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Performance analysis of uncoordinated Medium Access Control in Low Data Rate UWB networks

(Invited paper)

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***Abstract*— Impulse Radio Ultra Wide Band (IR-UWB) is gaining consensus within the recently formed IEEE 802.15.4a Task Group as a solution for providing combined communication and ranging in low data rate indoor/outdoor networks.**

In this work we propose a solution for Medium Access Control in low data rate IR-UWB networks that uses the specific features of IR-UWB and enables location-based network optimizations by providing and storing estimates of the distance between network terminals.

The performance of the protocol as a function of channel characteristics, transmission range, number of users and user data rates is evaluated by means of simulations, taking into account an accurate MUI model based on the concept of Pulse Collision. Results highlight that in all considered scenarios the protocol provides high throughput and low packet delay, and constitutes thus a viable solution for location-aware low data rate UWB networks.

***Index Terms*— Ultra Wide Band, MAC, Low Data Rate**

I. Introduction

The concept of ad-hoc networking gathered in the last few years an increasing interest, as it opens the way to new network scenarios and applications, that were precluded to traditional, infrastructure-based, wireless networks.

Within the ad hoc networking context, sensor networks are nowadays a hot research topic, due to the growing request for low data rate, low cost networks for mixed indoor/outdoor scenarios. The interest towards low data rate networks led in 2003 to the definition of the IEEE 802.15.4 standard for low rate, low complexity, low power wireless networks [1]. The 802.15.4 standard also forms the basis of the ZigBee technology, aiming at providing a comprehensive solution for low data rate networking, from physical layer to applications [2].

Both IEEE 802.15.4 and ZigBee are however unable to satisfy a key requirement in future applications of low data rate sensor networking, that is the capability of locate objects and people by means of distributed, infrastructure-independent positioning algorithms.

The introduction of positioning capability in low data rate networks is indeed the main goal of the recently formed IEEE 802.15.4a Task Group [3]. In the framework of such Task Group, Impulse Radio Ultra Wide Band (IR-UWB) radio emerged as an appealing solution [4]. Several features of UWB make this technology particularly attractive for indoor and outdoor low data rate wireless networks:

- The high temporal resolution inherent to IR-UWB, that provides high robustness in presence of multipath, thus allowing communications even in presence of several obstacles and in conditions of Non-Line-Of-Sight (NLOS) propagation.
- The accurate ranging capability, also provided by the high temporal resolution of IR-UWB signals, offering distance information that can be used to derive information on physical position of terminals in the network.

The above features derive from the key characteristic of IR-UWB signals, i.e. the use of a bandwidth that spans over several GHz in the range of frequencies going from 0 to 10 GHz.

The very same features that suggest the adoption of UWB as the basis for future location-aware, low data rate networks call for novel solutions at higher layers as well. The Medium Access Control protocol, in particular, must take into account UWB characteristics in order to efficiently support location-based applications.

In this work we propose a solution for Medium Access Control in low data rate IR-UWB networks that uses the specific features of IR-UWB and enables location-based optimizations of the network algorithms by evaluating and storing distance estimates, making them available for positioning and routing algorithms. A Multi User Interference (MUI) model specific for IR-UWB, based on the concept of collision between pulses, is then introduced. This MUI model is used to evaluate the performance of the proposed MAC protocol by means of simulations, as a function of channel characteristics, network size and user bit rates.

The paper is organized as follows. Section II introduces the proposed MAC protocol and the ranging scheme; Section III presents the Pulse Collision MUI model. Performance evaluation of the MAC protocol is carried out in Section IV, while Section V draws conclusions.

II. THE $(UWB)^2$ MAC PROTOCOL

The high temporal resolution of IR-UWB signals mentioned in the previous Section has the beneficial side effect of providing a strong robustness to MUI, in particular for low data rate applications [4]. As a consequence, the access to the medium in low data rate UWB networks can be heavily simplified. The most straightforward solution is an Aloha-like solution, as investigated in [5], [6]. The adoption of an Aloha-like approach would also increase the adaptability of the MAC to low cost solutions for UWB physical layer, since it does not rely on specific PHY functions, such as Carrier Sensing, and could thus adapt without significant changes to different PHY solutions.

