Performance of UWB Systems using a Temporal Detect-and-Avoid Mechanism

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Abstract— **According to the draft versions of the European and Japanese regulation authorities, UWB systems have to use detect and avoid (DAA) mechanisms to avoid interference with existing wireless services. Since most existing wireless services such as GSM, WLAN, and Bluetooth transmit their data burst-wise, we propose UWB transmission between adjacent bursts of such systems. Thus, not only interference from UWB systems is avoided but also interference to them. We refer to this kind of DAA mechanism as *temporal DAA*. Because the time of UWB transmission is reduced with such an approach, we investigate the performance of UWB systems using temporal DAA. Based on time domain measurements of different interference scenarios we show that with UWB still reasonable data rates are achieved and strict latency time requirements can be met.**

I. Introduction

Currently, the ECC and the Japanese regulatory authorities are working towards UWB regulations [1], [2]. Different from the regulations made by the FCC [3] in the USA a detect and avoid (DAA) mechanism is envisaged in Europe and in Japan that mitigates interference to existing wireless services. Since UWB coexistence and interference issues are very important, there exist several publications in this area. Up to now, most investigations of coexistence issues concern the interference of UWB devices on existing services, such as [4], [5]. There exist also some publications considering the impact of existing system's interference on UWB systems, such as [6], [7]. But only in few publications, such as in [8], [9], interference mitigation techniques are considered.

General interference mitigation methods, which are not limited to UWB only, are presented in [10]. There, collaborative and non-collaborative coexistence mechanisms are proposed. In the collaborative scenario, different wireless systems are able to share information and negotiate channel access. In the non-collaborative scenario, different systems do not have the ability to coordinate their transmission. There, wireless systems can only use strategies such as carrier sense multiple access (CSMA) or adaptive frequency hopping. The disadvantage of such strategies is that the channel is not used to its maximum efficiency. However, since existing services are usually not collaborating, we consider the non-collaborative approach as more promising for UWB systems and use it as basis for our considerations.

The IEEE 802.15 subgroups recently started to work on DAA mechanisms. According to [11] and [12] both subgroups 3a and 4a envision a frequency domain approach for DAA. Different from these approaches we propose to use the temporal cognitive medium access, which was presented in [13] as interference avoidance mechanism for UWB body area networks (BAN), as DAA mechanism in time domain. There, the UWB system detects any other active wireless system with a kind of receive signal strength indicator (RSSI). The UWB system transmits in the time between adjacent bursts of existing wireless systems where the channel is not occupied. Thus, coexistence between existing wireless services and UWB can be established on cost of throughput and latency time of the UWB system.

To determine the performance of a UWB system whose transmission time is limited by such a temporal DAA, we investigate UWB pulse rates and latency times achievable with the temporal cognitive MAC based on time domain measurements of existing wireless systems. Moreover, expressions for the achievable pulse rate, which directly translates into throughput, and for the optimum UWB packet length are derived. For the determination of reasonable interference scenarios we assume a BAN where both UWB transmitter and receiver are placed at the human body such as shown in [14]. Based on the different interference scenarios we show that reasonable UWB pulse rates can be achieved with the temporal DAA. Investigating the UWB packet delays, it is shown that UWB systems using the temporal DAA are able to meet strict latency time requirements with the optimum UWB packet length.

II. Considered Interferers

In this paper, we consider GSM, BT, and IEEE 802.11b WLAN as interferers. In Fig. 1, normalized time domain signals of GSM, BT, and WLAN are depicted. As expected from standards, BT and GSM show a periodic burst structure while WLAN does not exhibit such a periodicity. Nevertheless, for all burst interferers, segments between adjacent burst can be observed where the channel is not occupied. To avoid interference between UWB and existing wireless services that are active at the same time, we propose UWB transmission in the time between adjacent interferer bursts. We refer to this approach as *temporal DAA*.

