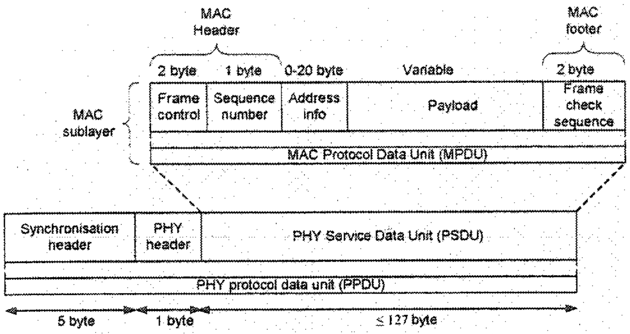

Figure 2. Frame structure of 802.15.4

is presented. The analysis of the results is given in section V and experimental validation is done in section VI. Finally, section VII concludes the paper.

II. DESCRIPTION OF IEEE 802.15.4

The IEEE 802.15.4-standard both defines the physical layer and the medium access layer. For the physical layer, 27 communication channels in three different frequency ranges are defined in the industrial scientific medical (ISM) band: 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. For North America the 915 MHz band is used at a raw data rate of 40 kbps. An overview of the modulation parameters is given in Table I. All of these channels use DSSS. The standard further specifies 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.

An IEEE 802.15.4 network operates either in a beacon enabled mode or in a non beaconed mode. In the beaconless mode, a simple CSMA/CA protocol is used. 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. The beaconed mode uses a superframe structure, see Fig. 1. A superframe starts with beacons sent by a dedicated device, called a coordinator, at predetermined intervals ranging from 15 ms to 251 s. The time between these beacons is split in an active and inactive period. In the inactive period, the device enters a low power mode during which no radio traffic is allowed. Communication between the devices in a PAN (Personal Area Network) only takes place in the active period. The active part is divided in 16 slots of equal size and consists of two groups: the contention access period (CAP) and an optional 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). By changing the duration of the active and inactive period, the PAN can operate under low duty cycle to save energy.

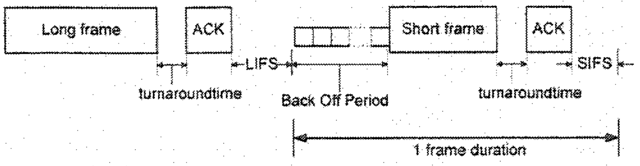

Figure 3. Frame sequence in 802.15.4. We notice the back off period and that long frames are followed by a long inter frame space and short frames by a short inter frame space

TABLE I
MODULATION PARAMETERS OF 802.15.4

Frequency band	Symbol rate (baud/s)	Modulation	Bit rate (kbps)
868.0-868.6 MHz	20 000	BPSK	20
902-928.0 MHz	40 000	BPSK	40
2.4-2.4835 GHz	62 500	16-ary orth.	250

The MAC sub layer supports multiple network 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).

The transmitted frames are followed by an Inter Frame Space (IFS) in order to allow the MAC layer a finite amount of time to process data received from the PHY. Before starting the back off period, the device will wait one IFS. Long frames are followed by a Long IFS (LIFS) and short frames by a Short IFS (SIFS). An example of a frame sequence, using acknowledgments (ACKs), is given in Fig. 2. If no ACKS are used, the IFS follows the frame immediately.

The MAC layer defines either a 64-bit IEEE address or a short 16-bit address assigned during the association period. The packet structure of IEEE 802.15.4 is shown in Fig. 3. 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.

A more thorough description of IEEE 802.15.4 can be found in [6].

III. RELATED WORK

Several papers have addressed the issue of performance analysis in IEEE 802.15.4. These papers mainly focus on the slotted version of IEEE 802.15.4 in a multihop environment or with multiple senders and receivers. The performance evaluation of [7] studies the throughput-energy-delay tradeoffs based on NS-2 simulations. It was found that in low duty networks a significant energy saving can be achieved by using the superframe structure, but these savings come at the cost of significantly higher latency and lower bandwidth. A more complete simulation based performance study was done in [8]. An interesting result is that in a non-beaconed mode and for low rate applications the packet delivery ratio of IEEE 802.15.4 is similar to IEEE 802.11. In [9] it was shown that the optimal network performance for slotted CSMA/CA is reached with an offered load in the range of 35% to 60%.

