Joint communication, ranging, and positioning in low data-rate UWB networks

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Abstract - **This work illustrates a possible solution for joint communication, ranging, and positioning for application in UWB sensor networks. The proposed system is based on the adoption of a specifically designed low data-rate (LDR) UWB-tailored MAC, named Uncoordinated, Wireless, Baseborn medium access for UWB communication networks $(UWB)^2$, that performs ranging based on the exchange of control packets. The ranging information provided by the MAC is the input to a distributed positioning protocol.**
Performance of the proposed solution is evaluated by simulation and measured as the percentage of positioned terminals as well as the percentage of positioning error, for varying network connectivity and ranging accuracy. Results show that the excellent ranging accuracy provided by UWB is an indispensable feature for applications requiring highly accurate positioning. Results also show that good network connectivity is an additional mandatory condition for designing robust location-aware protocols.

1 Introduction

The ad-hoc networking paradigm offers the possibility of designing flexible self-organizing networks and allows the definition of new network scenarios and applications, which were precluded to traditional infrastructure-based wireless networks [1].

Effective deployment of ad-hoc networks requires, however, to address a whole new set of design issues, ranging from hardware up to the application. Among new requirements one of the most challenging is introducing energy-awareness for extending the life of networks composed of terminals with limited power supply.

Energy-awareness is particularly relevant for sensor networks. The size of such networks, consisting of hundreds of terminals, makes battery replacement in all network components strongly unlikely. In such a context, knowing the spatial position of terminals can significantly improve energy management, by means, for example, of location-based routing protocols [2]. Position information is also crucial where data provided by sensors depend upon single sensor position, as for example in fire monitoring. The sensors are typically low-cost devices, and, therefore, the cost of equipping all sensors with Global Positioning System (GPS) cannot be afforded.

Under these restrictions, sensors can build a map of positions by applying a dedicated positioning protocol, possibly based on a distributed approach. Most of distributed positioning protocols proposed in the literature rely on the availability of distance information between terminals. The system requires, therefore, the presence of a Medium Access Control (MAC) module providing ranging information to the positioning module.

Ultra Wide Band (UWB) radio has the appeal, among others, of measuring distances with high precision. Thanks to this feature, UWB has gained popularity world-wide, and has become a top candidate for location-aware ad-hoc and sensor networks [3].

Ranging is not, however, the only concern; network density is another factor to be considered due to its impact on positioning accuracy. This is particularly true for networks where the set of active sensors varies in time due to sensors limited battery autonomy.

In this paper, propose a solution for UWB ranging and positioning based on a distributed MAC protocol, specifically designed to take advantage of the UWB ranging capability, in combination with the distributed Self Positioning Algorithm [4].

We evaluate the performance of the proposed solution in terms of positioning accuracy as a function of ranging accuracy and network density by means of computer simulations. The paper is organized as follows. Section 2 analyzes the ranging capabilities of UWB. Section 3 introduces the proposed MAC protocol, while section 4 presents the simulation results. Conclusions are drawn in section 5.

2 UWB ranging

UWB radio, thanks to its GHz-wide bandwidth, is particularly suited for being adopted as a basis for TOA based ranging, as proposed for example in [5]. The accuracy of the TOA estimation expressed by the variance of the TOA estimation error $\sigma_{\hat{\tau}}^2$ is in fact related to the bandwidth of the signal and SNR at the receiver. According to the general theory of ML estimators, in fact, the lower limit for $\sigma_{\hat{\tau}}^2$ in presence of Additive White Gaussian Noise is given by the Cramer-Rao lower bound [6]:

$$\sigma_{\hat{\tau}}^2 = \frac{N_0}{2\int_{-\infty}^{+\infty}(2\pi f)^2 |G(f)|^2\,df} \tag{1}$$

The maximum theoretical ranging performance made available by UWB signals can be thus evaluated by calculating such lower bound for an UWB pulse g(t) that fully exploits the energy made available by regulation.

In the following, we will consider the regulation released in February 2002 in the United States of America by the Federal Communication Committee (FCC) [7]. The FCC emission masks serve at present as a reference for UWB system design within and outside the USA. As far as Europe is concerned, for example, the European Radio Organization (ERO) issued in July 2003 a tentative definition of UWB emission masks which very closely followed the FCC settings [8] [1].

As a test case, we will adopt here the FCC emission mask for indoor UWB devices, presented in fig. 1.

Let us suppose that the pulse g(t) has a constant bilateral Power Spectral Density $|G(f)|^2$, i.e.:

$$|G(f)|^2 = \begin{cases} G_0 & for \quad f \in [f_L, f_H] \cup [-f_H, -f_L] \\ 0 & outside \end{cases} \tag{2}$$

Eq. (1) can be thus written as follows:

$$\sigma_{\hat{\tau}}^2 = \frac{N_0}{8\pi^2\int_{-\infty}^{+\infty}f^2|G(f)|^2 df} = \frac{N_0}{8\pi^2 2\int_{f_L}^{f_H}f^2 G_0 df} =$$
$$= \frac{N_0}{8\pi^2 2G_0\left[\frac{f^3}{3}\right]_{f_L}^{f_H}} = \frac{N_0}{\frac{8}{3}\pi^2 2G_0\left(f_H^3 - f_L^3\right)} \tag{3}$$