In this approach, devices transmit in an uncoordinated fashion, relying on the resilience to MUI offered by UWB for achieving correct reception in presence of multiple simultaneous links.

With regard to the duty cycle of emitted signals, low data rate scenarios usually lead to an average Pulse Repetition Period (PRP), that is the average time between two consecutive pulses emitted by a device, in the order of $10^{-4}/10^{-5}$ s, with an average duration of emitted pulses typically on the order of 10^{-10} s. Theoretical duty cycle of the signals can be thus as low as 10^{-6}. A detailed analysis of this issue requires however the introduction of a channel model, in order to take into account the effect of propagation on the duration of the pulses.

Furthermore, if Time Hopping (TH) is the selected coding technique, TH – Code Division Multiple Access (TH-CDMA) is a natural choice for multiple access. The adoption of TH-CDMA can introduce an additional degree of freedom, since the effect of pulse collisions is further reduced by the adoption of different codes on different links.

Under this hypothesis, two components cooperate in determining the robustness of to MUI:

- Low duty cycle of emitted signals
- Association of different TH-Codes to different links.

These considerations led to the definition of the Uncoordinated, Wireless, Baseborn protocol for UWB ($(UWB)^2$) MAC protocol, based on the combination of ALOHA with TH-CDMA. In the following, we will provide a brief description of the $(UWB)^2$ MAC protocol; a detailed description can be found in [6].

$(UWB)^2$ is a multi-channel MAC protocol. Multi-channel access protocols have been widely investigated in the past, since the adoption of multiple channels may significantly increase the achievable throughput. CDMA, in particular, is a well-known solution for designing multi-channel MAC protocols for wireless networks, and its application to ad hoc networking has been widely investigated [7], [8].

A key issue in the application of CDMA strategy to ad hoc networks is the code assignment algorithm. An overview of possible code assignment solutions is provided in [9]:

1. Common code scheme: all terminals share the same code, and code collisions are avoided thanks to phase shifts between different links.
2. Receiver code scheme: each terminal has a unique code for receiving, and the transmitter uses the code of the intended receiver for transmitting a packet.
3. Transmitter code scheme: each terminal has a unique code for transmitting, and the receiver switches to the code of the transmitter for receiving a packet.
4. Hybrid scheme: a combination of the above schemes.

$(UWB)^2$ adopts a hybrid scheme, based on the combination of a Common code for signaling and Transmitter codes for data transfers. This solution has the advantage of allowing an increased multiple access capability if compared to the cases of Common and Receiver TH-Code, while still allowing a terminal to listen on a single TH code in the idle mode.

Furthermore, the exchange of packets between transmitter and receiver in order to set-up the data transmission can enable a simple ranging procedure, based on a three way exchange. During set-up, transmitter Tx and receiver Rx set up a DATA packet transmission by exchanging a Link Establishment (LE) packet transmitted on the Common Code, followed by a Link Confirm (LC) packet transmitted on the Transmitter Code of the receiver Rx, and finally by the DATA packet on the Transmitter Code of transmitter Tx. This handshake allows the determination of the distance Tx-Rx to both the devices involved in the communication.

It should be noted that, even in the case TH-CDMA is not adopted, the low duty cycle of emitted signals could by itself guarantee the requested robustness to MUI. This possibility should be taken into account especially for very low-cost devices (such as RF Tags), for which very simple solutions, such as On-Off Keying (OOK) without TH-CDMA are a suitable option.

Note that, in the hypothesis of not having TH-CDMA, the LE/LC/DATA handshake for the exchange of information on the adopted TH-code described above would be no longer mandatory. Nevertheless, the handshake would still be required in order to support the ranging procedure, in combination with a solution for the management of ranging information. Such solution can be described as follows. Each terminal i maintains a ranging database for all neighboring terminals; each entry of the database contains the ID j of the neighbor, the estimated distance to j, and a timestamp indicating the time at which the estimation was performed. An example of the database is presented in Table I.