A more theoretical approach was used in [10] where the network is modeled using discrete Markov chains. The throughput and energy consumption were analyzed in saturation conditions for a varying number of nodes in a star topology. In [11] a similar model is defined that considers more parameters. The results show that the average access delays may be quite high if the throughput exceeds 50%.

This paper will focus on the unslotted version of 802.15.4. The approach is similar as the one used in [12] and [13] for IEEE 802.11. A general formula is drawn up and analyzed.

The frequency band with the most number of channels and highest data rates in IEEE 802.15.4 is the 2.4 GHz-band. This is the same band used by IEEE 802.11 (WiFi) [14] and IEEE 802.15.1 (Bluetooth) [15]. These technologies will cause interference when used simultaneously. The interference between WiFi and 802.15.4 was investigated in [16] and [17]. 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.

IV. CALCULATIONS

A. Assumptions

In this paper, we are interested in the throughput of the MAC-layer as seen in the OSI-protocol stack. Therefore, we define the maximum throughput of IEEE 802.15.4 as the number of data bits coming from the upper layer (i.e. the network layer) that can be transmitted. In these theoretical calculations, we will only examine the unbeaconed version of the protocol (i.e. without the superframes). This version has the least overhead so it will give us an upper bound on the maximum throughput of the protocol. The formula will be valid for the different frequency bands. However, the parameters used will have different values at the different frequencies, see section V.

The maximum throughput is calculated between only one sender and only one receiver which are located close to each other. Hence, 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).

B. 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 Fig. 3, i.e. back off scheme, sending of an acknowledgement… In other words, the delay is the time needed to transmit one 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 Fig. 2. 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 in seconds
$T_{frame}(x)$ = Transmission time for a payload of *x* byte
T_{TA} = Turn around time
T_{ACK} = Transmission time for an ACK
T_{IFS} = IFS time

For the IFS, SIFS is used when the MPDU (= $L_{MAC\_HDR} + L_{MAC\_FTR} + payload$) is smaller than or equal to 18 bytes. Otherwise, LIFS is used.

In the following, we will calculate the different times. The back off period is expressed as follows:

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

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

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: (2^{BE}-1)/2 or 3.5.

The total duration of the frame:

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

TABLE II
VALUES FOR PARAMETERS *A* AND *B* IN EQUATIONS 6 AND 7

# address bits		868 MHz		915 MHz		2.4 GHz	
		a	b	a	b	a	b
0 bits	ACK	0.0004	0.0149	0.0002	0.00745	0.000032	0.002656
	no ACK	0.0004	0.0099	0.0002	0.00495	0.000032	0.002112
16 bits	ACK	0.0004	0.0181	0.0002	0.00905	0.000032	0.002912
	no ACK	0.0004	0.0131	0.0002	0.00655	0.000032	0.002368
64 bits	ACK	0.0004	0.0229	0.0002	0.01145	0.000032	0.003296
	no ACK	0.0004	0.0179	0.0002	0.00895	0.000032	0.002752

(4)

L_{PHY} = Length of the PHY 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

The $L_{ADDRESS}$ 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 1 PAN-identifier is 2 bytes.

The duration of an acknowledgement is calculated as follows:

$$T_{ACK} = 8 * \frac{L_{PHY} + L_{MAC\_HDR} + L_{MAC\_FTR}}{R_{data}} \quad (5)$$

If no acknowledgements are used, $T_{turnaround}$ and T_{ack} are omitted.

Summarizing, we can express the throughput and the delay using the following formulas:

$$TP = \frac{8 \cdot x}{a \cdot x + b} \quad (6)$$

$$delay(x) = a \cdot x + b \quad (7)$$

In this equations, *a* and *b* depends on the length of the data bytes (SIFS or LIFS), the length of the address used (64 bit, 16 bit or no addresses) and the frequency band we are working in. The parameter *a* expresses the delay needed for sending 1 data byte, parameter *b* is the time needed for the protocol overhead for sending one packet.

IV. ANALYSIS

In this section, we analyze the throughput, bandwidth efficiency and delay of IEEE 802.15.4 for a number of different scenarios based on the formula above. These scenarios comprehend the use of the different address lengths (64 bit or 16 bit addresses), the use of acknowledgements (ACKs) or not and the different frequencies.