In the following, we assume that the channel has two different states: occupied or idle. If the channel is occupied, no UWB transmission is possible, i.e., UWB transmission is only possible if the channel is idle. This determination of idle times can be done in real systems by a kind of RSSI. Since in a BAN both transmitter and receiver are in close vicinity, they

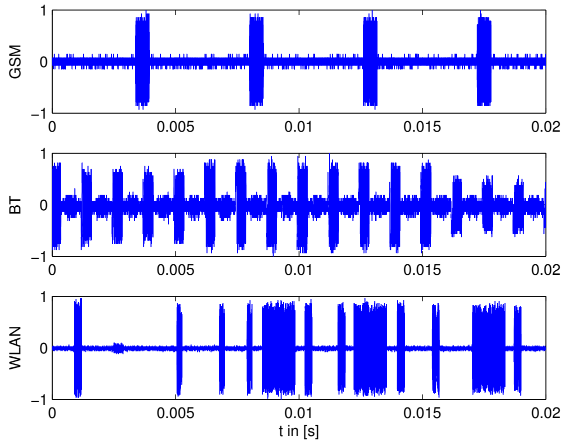

Fig. 1. Measured time domain signals of GSM, BT, and WLAN

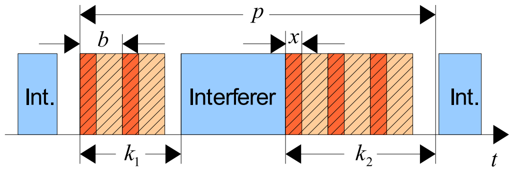

Fig. 2. Scheme to determine the maximum pulse rate with interfering bursts (solid) and UWB packets (lined)

detect an interferer almost at the same time. For evaluation of the UWB performance using temporal DAA, we measure the interference with a real time sampling oscilloscope.

III. Temporal DAA

In Fig. 2, one exemplary channel occupancy is shown. We assume that the UWB device has a sleep mode. After wake up the UWB device senses the channel with a kind of RSSI and directly transmits its data if the channel is not occupied by any interferer. Then, the UWB device has to transmit its data in a given latency time p. Each UWB packet has a packet duration b. Within each UWB packet (diagonal lined in Fig. 2), a preamble of duration x is present, e.g., used for synchronization issues. The number of unoccupied time slots N in a given latency time is determined by the interferers burst structure and the latency time, e.g., $N = 2$ for the example in Fig. 2. The duration of the ith unoccupied time slot is given by k_i. For this investigation we assume that we are transmitting pulses with a pulse rate that both FCC peak and average power limit are fulfilled. Thus, the pulse repetition frequency is limited to 1Pulse/μs [15], i.e., the maximum achievable pulse rate without interference is 1 MPulse/s. Since UWB pulse widths are below 2ns not only the UWB receiver but also the UWB transmitter can eavesdrop for any interferer in the time between two transmit pulses using a RSSI. Thus, a DAA mechanism in time domain can be established avoiding interference from UWB to existing wireless systems.

Based on the assumptions above, the following expression for the average pulse rate $r(b)$ can be achieved:

$$r(b) = \frac{b-x}{p} \cdot E\left\{\sum_{i=1}^{N} \left\lfloor \frac{k_i}{b} \right\rfloor\right\} \tag{1}$$

where $\lfloor\cdot\rfloor$ rounds the argument to the next smaller integer. The expectation $E\{\cdot\}$ is taken over different channel realizations. Division by p leads to a normalized pulse rate in Pulses/s. It can be seen that the packet length b has strong impact on $r(b)$. On one hand, the number of pulses per packet $b-x$ increases with b, on the other hand, the number of packets per empty slot time $\lfloor \frac{k_i}{b} \rfloor$ decreases with increasing packet length. This shows that there exists an optimum packet length that yields the maximum pulse rate.

