EMC Europe Workshop 2005: Electromagnetic Compatibility of Wireless Systems, September 19 – 21 2005, Rome, Italy.

Uncoordinated Access to the Wireless Medium for UWB Ad-Hoc Networks

Luca De Nardis, Maria-Gabriella Di Benedetto
School of Engineering, University of Rome La Sapienza
Infocom Department, Via Eudossiana, 18 – 00184 Rome, Italy
email: {lucadn, dibenedetto}@newyork.ing.uniroma1.it

Abstract—**In this paper, we propose to adopt an uncoordinated medium access strategy for application in UWB low data rate ad-hoc networks. The specific case of impulse radio transmission format is considered, where radiated signals are baseband and formed by sequences of very short pulses of energy.**

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.

The proposed medium access strategy takes advantage of the specific features of impulse radio such as accurate and robust ranging.

The strategy is tested by simulating a network of IR-UWB nodes with settings that are typical of a low data rate framework. The system integrates an IR-UWB specific multi user interference model based on the concept of pulse collision. Results indicate that the proposed method leads to high throughput and low packet delay, and forms therefore a valid approach to the design of the medium access module in low data rate UWB networks.

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

I. INTRODUCTION

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 [1]. The 802.15.4 standard also forms the basis of ZigBee, aiming at providing a comprehensive solution for low data rate networking, from physical layer to applications [2].

Both IEEE 802.15.4 and ZigBee lack a key feature for low data rate sensor networks, that is the capability of locating entities by means of distributed, infrastructure-independent positioning algorithms.

The IEEE 802.15.4a Task Group has as its main goal in introducing the positioning capability in low data rate networks [3]. Within this framework, Impulse Radio Ultra Wide Band (IR-UWB) radio is a favored solution [4].

The most attractive features of IR-UWB for both indoor and outdoor low data rate applications are: the high temporal resolution inherent to this method, and the accurate ranging capability. These features derive from the ultra wide bandwidth that spans over several GHz. These very same features suggest the design of specific medium access strategies and protocols.

In this paper, we propose a medium access strategy for application in low data rate IR-UWB networks. A Multi User Interference (MUI) model specific for IR-UWB, based on the concept of collision between pulses, is integrated in the system model. The strategy is tested by simulating a network of IR-UWB nodes with settings that are typical of a low data rate framework.

The paper is organized as follows. Section II introduces the proposed MAC protocol and corresponding ranging scheme. Simulations are described in Section III and discussed in Section IV.

II. UNCOORDINATED ACCESS TO THE WIRELESS MEDIUM

The high temporal resolution of IR-UWB signals inherently provides a strong robustness to MUI, in particular for low data rate applications [4]. We suggest that in this context medium access can be heavily simplified. A straightforward approach can be based on the Aloha paradigm, as investigated in [5], [6].

According to the Aloha 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.

When Time Hopping (TH) coding is adopted, TH – Code Division Multiple Access (TH-CDMA) is a natural choice for multiple access. The adoption of TH-CDMA may introduce an additional degree of freedom, since the effect of pulse collisions might be further reduced by the adoption of different codes on different links. Under this hypothesis, two components cooperate in determining robustness to MUI: low duty cycle of emitted signal and 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. We summarize below the $(UWB)^2$ MAC protocol. For a detailed description see [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 to ad hoc networks is the code assignment algorithm. An overview of possible code assignment methods can be given as follows [9]:

Portions of this work will be presented at the 1^{st} IEEE/CreateNet International Workshop on "Ultrawideband Wireless Networking," Boston, MA, USA, October 7, 2005.

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.

Note that, also when TH-CDMA was not adopted, the low duty cycle of emitted signals could by itself guarantee 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-coding are a suitable option. We therefore tested the proposed method also with no TH-coding, that is when robustness to MUI is only determined by the processing gain offered by impulse radio.

When TH-CDMA is not implemented, the LE/LC/DATA handshake for the exchange of information described above is no longer mandatory. In any case, the handshake is still required to support ranging. We therefore implemented a procedure by which each terminal *i* stores a ranging database for all its neighbors; 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. A database example 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 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 one of these 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, offering a database of distances that can be used by upper layers, for example for positioning purposes.

III. DESCRIPTION OF SIMULATION

The (UWB)^2 protocol described in Section II above 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 Ghassemzadeh 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:

$$\begin{aligned} PL\big|_{dB} &= PL_0 + 10\mu_\gamma \log_{10}(d) + 10 n_1 \sigma_\gamma \log_{10}(d) + \\ &+ n_2 \mu_\sigma + n_2 n_3 \sigma_\sigma \end{aligned} \qquad (1)$$

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 taken from [12].

The UWB network simulator was used to analyze the performance of (UWB)^2 as a function of channel characteristics (LOS vs NLOS) and number of terminals.The main settings used during simulations are presented in Table II.