The following parameters from section III are different in the distinct frequency bands:

$$\begin{array}{lcl} T_{BOslots} & = & 20 \cdot T_S \\ T_{TA} & = & 12 \cdot T_S \\ T_{SIFS} & = & 12 \cdot T_S \end{array} \quad (8)$$

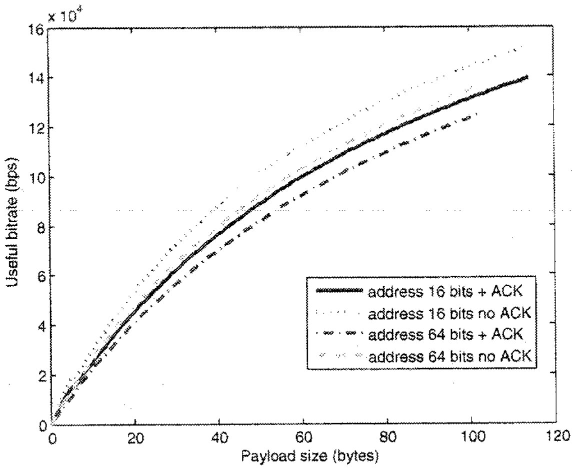

Figure 4. Useful bitrate in function of a varying payload size for the short and long address scheme, with or without ACK. The frequency is 2.4 GHz

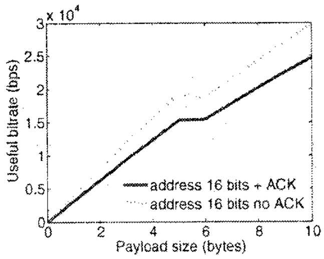

Figure 5. Snapshot of Fig. 4 for an address size of 16 bits. The transition from SIFS to DIFS can be seen clearly

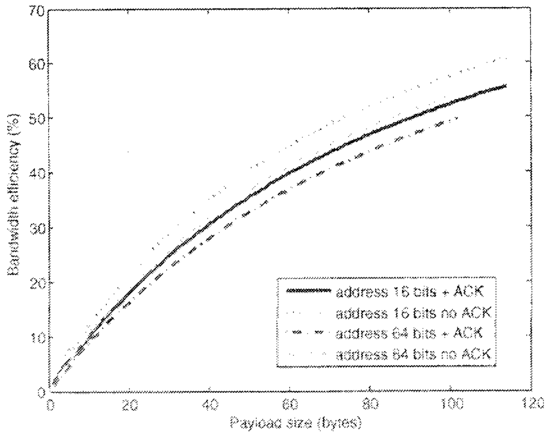

Figure 6. Bandwidth efficiency for a varying payload size. The frequency is 2.4 GHz

TABLE III
MAXIMUM BITRATE AND BANDWIDTH EFFICIENCY

# address bits		868 MHz		915 MHz		2.4 GHz	
		Maximum bitrate (bps)	Maximum efficiency (%)	Maximum bitrate (bps)	Maximum efficiency (%)	Maximum bitrate (bps)	Maximum efficiency (%)
0 bits	ACK	15 322	76.6	30 644	76.6	148 780	59.5
	no ACK	16 627	83.1	33 254	83.1	162 234	64.9
16 bits	ACK	14 317	71.6	28 634	71.6	139 024	55.6
	no ACK	15 537	77.7	31 073	77.7	151 596	60.6
64 bits	ACK	12 810	64.1	25 620	64.1	124 390	49.8
	no ACK	13 901	69.5	27 802	69.5	135 638	54.3

TABLE IV
MINIMUM AND MAXIMUM DELAY

# address bits		868 MHz		915 MHz		2.4 GHz	
		Minimum delay (ms)	Maximum delay (ms)	Minimum delay (ms)	Maximum delay (ms)	Minimum delay (ms)	Maximum delay (ms)
0 bits	ACK	13.5	63.7	6.75	31.85	2.21	6.56
	no ACK	8.5	58.7	4.25	29.35	1.66	6.02
16 bits	ACK	16.7	63.7	8.35	31.85	2.46	6.56
	no ACK	11.7	58.7	5.85	29.35	1.92	6.02
64 bits	ACK	22.9	63.7	11.45	31.82	3.30	6.56
	no ACK	17.9	58.7	8.95	29.35	2.75	6.02

$$T_{LIFS} = 40 \cdot T_S$$

where T_S represents the duration of one symbol. The value of T_S can be derived from Table I for the different frequency bands.