TABLE I - EXAMPLE OF RANGING DATABASE

Neighbor ID	Distance (m)	Timestamp (s)
1	3.57	25.627
4	2.45	21.354
...	...	...
2	7.23	22.126

Whenever a terminal i exchanges a DATA packet with a neighbor j, i searches the database in order to check the two following conditions:

1. The ID of j is present in the database, i.e. a distance estimation was performed in the past;
2. If condition 1. is met, the corresponding distance estimation is up-to-date, based on the corresponding timestamp.

If either of the two conditions is not met, i initiates the LE/LC handshake, and the distance estimation is eventually updated.

The above ranging management solution introduces the support for ranging at the MAC layer, offering a database of distances that can be used by upper layers, for example for positioning purposes.

Both the handshake procedure and the ranging management solution were implemented in the MAC, and their impact is taken into account in the simulation results presented in Section IV.

III. BER EVALUATION UNDER THE PULSE COLLISION MODEL

In this section, we will provide an analytical expression of the average BER for a receiver affected by the presence of both thermal noise and MUI, that will be used in the performance evaluation carried out in Section IV. We assume that the reference transmitter adopts IR-UWB signals employing Pulse Position Modulation (PPM) in combination with Time Hopping (TH) coding for transmitting a binary sequence **b** towards the reference receiver. A general flat AWGN channel is assumed for modelling propagation. Reference transmitter and receiver are assumed to be perfectly synchronized. The channel output is corrupted by thermal noise and MUI generated by N_i interfering and asynchronous IR-UWB devices. The received signal at the receiver input writes:

$$s_{RX}(t) = r_u(t) + r_{mui}(t) + n(t) \tag{1}$$

where $r_u(t)$, $r_{mui}(t)$, and $n(t)$ are the useful signal, MUI, and thermal noise, respectively. As regards $r_u(t)$, one has:

$$r_u(t) = \sqrt{E_u}\sum_j p_0\left(t - jT_S - \theta_j - \varepsilon b_{\lfloor j/N_S \rfloor} - \tau\right) \tag{2}$$

where $p_0(t)$ is the energy-normalized waveform of the transmitted pulses, E_u is the received energy per pulse, T_S is the average pulse repetition period, $0 \le \theta_j < T_S$ is the time shift of the j-th pulse provoked by the TH code, ε is the PPM shift, b_x is the x-th bit of **b**, N_S is the number of pulses transmitted for each bit, and $\lfloor x \rfloor$ is the lower integer part of x. As regards $r_{mui}(t)$, we assume that all interfering signals are characterized by same T_S, and thus:

$$r_{mui}(t) = \sum_{n=1}^{N_i}\sqrt{E^{(n)}}\sum_j p_0\left(t - jT_S - \theta_j^{(n)} - \varepsilon b_{\lfloor j/N_j^{(n)} \rfloor} - \tau^{(n)}\right) \tag{3}$$

where $E^{(n)}$ and $\tau^{(n)}$ are received energy per pulse and delay for the n-th interfering user, respectively. The relative delay $\Delta\tau^{(n)}=\tau-\tau^{(n)}$ is assumed to be a random variable uniformly distributed between 0 and T_S. The terms $\theta_j^{(n)}$, $b_x^{(n)}$ and $N_S^{(n)}$ in Eq. (3) are the time shift of the j-th pulse for user n, the x-th bit generated by user n, and the number of pulses per bit for the n-th transmitter, respectively. Both TH codes and data bit sequences are assumed to be randomly generated and correspond to pseudo noise sequences, that is, $\theta_j^{(n)}$ terms are assumed to be independent random variables uniformly distributed in the range $[0,T_S)$, and $b_x^{(n)}$ values are assumed to be independent random variables with equal probability to be "0" or "1". Finally, signal $n(t)$ in Eq. (1) is Gaussian noise, with double-sided power spectral density $\mathcal{N}_0/2$.