Since (1) is discontinuous, it is not possible to determine the optimum UWB packet length by calculation of the derivative. Therefore, we derive an approximation for the achievable pulse rate. $\lfloor\cdot\rfloor$ can be written as

$$\left\lfloor \frac{k_i}{b} \right\rfloor = \frac{k_i}{b} - c \tag{2}$$

with $c \in [0, 1)$. Setting $c = 0$, an upper bound for the pulse rate in (1) can derived as

$$r_{\text{max}}(b) = \frac{b-x}{p} \cdot E\left\{\sum_{i=1}^{N} \left(\frac{k_i}{b}\right)\right\}. \tag{3}$$

This corresponds to having an integer number of UWB packets with packet length b plus one packet with a reduced packet length $b' = c{\cdot}b$ in each empty slot of duration k_i, i.e. the whole time between interferer bursts is used for UWB transmission. Please note, that the preamble of this variable packet also scales with its packet length b'. The corresponding packet placement is shown exemplarily in Fig. 3 a).

A lower bound for the pulse rate in (1) can be achieved by setting $c = 1$.

$$r_{\text{min}}(b) = \frac{b-x}{p} \cdot E\left\{\sum_{i=1}^{N} \left(\frac{k_i}{b} - 1\right)\right\} \tag{4}$$

In this case always the whole idle time less the time for one UWB packet is used for UWB transmission. Corresponding to the example in Fig. 3 a), the packet placement for the lower bound is shown in Fig. 3 b). As well as for the upper bound, the preamble length of the variable packet scales here, too. Instead of considering the maximum and minimum value of c, we assume now a uniform distribution of c in $[0, 1)$, i.e., $E\{c\} = \frac{1}{2}$. This means that half a UWB packet per idle time slot is lost in average. Using this expectation value, an approximation for the achievable pulse rate in (1) is given by

$$r_{\text{approx}}(b) = \frac{b-x}{p} \cdot E\left\{\sum_{i=1}^{N} \left(\frac{k_i}{b} - \frac{1}{2}\right)\right\} \tag{5}$$

We use $r_{\text{approx}}(b)$ to calculate the derivative and to determine the optimum UWB packet length. We find the optimum from

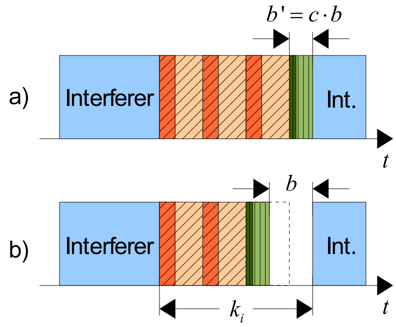

Fig. 3. UWB packet distribution in an unoccupied slot of duration k_i, a) using $r_{\max}(b)$ from (3), and b) using $r_{\min}(b)$ from (4); Interferer bursts are plotted solid, UWB packets are plotted diagonal lined, and fractional UWB packets are vertical lined

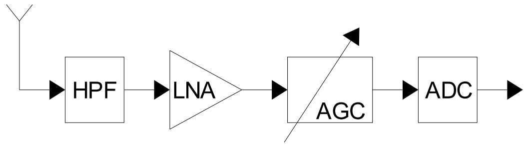

Fig. 4. Receiver model for clipping considerations

(5) as:

$$\begin{aligned} \frac{dr_{\text{approx}}}{db} &= \frac{\bar{N}E\{k_i\}x}{p\,b^2} - \frac{\bar{N}}{2p} = 0 \\ \Rightarrow \frac{\bar{N}}{2p} &= \frac{\bar{N}E\{k_i\}x}{p\,b^2} \\ \Rightarrow b &= \pm\sqrt{2E\{k_i\}x} = b_{\text{opt}} \end{aligned} \tag{6}$$

$\bar{N}$ denotes the mean value of N. In (6), only the positive solution for the UWB packet length makes sense. It can be seen that the preamble length x and the expectation over the length of idle time slots k_i determine the optimum UWB packet length. Although p is not explicitly contained in the expression for b_{opt} in (6) it is implicitly contained in $E\{k_i\}$. Hence, the latency time p has an impact on the optimum packet length if p is smaller than the usual idle time between two interfering bursts.