In Table II, the values for a and b are given for the different scenarios, under the assumption that the total packet size is larger than 18 bytes (i.e. LIFS is used). It can be seen that the value of a only depends on the frequency band, which is consistent with the definition of a.

A. Bandwidth efficiency

The bandwidth efficiency is expressed as

$$\eta = \frac{TP}{R_{data}} \tag{9}$$

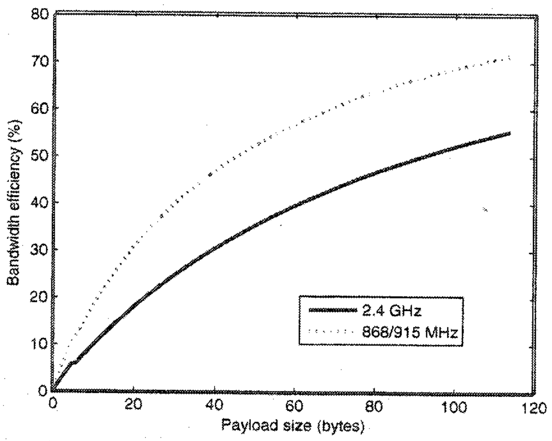

Figure 7. Comparison of the bandwidth efficiency for 2.4 GHz and 868/915 MHz band

We will begin our analysis with the results for the 2.4 GHz band. Fig. 4 gives the number of useful bits and Fig. 6 shows the bandwidth efficiency. In the figures, the payload size represents the number of bits that are received from the upper layer. In section II 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 (i.e. 16 bits), the maximum payload size is 114 bytes. This can be calculated as follows: $MPDU = L_{MAC\_HDR} + L_{ADDRESS} + L_{MAC\_FTR}$, 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. 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 [12-13] 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, Fig. 5, is caused by the transition of the use of SIFS to LIFS: at that precise 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 Fig. 4 and 6 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. They were omitted for reasons of clarity.

Looking at the figures of Table III, we can see that for 2.4 GHz an efficiency of 64.9% can be reached under optimal circumstances, i.e. when no addresses and no acknowledgements are used. 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

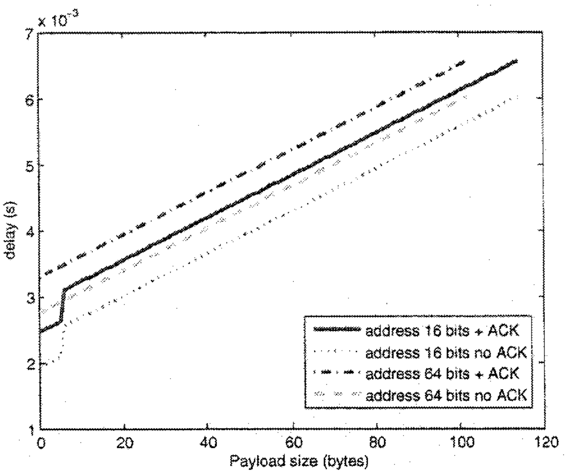

Figure 8. Minimum delay as a function of the payload size. The frequency is 2.4 GHz

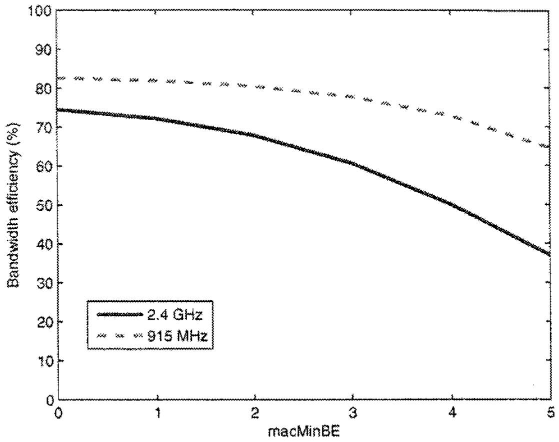

Figure 9. The bandwidth efficiency for different values of *macMinBE* in the 2.4 GHz and 915 MHz band with short addresses and without acknowledgments