The optimum single-user receiver for the above system model is formed of a coherent correlator followed by a ML detector [4]. In every bit period, the correlator converts the received signal of Eq. (1) into a decision variable Z, which forms the input of the detector. Soft decision detection is performed, that is, the signal formed by N_S pulses is considered as a single multi-pulse signal. The received signal is thus cross-correlated with a correlation mask that is matched with the train of pulses representing one bit. The input of the detector Z, for a generic bit b_x, can be thus expressed as follows:

$$\begin{aligned} Z = & \int_{xN_S T_S+\tau}^{(x+1)N_S T_S+\tau} s_{RX}(t)\cdot \\ & \cdot \sum_{j=xN_S}^{(x+1)N_S}\left(p_0\left(t - jT_S - \theta_j - \tau\right) - p_0\left(t - jT_S - \theta_j - \tau\right)\right)dt \end{aligned} \tag{4}$$

By introducing signal $s_{RX}(t)$ as in Eq.(1) into Eq.(4) we recognize that the decision variable consists of three independent terms, that is: $Z=Z_u+Z_{mui}+Z_n$, where Z_u is the signal term, Z_{mui} is the MUI contribution, and Z_n is the noise contribution, which is a Gaussian variable with zero mean and variance $\sigma_n^2= N_S\mathcal{N}_0\gamma(\varepsilon)$, where $\gamma(\varepsilon)=1-R_0(\varepsilon)$, and where $R_0(\varepsilon)$ is the autocorrelation function of the pulse waveform $p_0(t)$ [4]. Bit b_x is estimated by comparing the Z term in Eq. (4) with a zero-valued threshold according to the following rule: when Z is positive decision is "0", when Z is negative decision is "1". By observing that the signal term Z_u is:

$$Z_u = \begin{cases} +N_S\sqrt{E_u}\gamma(\varepsilon) & for\ b=0 \\ -N_S\sqrt{E_u}\gamma(\varepsilon) & for\ b=1 \end{cases} \tag{5}$$

one has that for independent and equiprobable transmitted bits the average probability of error on the bit at the output of the detector is $BER = Prob\{Z<0|b=0\} = Prob\{Z_{mui}<-y\}$, where $y= Z_{mui}+Z_n$ is a Gaussian random variable with mean $N_S\sqrt{E_u}\gamma(\varepsilon)$ and variance $N_S\mathcal{N}_0\gamma(\varepsilon)$. Such probability can be evaluated by first computing the conditional BER for a generic y value, and by then averaging over all possible y values, that is:

$$BER = \int_{-\infty}^{+\infty} \Pr ob\{Z_{mui} < -y \mid y\} p_Y(y) dy \qquad (6)$$

where $p_Y(y)$ is the Gaussian probability density function of y.

Following the approach presented in [10] $Prob(Z_{mui}<-y|y)$ can be expanded in order to take into account collisions between pulses of different transmissions. One obtains:

$$BER = \sum_{n=0}^{N_S N_i} P_C(n) \int_{-\infty}^{+\infty} \Pr ob\{Z_{mui} < -y \mid y, n\} p_Y(y) dy \qquad (7)$$

where $P_C(n)$ is the probability of having n collisions at the receiver input among the pulses transmitted by the reference user, and the pulses transmitted by the interfering users. For independent interferers, $P_C(n)$ can be expressed through the binomial distribution:

$$P_C(n) = \binom{N_S N_i}{n} (P_0)^n (1 - P_0)^{N_S N_i - n} \qquad (8)$$

where P_0 is the probability that an interfering device produces a colliding pulse within a single T_S. Under the hypothesis that the pulse width T_M is much smaller than the average pulse repetition period T_S, one can assume $P_0 = (2T_M + \varepsilon)/T_S$, that is, P_0 is computed as the fraction of T_S during which the presence of an interfering pulse and produce non-zero contributions to Z_{mui}. As regards $Prob(Z_{mui}<-y|y,n)$, one can adopt the linear approximation suggested in [10] that is:

$$\Pr ob(Z_{mui} < -y \mid y, n) = \begin{cases} 1 & \text{for } \; y \le -\zeta(n) \\ 1 - \dfrac{P_C(n)}{2}\left(1 + \dfrac{y}{\zeta(n)}\right) & \text{for } \; \zeta(n) < y \le 0 \\ \dfrac{P_C(n)}{2}\left(1 - \dfrac{y}{\zeta(n)}\right) & \text{for } \; 0 < y \le \zeta(n) \\ 0 & \text{for } \; y > \zeta(n) \end{cases} \qquad (9)$$

where:

$$\zeta(n) = \sum_{j=1}^{N_i} \left(\left\lceil \frac{N_C - j + 1}{N_i} \right\rceil \sqrt{E_S^{(j)}} \right) \qquad (10)$$

and $E_S^{(1)}$, $E_S^{(2)}$, ..., $E_S^{(Ni)}$ are the interfering energies $E^{(1)}$, $E^{(2)}$, ..., $E^{(Ni)}$ of Eq. (3), sorted in descending order, that is $E_S^{(j)} \ge E_S^{(j+1)}$ for $j \in [1, N_i - 1]$.

By substituting the linear expression in Eq. (9) into Eq. (7), one obtains the following approximate expression for the average BER at receiver output:

$$\begin{aligned} \text{BER} \approx \; & \frac{1}{2} erfc\left(\sqrt{\frac{1}{2} \frac{N_S E_u}{\mathcal{N}_0} \gamma(\varepsilon)} \right) \\ & + \sum_{n=0}^{N_i N_S} \frac{P_C(n)}{2} \Omega\left(\frac{N_S E_u}{\mathcal{N}_0} \gamma(\varepsilon), \frac{\zeta(n)^2}{N_S \mathcal{N}_0 \gamma(\varepsilon)} \right) \end{aligned} \qquad (11)$$

where:

$$\begin{aligned} \Omega(A, B) = \; & \frac{1}{2} erfc\left(\sqrt{\frac{A}{2}} - \sqrt{\frac{B}{2}} \right) \\ & + \frac{1}{2} erfc\left(\sqrt{\frac{A}{2}} + \sqrt{\frac{B}{2}} \right) - erfc\left(\sqrt{\frac{A}{2}} \right) \end{aligned} \qquad (12)$$

The BER expression in Eq. (12) includes a first term that only depends on signal to thermal noise ratio at the receiver input, and a second term accounting for MUI. The proposed approach was demonstrated in [10] to guarantee high accuracy in estimating receiver performance, even in the presence of scarcely populated systems, or systems with dominating interferers, or low-rate systems.

IV. PERFORMANCE ANALYSIS

The $(UWB)^2$ protocol described in Section II was tested by means of simulations, using a UWB network simulator developed in the framework of the OMNeT++ environment [11].

The channel module in the simulator implements the path loss model proposed by Tarokh and Ghassmezadeh in [12]. This model takes into account the effect of shadowing and foresees both Line Of Sight (LOS) and Non Line Of Sight (NLOS) propagation; the path loss is given by the formula:

$$\begin{aligned} PL\big|_{dB} = \; & PL_0 + 10\mu_\gamma \log_{10}(d) + 10 n_1 \sigma_\gamma \log_{10}(d) + \\ & + n_2 \mu_\sigma + n_2 n_3 \sigma_\sigma \end{aligned} \qquad (13)$$

where PL_0 is the path loss at 1 meter from the transmitter and n_1, n_2 and n_3 are Gaussian variables; he values assumed by the parameters μ_γ and σ_γ define the statistical characteristics of the path loss exponent while μ_σ and σ_σ model the effect of shadowing. The values for path loss and shadowing parameters are reported in Table II.