IV. Sphere of Interference

To determine reasonable interference scenarios we evaluate the minimum distances between existing systems and a UWB device where the interference to the UWB device is not harmful. If the instantaneous signal power of an interferer is too high, the UWB receiver suffers from clipping and no UWB transmission is possible. For this evaluation we assume the receiver model in Fig. 4. This model consists of a high pass filter (HPF), a low noise amplifier (LNA), an automatic gain control (AGC) and an analog-to-digital converter (ADC) with 6 bit resolution. We assume that 3 bit are used for the desired UWB signal while the remaining 3 bit are a reserved for noise and interference, until the receiver suffers from clipping. The LNA and the AGC are assumed to be perfect and do not cause any clipping. The AGC amplifies the desired UWB receive signal in such a way that it fits best into the desired 3 bit

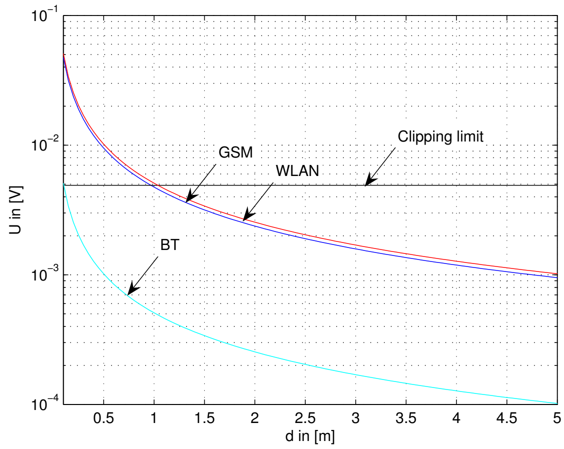

Fig. 5. Signal amplitudes of interferers at the UWB receiver considering free space attenuation and a 5th order Butterworth filter with $f_l = 3.1$GHz

range of the ADC. If the input signal of the ADC exceeds the 6 bit resolution due to an interference signal, the ADC suffers from clipping and no UWB signal can be resolved. Otherwise, we assume that a UWB signal can be detected by signal processing if the ADC is not clipping. Based on the assumptions above, the ADC is clipping for any noise or interference signal that is larger than seven times the desired signal amplitude.

In Fig. 5, signal amplitudes of BT, GSM, and IEEE 802.11b WLAN are shown for distances up to $d = 5$ meters. Each system is transmitting with its maximum allowed transmit power. Only free space attenuation is assumed for the interferers and a 5th order Butterworth high pass with $f_l = 3.1$GHz in the UWB receiver. Assuming a UWB system with $B = 500$MHz bandwidth the maximum transmit power in the peak power limit is $P_{\text{TX},500} = 10$dBm [3]. If we assume an attenuation of 60dB for the UWB signal, which is reasonable for the ear-to-ear link [16], the receive signal power $P_{\text{RX},500} = -50$dBm. This corresponds to a signal amplitude of 0.7mV @ 50 Ω and thus to a clipping limit of 4.9mV. This clipping limit is exceeded by the interferer amplitudes only for distances below 1m as shown in Fig. 5. Thus, considering BAN applications only devices in the direct environment of a person are possible interferers.