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

In the other frequency bands, a similar conclusion can be made. Fig. 7 gives a comparison of the bandwidth efficiency for 2.4 GHz and 868/915 MHz band. A summary can be found in Table III where the maximum bit rate and bandwidth efficiency of the scenarios are given. We see that the bandwidth efficiency is higher for the lower frequency bands and the same for both lower bands. This can be explained as follows. Both bands use BPSK as modulation scheme, see Table I. This means that there is 1 bit per symbol. The 2.4 GHz band on the other hand uses a 16-ary orthogonal modulation with 4 bits per symbol. Some of the time parameters, such as the duration of a SIFS, depend on the duration of 1 symbol, see (8). Thus, as the lower bands only have 1 bit per symbol and the 2.4 GHz band 4 bits per symbol, the proportion of the fixed duration to the amount of information that can be sent is higher in the 2.4 GHz band. Consequently, the bandwidth efficiency will be lower in the highest frequency band.

In the lower frequency bands, an efficiency of 83.1% can be reached when no addresses and no ACK are used. The worst result reaches an efficiency of 64.5%. The data rate obtained in the 868 MHz band is exactly half as much as the one in the 915 MHz. Indeed, the baud rate in the 915 MHz band is twice as high as the one in the 868 MHz band (40 kbaud and 20 kbaud respectively) and in both bands 1 bit per symbol is used.

B. Delay

Fig. 8 gives the minimum delay each packet experiences for varying packet sizes in the 2.4 GHz band. Table IV gives the minimum and maximum delay for the different scenarios. The minimum delay is calculated by sending a packet without any data bits immediately from 1 sender to 1 receiver. In other words, the minimum delay is the time needed to send and process an empty packet in a single hop environment. The propagation delay is not taken into account and no retransmissions are assumed. 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 10 bytes. The jump in the graph for the short address length is caused by the IFS-mechanism. The same behavior is found for the other frequency band.

The maximum delay is found by sending a full packet, i.e. the MPDU is set to the maximum of 127 bytes. This means that the maximum payload is independent of the number of address bits. However, as can be seen in Fig. 8, the maximum number of payload bits differs when the short or long address is used. We see that the maximum delay is a little bit higher than 6 ms in the 2.4 GHz region when a full packet is sent. This delay is acceptable for delay bound applications. The lower bands experience a significant higher delay, which is to be expected as the data rate is lower. In these frequency bands it is more important to look to the minimum delay, especially in the 868 MHz band. These figures can offer a more thorough insight in the limitations of IEEE 802.15.4 when designing and implementing a network based on this protocol. For example, if one plans to use the 868 MHz band in order to lower the coexistence issues, it is important to know the minimum delay bounds.

C. Influence of back off window

The IEEE 802.15.4 protocol uses CSMA/CA. This means that when a device wants to transmit data, the device waits for a random number of back off periods before trying to access the channel. The back off time is randomly generated in the interval $[0, 2^{BE}-1]$, see section IV. The maximum value of BE is 5, which means that the number of back off slots is limited to 31. This is significantly lower than the maximum number of 1023 back off slots in IEEE 802.11 [14]. This will influence the network throughput when multiple radios are used as collisions will be more likely due to the small back off interval.

The initial value of BE at the first back off is called *macMinBE* and has a default value of 3. However, this value can be altered in the range of [0,5]. When *macMinBE* is set to 0, no collision avoidance is done in the first attempt to access the channel.

The *macMinBE* value has a significant influence on the bandwidth efficiency. Fig. 9 shows the bandwidth efficiency for the frequency bands of 2.4 GHz and 915 MHz. 16 bit addresses are used without acknowledgement. When the *macMinBE* is set to 0, an efficiency of 74.5% is reached (or 186 270 bps), when set to 5, the efficiency is only 37.0% (or 92 532 bps). The default case resulted in an efficiency of 60.6%, see Table II. The difference is quite large. If we look at the scenario where no addresses are used and without acknowledgement, we see an efficiency of 79.7 % when no collision avoidance is used. In the default case, only 64.9% was reached, Table II. Therefore, it is interesting to lower the *macMinBE* value when only one sender and receiver are used. Further, it can be seen that the 2.4 GHz suffers more from an increasing value of *macMinBE*. This behavior is expected as the 2.4 GHz band uses more bits per symbol.