TABLE II - VALUES OF PATH LOSS PARAMETERS PROPOSED IN [12]

Parameter	Value (LOS)	Value (NLOS)
PL_0	47 dB	51 dB
μ_γ σ_γ	1.7±0.3	3.5±0.97
μ_σ σ_σ	1.6±0.5	2.7±0.98

The UWB network simulator was used to analyze the performance of $(UWB)^2$ as a function of the following system parameters:

- Channel characteristics (LOS vs NLOS)
- Number of terminals
- Transmission range
- Transmission rate

Furthermore, in all simulations we compared the pure, slot-free Aloha strategy with a slotted Aloha strategy. This comparison was motivated by the fact that, as well known, in narrowband networks slotted Aloha guarantees a higher (up to two times) throughput with respect to pure Aloha, thanks to a lower probability of packet collision.

Our goal was to verify if this large performance gap is also present in low bit rate UWB networks, where the negative impact of packet collisions is mitigated by the high processing gain.

The main settings used during simulations are provided in Table III.

TABLE III - SIMULATION SETTINGS

Parameter	Setting
Number of nodes:	From 5 to 25
Area:	50 m × 50 m
Network physical topology:	Random topology
Channel model:	See eq. (13) and [12]
User bit rates:	From 10 kb/s to 100 kb/s
Transmission range:	30 m, 50 m, 70 m (full coverage)
Transmission rate over the wireless channel:	1 Mb/s
Packet generation model:	Poisson generation process, uniform distribution for destination node
DATA packet length:	2000 bits (+ 100 bits for Sync trailer)
Interference Model:	Pulse Collision (see section III)
Physical layer settings	$N_s = 10$, $T_s = 10^{-5}$ s $T_m = 1$ ns No FEC
Performance indicators	Throughput, Delay

With reference to Table III, note that:

1. The transmission range is not defined as a hard limit between perfect reception and no reception at all. More realistically, the range is defined as the maximum distance over which a given QoS requirement is met. In particular, we define the range as the maximum distance at which, in average, a BER equal to 10^{-6} is achieved in presence of thermal noise. This corresponds, for each transmission range and channel scenario, to a nominal transmit power value P_{TX}.

   The transmit power values corresponding to the transmission ranges considered in Table III are given in Table IV for both LOS and NLOS channel scenarios.

TABLE IV - TRANSMIT POWER CORRESPONDING TO TRANSMISSION RANGES

R_{TX}	P_{TX} (LOS)	P_{TX} (NLOS)
30 m	$8.39*10^{-6}$ (-20.8 dBm)	$8.64*10^{-3}$ (9.4 dBm)
50 m	$2.17*10^{-5}$ (-16.6 dBm)	$6.12*10^{-2}$ (17.9 dBm)
70 m	$3.98*10^{-5}$ (-14 dBm)	$2.13*10^{-1}$ (23.3 dBm)

2. Note that in NLOS conditions even the shortest transmission range considered requires a transmit power that cannot be achieved by UWB devices compliant to FCC regulation [13]. Nevertheless, we performed simulations in the NLOS scenario to determine the effect of a higher path loss (that is of a higher path loss exponent) on the behavior of the network in terms of generated MUI.
3. In order to focus the analysis on scenarios where MUI is the predominant source of errors, packet transmissions are only allowed between terminals that are within transmission range; this assures that for each packet the received power is high enough to meet the QoS requirements in absence of interference.
4. The performance indicators are defined as follows:
   - Throughput – ratio between correctly received packets and transmitted packets (each retransmission of the same packet is considered as a new transmission).
   - Delay – difference between the time when the packet is inserted in the transmission queue at the transmitter and the time when the correct reception of the packet ends: the delay includes thus waiting time in the queue, propagation delay, backoff intervals between subsequent retransmission attempts, and packet transmission time for each transmission attempt.

The results of simulations comparing the performance of the proposed MAC in LOS vs. NLOS scenarios as a function of the number of terminals are presented in Fig. 1 and Fig. 2, showing throughput and delay respectively. The results were obtained considering a bit rate R = 10 kb/s.