V. Performance Evaluation

In this section, we investigate the performance of a UWB system with the temporal DAA as described in Section III. We consider GSM, BT, IEEE 802.11b WLAN, and a combination of these three interferers, which we refer to as meeting room scenario. Based on time domain measurements of these interference scenarios we evaluate data rates for the UWB system using the expressions given in Section III. It is assumed that each UWB packet contains a preamble of $x = 100\mu$s duration. For each interference scenario we show the measured pulse rate $r(b)$ and the approximation $r_{\text{approx}}(b)$. For completeness, the lower bound $r_{\min}(b)$ and the upper bound $r_{\max}(b)$ are also given. Since in particular for speech transmission strict latency time limits have to be fulfilled, we moreover investigate the time that UWB packets are delayed when another wireless system is active. Therefore, the time delay between wake up of the UWB device and the beginning of the next successful transmitted UWB packet is shown for different packet lengths. We consider 50%, 10%, and 1% outage-delay as well as the maximum occurred delay, which corresponds to a 0% outage. At the outage delays a certain percentage of all packets has a delay less than the given one. For example, the 1% outage-delay means that 99% of all UWB packets are transmitted successfully with a delay less than the determined. All following evaluations are based on time domain measurements of the interference (see Fig. 1).

A. GSM

In Fig. 6 and Fig. 7, the pulse rates are shown for UWB if it is interfered by one GSM device assuming a latency time of $p = 2$ms and $p = 5$ms, respectively. The pulse rates are determined by applying the pulse rate equations given in Section III on 10000 randomly chosen measurement samples of duration p. It can be seen that $r(b)$ lies for all UWB packet lengths between the lower bound $r_{\text{min}}(b)$ and the upper bound $r_{\text{max}}(b)$. The approximation $r_{\text{approx}}(b)$ in Fig. 6 follows the trend of $r(b)$. The steps and the zigzag behavior of $r(b)$ are caused by the latency time $p = 2$ms. Since GSM is transmitting a burst of 577μs duration every 4.6ms the channel is idle during the latency time of 2ms for a number of measurement samples, i.e., in many cases 2ms long UWB packets can be transmitted without collision. For packet lengths $b = \frac{p}{k}, k \in \mathbb{N}$, $r(b)$ exhibit steps. At these packet lengths, increasing the packet length slightly, one packet less can be transmitted in a given empty slot, which decreases the pulse rate notably.

In Fig. 7, the pulse rates are shown for a latency time of $p = 5$ms. There, the influence of the latency time is smaller since the pulse rate is dominated by the GSM burst structure, which has an idle time of 4.1ms. Thus, it can be seen that no UWB packets longer than this time can be transmitted. Up to the packet length of 4.1ms $r_{\text{approx}}(b)$ fits $r(b)$ well. Since the maximum idle time is now longer than for $p = 2$ms the pulse rates and the optimum packet length are higher. For a latency time of $p = 2$ms, the maximum pulse rate of 583 kPulses/s is achieved with $b_{\text{opt,2ms}} = 544\mu$s long UWB packets and for $p = 5$ms the maximum pulse rate of 639 kPulses/s is achieved with $b_{\text{opt,5ms}} = 693\mu$s.

The evaluation of the time delays is also based on time domain measurements of the interference. 10000 wake up times of the UWB device are chosen randomly. For each wake up time, the time delay between wake up and the beginning of the next successful transmitted UWB packet is determined. We do not consider that further UWB packets might be transmitted without any delay after the first successful transmission in an idle time slot. Such a consideration would result in lower time delays. Thus, the time delays shown in Fig. 8 for different packet lengths can be regarded as worst case. It can be seen that the delays increase linearly with increasing packet length. The maximum delay is given if a UWB packet slightly does not fit into the idle time slot before a GSM burst, i.e. the maximum delay is about $b + 577\mu$s. This results in a linear

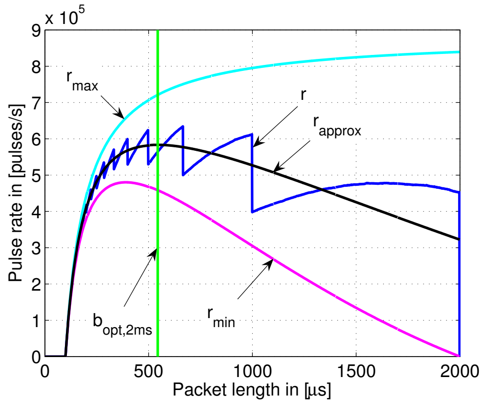

Fig. 6. Achievable UWB pulse rate with one GSM interferer present, assuming $p = 2$ms and $x = 100\mu$s