Now let's consider a scenario with multiple senders and receivers. In dense networks with high traffic loads, a lot of collisions will occur and the nodes will back off several times. The maximum back off time is 31 and is reached after 2 back offs if the default value is used and after 5 back offs when no collision avoidance is done on the first attempt. Consequently, most of the nodes will have the maximum back off interval and the influence of differentiating the *macMinBE* will be limited. The (aggregated) throughput of the nodes will decrease due to the large back off interval. In low density networks, the probability of a collision will be significantly lower. Therefore it would be interesting to lower the *macMinBE* in such scenarios.

V. EXPERIMENTAL RESULTS

In our analysis above, we have determined the theoretical throughput of IEEE 802.15.4. In this section, we compare this analysis with experimental results. We have measured the throughput between two radios that use the IEEE 802.15.4 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. [18]. The radio operates at 2.4 GHz and libraries are included which implement the IEEE 802.15.4-standard. We used the highest channel (channel 26) as this channel does not overlap with any of the channels of IEEE 802.11 [14]. This way we minimize the interference caused by the 802.11 radio transmission. This channel does still overlap with the Bluetooth spectrum [15]. However, Bluetooth uses a frequency hopping technique, so the interference will be limited to a short time. Therefore we have measured over a period of 1 day. Although we have tried to minimize the interference, not all of the packets were received correctly. Consequently, some of the packets needed to be retransmitted. This not only causes an extra delay due to the second transmission, but also an increase of the size of the back off window. This mechanism will negatively influence the experimental throughput. We have placed the sender and receiver 1 meter apart at a height of 1 meter.

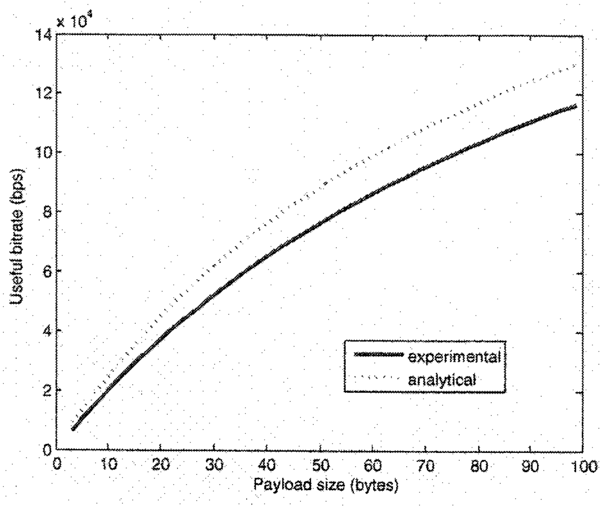

Figure 10. Comparison between analytic result and experiment

Fig. 10 gives a comparison between the theoretically and experimentally obtained results when a short address and an acknowledgement are used. Once again, we varied the number of payload bytes. We see that the experimental curve is lower than the one obtained analytically. This is to be expected as the theoretical analysis offers an upper bound to the throughput. We further notice that the 2 graphs have the same curve. The relative difference between the two curves is steady at about 11 %. We have fitted the experimental curve with (6) and obtained the following values for *a* and *b* respectively: 0.0000324 and 0.00359. The theoretical values can be found in table II (16 bit address and ACK used). It can be seen that the main difference is to be found 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 s).

We also measured the throughput for the scenario where long addresses are used without acknowledgments. Again a lower throughput than theoretically expected is achieved. Now we see a difference of about 9%. The fitted values for *a* and *b* are 0.00003201 and 0.003721 respectively. The extra delay is about 520 μs and once again independent of the number of bits sent. The time difference between the two scenarios is comparable. The experimental results match better when no ACKs are used. This is to be expected as no retransmissions will occur when packets get lost.

This allows us to conclude that the difference between the experimental and theoretical results is mainly due to delays caused by the electronics of the radios used and the occurrence of retransmissions.

VI CONCLUSION

The maximum throughput and minimum delay were determined under the condition that there is only one radio sending and one 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 which will result in collisions and longer back off periods. This also will result in lower throughput and larger delays.

We have presented the exact formula for determining the maximum throughput of the unbeaconed version of IEEE 802.15.4 for different frequency bands and scenarios. It was concluded that the throughput varies with the number of data bits in the packet. In the 2.4 GHz band a maximum throughput of 163 kbps or an efficiency of 64.9% can be achieved. The other frequency bands offer a higher efficiency, but a lower effective throughput. By changing the back off exponent, a higher throughput can be obtained. It is concluded that the bandwidth efficiency is rather low due to the small packet size imposed in the standard.

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