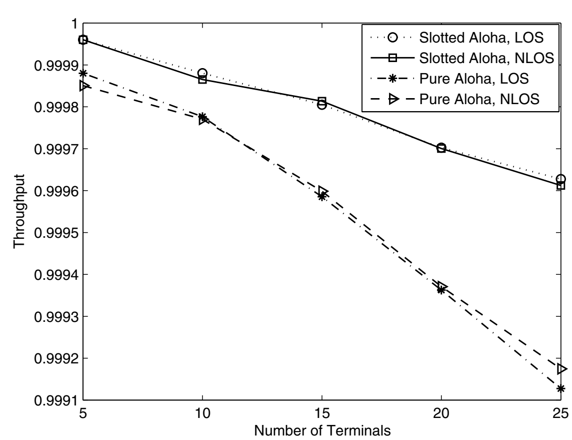

Fig. 1. Throughput as a function of number of terminals for a full connectivity scenario (R_{TX} = 70 m) with User bit rate R =10 kb/s (Circle: Slotted Aloha, LOS channel; Square: Slotted Aloha, NLOS channel; Diamond: Pure Aloha, LOS channel; Triangle: Pure Aloha, NLOS channel).

Fig. 1 shows that both Slotted Aloha and Pure Aloha lead to very high Throughput in these conditions. Although slotted Aloha leads to a slightly higher value of throughput, the difference is quite small, in the order of 0.05%. This confirms that for low data rates UWB networks the MUI resilience guaranteed by Impulse radio UWB is good enough to potentially allow for reliable transmissions, since the negative of packet collisions is significantly mitigated. As one could expect, the gap between the two strategies increases as the number of terminals (and as a consequence the offered traffic) increases. Also note in Fig. 1 that LOS and NLOS scenarios are characterized by comparable results: this is justified by the fact that in both scenarios the P_{TX} power is selected accordingly to the values reported in Table IV. As a consequence, in both scenarios MUI is the main cause of packet errors, while the effect of noise is negligible; since the BER floor defined by MUI can be considered to be independent by the transmit power, as long as the ratios between transmit power levels of all terminals are kept constant, the two scenarios are characterized by similar throughput values.

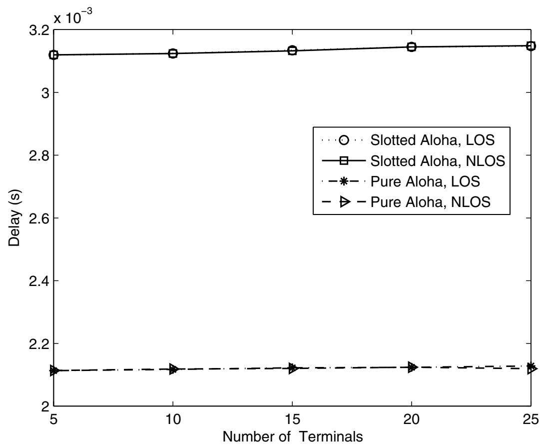

Fig. 2. Delay as a function of number of terminals for a full connectivity scenario (R_{TX}= 70 m) with User bit rate R=10 kb/s (Circle: Slotted Aloha, LOS channel; Square: Slotted Aloha, NLOS channel; Diamond: Pure Aloha, LOS channel; Triangle: Pure Aloha, NLOS channel).

Fig. 2 shows the delay for the same simulation settings and indicates that the slotted Aloha approach leads in average to a higher delay. This is due to the fact that in Pure Aloha a packet is sent immediately, as soon as it is inserted in the queue, and thus in case of low packet error rates, the delay is limited to the packet transmission time over the channel. Oppositely, in the case of Slotted Aloha the packet remains in average a time $T_{SLOT}/2$ in the queue, where T_{SLOT} is the duration of the slot, waiting for the beginning of the first slot after the insertion in the queue (the first useful for transmitting the packet). This accounts for the difference of about 1 ms in the average delay between the two strategies, remembering that we chose packet of 2000 bits, with a transmission time over the channel $T_{TRANSMIT} \cong T_{SLOT} \cong 2$ ms. The result confirms thus that, in the conditions considered in these simulations, the processing gain guaranteed by UWB is high enough to manage the traffic without appreciable effects of MUI.