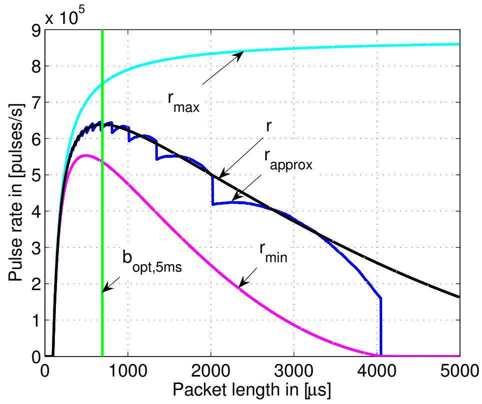

Fig. 7. Achievable UWB pulse rate with one GSM interferer present, assuming $p = 5$ms and $x = 100\mu$s

increase of the time delays with increasing packet length. The packet delays for $b_{\text{opt,5ms}}$ are higher compared to $b_{\text{opt,2ms}}$. The maximum delays at $b_{\text{opt,2ms}}$ and $b_{\text{opt,5ms}}$ are about 1120μs and 1269μs, respectively. About 1% of all packets have a delay close to the maximum delay. However, due to the long idle times in GSM, the 50% outage shows that 50% of all packets shorter than about 1800μs are transmitted without any delay and longer packets are only slightly delayed.

B. BT

Due to the periodical BT burst structure the assumption $E\{c\} = \frac{1}{2}$ is not fulfilled for BT interference. However, in the range of short packet lengths, where the optimum packet length is located, $r_{\text{approx}}(b)$ and $r(b)$ match well as shown in Fig. 9. In presence of a BT interferer the maximum pulse rate of 371 kPulses/s can be achieved using packets of 372μs duration. The pulse rate is mainly influenced by the burst structure, i.e. for packets longer than 884μs the pulse rate drops to 0 because it is not possible to transmit any UWB packets. This limit is given by the maximum idle time of BT, which has a repetition time of 1250μs and a burst length of 366μs.

Therefore, also the packet delays in Fig. 10 are only plotted up to a packet length of 884μs. For shorter packet lengths the curves exhibit a linear increase since the maximum delay is

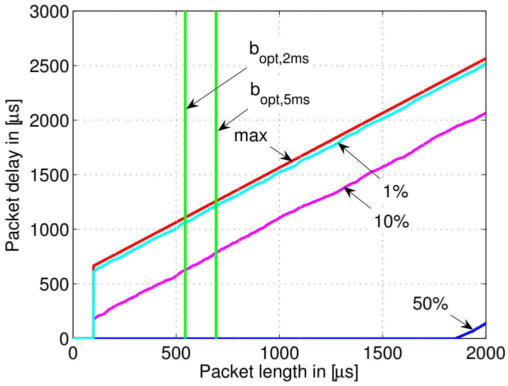

Fig. 8. Packet delays with one GSM interferer present

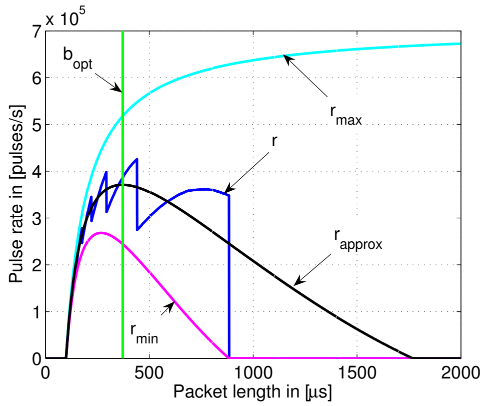

Fig. 9. Achievable UWB pulse rate with one BT interferer present, assuming $p = 2\text{ms}$ and $x = 100\mu\text{s}$