TABLE II
SIMULATION SETTINGS

Parameter	**Setting**
Number of nodes:	From 5 to 25
Area:	50 m × 50 m
Network topology:	Random topology
Channel model:	See eq. (1) and [12]
User bit rates:	10 kb/s
Transmission range:	70 m (full coverage)
Transmission rate over the 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
Physical layer settings	$N_s = 10$, $T_s = 10^{-5}$ s, $T_m = 1$ ns No FEC

With reference to Table II, 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 channel scenario to a nominal transmit power value P_{TX}. The transmit power values corresponding to the transmission range considered in Table II are given in Table III for both LOS and NLOS channel scenarios.

TABLE III
TRANSMIT POWER CORRESPONDING TO TRANSMISSION RANGE AND CHANNEL SETTINGS

R_{TX}	P_{TX} (LOS)	P_{TX} (NLOS)
70 m	$3.98 \cdot 10^{-5}$ (-14 dBm)	$2.13 \cdot 10^{-1}$ (23.3 dBm)

2. Note that in NLOS conditions even the considered transmission range requires a transmit power that cannot be achieved by UWB devices compliant to FCC regulation [13]. Nevertheless, we performed simulations using the NLOS scenario to determine the effect of a higher path loss (and in particular 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 the predominant source of errors is MUI, a terminal that generates a new packet only considers as potential destinations those terminals that are within its transmission range; this assures that a packet will always reach the intended destination with a received power high enough to meet the QoS requirement.

The simulator integrates a MUI measurer based on the concept of pulse collision as proposed in [6] and further refined in [10], providing the average BER at receiver output as follows:

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

where:

$$\begin{aligned}\Omega(A,B) = & \frac{1}{2} erfc\left(\sqrt{\frac{A}{2}} - \sqrt{\frac{B}{2}}\right) \\ & + \frac{1}{2} erfc\left(\sqrt{\frac{A}{2}} + \sqrt{\frac{B}{2}}\right) - erfc\left(\sqrt{\frac{A}{2}}\right)\end{aligned} \quad (3)$$

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.

IV. DISCUSSION OF SIMULATION RESULTS AND CONCLUSIONS

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 Figure 1 and Figure 2, showing throughput and delay respectively. The results were obtained considering a bit rate R = 10 kb/s.

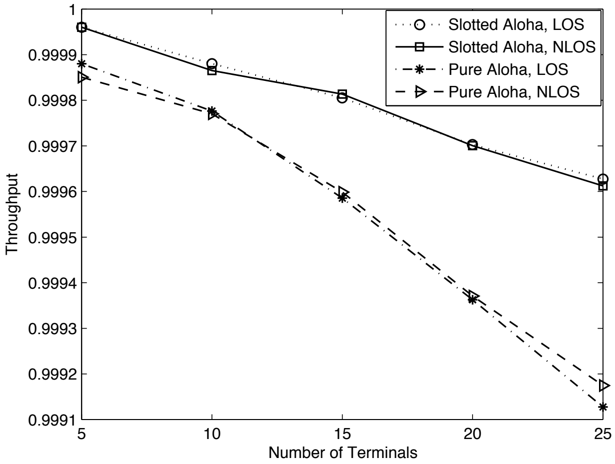

Fig. 1. Throughput as a function of number of terminals for a full connectivity scenario (R_{TX} = 70 m) with User bit rate R =10 kb/s (Circle: Slotted Aloha, LOS channel; Square: Slotted Aloha, NLOS channel; Diamond: Pure Aloha, LOS channel; Triangle: Pure Aloha, NLOS channel).

Figure 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 Figure 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.

Figure 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.

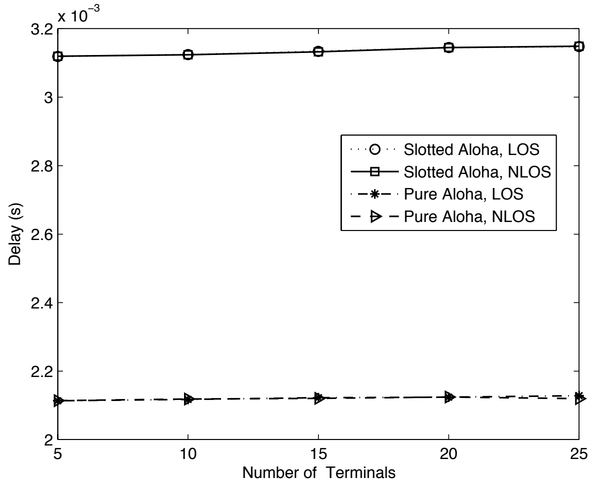

Fig. 2. Delay as a function of number of terminals for a full connectivity scenario (R_{TX}= 70 m) with User bit rate R=10 kb/s (Circle: Slotted Aloha, LOS channel; Square: Slotted Aloha, NLOS channel; Diamond: Pure Aloha, LOS channel; Triangle: Pure Aloha, NLOS channel).

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.

ACKNOWLEDGMENT

This work was partially supported by the European Union under the 6th Framework Integrated Project n.506897 - P.U.L.S.E.R.S.

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