We also analyzed the impact of different user bit rates on network performance, focusing on a topology composed of 5 nodes. We compared the slotted Aloha and the pure Aloha approach for two different user bit rates: R = 10 kb/s and R = 100 kb/s. The throughput obtained in these simulations is shown in Fig. 3 as a function of the transmission range.

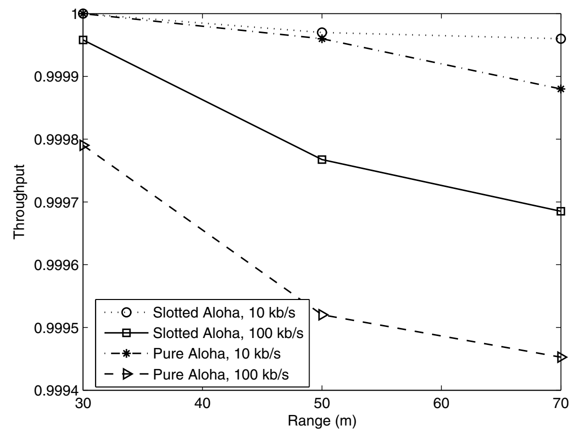

Fig. 3. Throughput as a function of transmission range in a LOS scenario (Circle: Slotted Aloha, R = 10 kb/s; Square: Slotted Aloha, R = 100 kb/s; Diamond: Pure Aloha, R = 10 kb/s; Triangle: Pure Aloha, R = 100 kb/s).

Fig. 3 shows that the increase in the user bit rates has a significant effect on network performance, since it increases the offered traffic and thus moves the network closer to the limits of the Aloha approach. In particular, it can be observed that the pure Aloha approach is more sensible to this effect, since it has a lower capacity of accepting high traffic loads. The impact of a higher offered traffic is also highlighted by the higher delay experienced by packets, as shown in Fig. 4, presenting the delays measured in the same simulation runs. Again, the delay increase is proportionally higher in the case of the pure Aloha strategy.

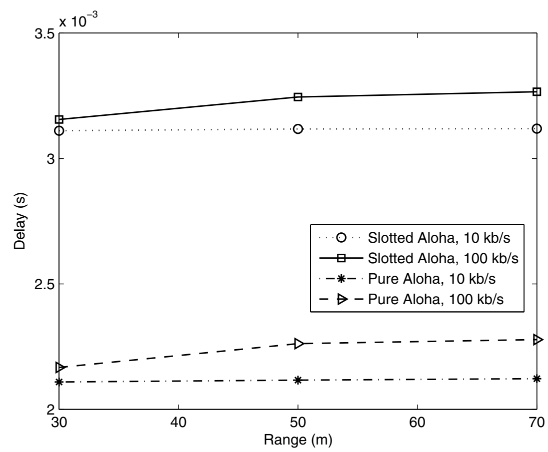

Figure 4. Throughput as a function of transmission range in a LOS scenario (Circle: Slotted Aloha, R = 10 kb/s; Square: Slotted Aloha, R = 100 kb/s; Diamond: Pure Aloha, R = 10 kb/s; Triangle: Pure Aloha, R = 100 kb/s).

V. Conclusion

In this work a MAC protocol for low data rate, location-aware Impulse Radio UWB networks is proposed. The protocol adopts an Aloha-like approach for medium access, combined with CDMA guaranteed by the use of Time Hopping codes. The protocol can operate in either a slot-free (pure) or a slotted fashion, thus guaranteeing a high adaptability to both centralized and distributed network architectures. The protocol also includes a ranging procedure in order to enable location-based protocols at the higher layers.

The performance of the protocol in both pure and slotted modes of operation was evaluated by means of simulations, taking into account an accurate MUI model based on the concept of Pulse Collision. Throughput and packet delay were analyzed as a function of channel characteristics, number of users and user data rates. Simulation results show that the slotted version of the protocol provides a slightly higher throughput, balanced however by the lower delay guaranteed by the pure version. Results highlight that in all considered scenarios the protocol provides high throughput and low delays in both pure and slotted modes, and constitutes thus a viable solution for UWB low data rate networks.

Acknowledgment

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