here given approximately by the maximum BT burst length plus the respective packet length, i.e. $b + 366\mu$s. The maximum delay at b_{opt} is 737μs. As well as for GSM 1% of all packets have a delay close to the maximum delay. Since BT bursts are shorter than GSM bursts also the maximum time delays are shorter compared to GSM but the shorter repetition time of BT bursts leads to a larger number of UWB packets that are delayed. Thus, the 50% outage delay at b_{opt} is 105μs. Only for UWB packets shorter than about 270μs the 50% outage delay shows no delays.

C. WLAN

The measured pulse rates for WLAN, which are shown in Fig. 11, do not exhibit such a zigzag behavior as the ones for GSM and BT. This is due to the non-periodic burst structure of WLAN. Due to this fact also the assumption $E\{c\} = \frac{1}{2}$ holds and $r_{\text{approx}}(b)$ and $r(b)$ match very well. Nevertheless, the maximum pulse rate of 364 kPulses/s, which can be achieved with packets of 407μs duration, is close to the pulse rate that can be achieved when a BT device is interfering.

Due to the non-periodic burst structures of WLAN the packet delays are not anymore linear increasing with the packet length as it can be seen in Fig. 12 and it can happen that a packet is delayed for a relatively long time. Using UWB packets with the optimum packet length b_{opt} the maximum

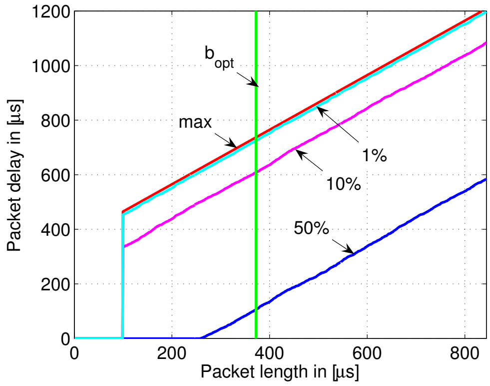

Fig. 10. Packet delays with one BT interferer present

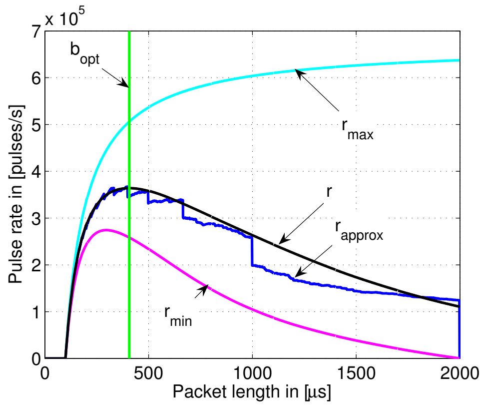

Fig. 11. Achievable UWB pulse rate with one WLAN interferer present, assuming $p = 2\text{ms}$ and $x = 100\mu\text{s}$

delay is about 4697μs but increasing the packet length only slightly the maximum time delay increases substantially. Since the measurement samples have a duration of only 10ms it can be observed that some packets with duration longer than about 550μs cannot be transmitted with a delay of 10ms or less. For packet lengths of 929μs and 1218μs even 1% and 10% of all packets cannot be transmitted with a delay of 10ms or less, respectively.

D. Meeting room scenario

Since in many cases not only one interferer is present we also consider a meeting room scenario with 3 GSM connections, 1 WLAN downlink, 2 WLAN uplinks, and 1 BT connection active at the same time. This is a reasonable maximum number of interferers inside a sphere with radius of 1m around the UWB device mounted at the body. Thus, the meeting room scenario can be regarded as a worst case scenario. Since the interferers are not synchronized the pulse rates decrease compared to the cases where only one interferer is present as shown in Fig. 13. Due to the repetition time of BT bursts the maximum packet length is here also limited to 844μs. Up to this packet length $r_{\text{approx}}(b)$ and $r(b)$ match well. The maximum pulse rate of about 169 kPulses/s can be achieved with a packet length of 303μs. Since the interferers are not synchronized the channel idle times are not periodic

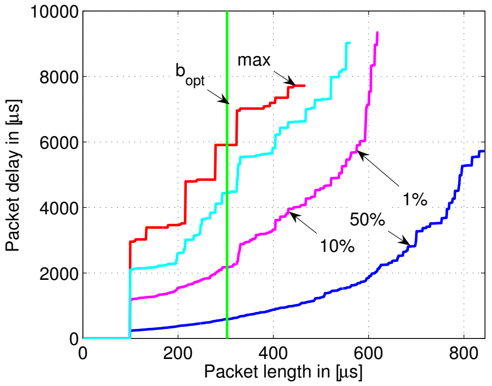

Fig. 14. Packet delays with three GSM, three 802.11b WLAN, and one BT interferer present at the same time

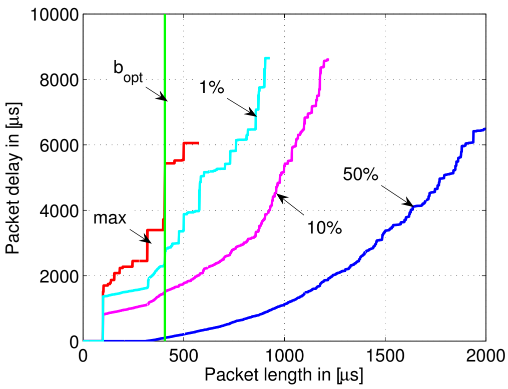

Fig. 12. Packet delays with one WLAN interferer present

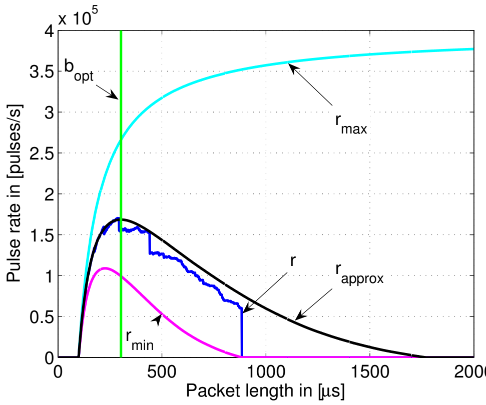

Fig. 13. Achievable UWB pulse rate with three GSM, three 802.11b WLAN, and one BT interferer present at the same time, assuming $p = 2$ms and $x = 100\mu s$

and the idle times are shorter than in the cases of only one active interferer. Hence, packet lengths are shorter and pulse rates are smaller than in the previous cases.

The non-synchronicity of the interferers causes also longer packet delays as shown in Fig. 14. It can be observed that the delays are much higher than in the cases when only one interferer is present. The maximum delay at b_{opt} is $5910\mu s$ while the 50% outage delay is $591\mu s$. It can be observed that some packets with duration longer than about $470\mu s$ cannot be transmitted with a delay of 10ms or less. 1% and 10% of all packets cannot be transmitted with a delay less than 10ms if the packet lengths are $563\mu s$ and $621\mu s$, respectively.

VI. Conclusions

In this paper, we proposed to use a temporal DAA mechanism for interference avoidance between existing wireless systems and UWB. An expression for the achievable UWB pulse rate in presence of burst interferers was presented. Using an approximation of this expression, we showed that the optimum UWB packet length is only determined by the preamble length, the expectation of the empty slot durations, and the latency time. It could be observed that the optimum UWB packet length decreases with increasing occupied time of the channel. Although, UWB systems with temporal DAA are allowed to transmit only during a fraction of the whole time, we showed that reasonable pulse rates and outage delays were achieved with GSM, BT, and WLAN as interferers as well as for a meeting room scenario.

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