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[1]In November 2004 the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) released a new draft of UWB emission masks ([9]), with emission levels significantly lower than FCC levels.
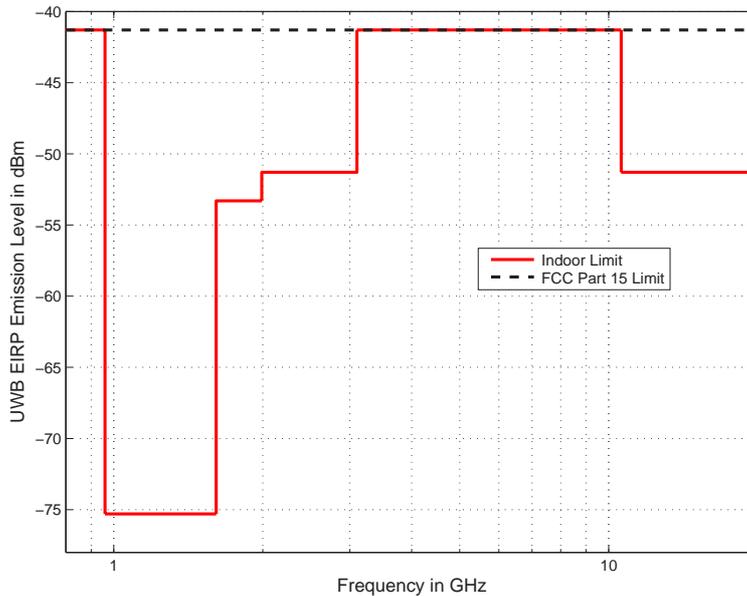
Figure 1: FCC emission masks for UWB indoor devices.

And one can write:

$$\sigma_{\hat{\tau}}^2 = \frac{N_0}{\frac{8}{3}\pi^2 2G_0(f_H - f_L)\left(f_H^2 + f_H f_L + f_L^2\right)} =$$
$$= \frac{N_0}{\frac{8}{3}\pi^2 2G_0 B\left(f_H^2 + f_H f_L + f_L^2\right)} \tag{4}$$

Eq. (4) shows that the variance in delay estimation is inversely proportional to the signal monolateral bandwidth occupation B and to a term which depends on the lower and upper frequencies f_H and f_L. It can be easily shown that, for a fixed bandwidth B, this term increases as f_H increases.

Let us consider an IR-UWB signal which fully exploits the frequency band [3.1 - 10.6] GHz with the maximum PSD allowed by the FCC. We obtain the following values: $B = 7.5$ GHz, $f_H = 10.6$ GHz, $f_L = 3.1$ GHz, $2G_0 = 7.413 \cdot 10^{-14}$ W/Hz and $N_0 \cong 4 \cdot 10^{-21}$ W/Hz for a noise temperature $T_s = FT_0$ with F = 7 dB. The limit given by eq. 4 then writes:

$$\sigma_{\hat{\tau}}^2 = 8.82 \cdot 10^{-39} \tag{5}$$

This corresponds to a lower bound on average distance estimation error equal to $c\sigma_{\hat{\tau}} = 2.82 \cdot 10^{-11}$ m. The above result provides only a theoretical bound for delay estimation error. Receiver hardware limitations, reduced efficiency in the generation of the transmitted signal, and the presence of multipath and multi-user interference lead to a far lower accuracy [10]and UWB ranging accuracy is expected to be in the order of tens of centimeters. It has been proved that with this ranging accuracy one can obtain a positioning accuracy in the order of 50 centimeters [11].

3 The $(UWB)^2$ MAC protocol

In this paper, we assume that information data is organized in packets that are exchanged between nodes in an Aloha fashion, as defined in the specifically designed low data-rate (LDR) UWB-tailored MAC named Uncoordinated, Wireless, Baseborn medium access for UWB communication networks $(UWB)^2$ [12].

$(UWB)^2$ is based on a physical layer which uses pulsed emissions of very short pulses which are modulated in position (Pulse Position Modulation, PPM) by the information bits. The duty cycle of emitted signals depends thus on the ratio between the Pulse Repetition Period (PRP), i.e. the average interval between two consecutive pulses, and the duration of a pulse. In the case of low data rate transmissions, where bit rates in the order of 100 kb/s, or below, can be considered as an acceptable target, this corresponds to signal duty cycles as low as 10^{-6}: the adoption of short pulses offers thus an intrinsic protection from MUI.

In order to mitigate energy peaks at multiples of the average pulse repetition frequency, time intervals between UWB pulses are randomized using Time Hopping (TH) codes, which introduce additional pseudo-random delays between pulses. The adoption of the TH principle also forms the basis for multiple access, by assigning different TH codes to different users, in a TH Code Division Multiple Access (TH-CDMA) fashion.

Multi-channel CDMA MAC algorithms, commonly referred to as multi-code, have been intensively investigated for Direct Sequence (DS) CDMA networks. Among all we cite random CDMA access [13], and, more recently, Multi-Code Spread Slotted Aloha [14]. Note, however, that although in the last years most of the research efforts were focused on DS CDMA, Frequency Hopping (FH) CDMA and TH CDMA also provide viable solutions.

Performance of multi-code MAC protocols are limited by two factors:

1. MUI, caused by the contemporary transmission of different packets from different users on different codes;

2. Collisions on the code, caused by the selection of the same code by two different transmitters within radio coverage.

Robustness of the system to MUI is determined by the cross correlation properties of the codes; The lower the cross correlation between different codes, the higher the number of possible simultaneous transmissions. The effect of code collisions can be mitigated by adopting appropriate code selection protocols. The task of assigning codes to different transmitters in the same coverage area is a challenging issue in the design of distributed networks. Within this framework, Sousa and Silvester ([15]) provided a thorough overview of possible code assignment solutions:

1. Common code: all terminals share the same code, relying on phase shifts between different links for avoiding code collisions.

2. Receiver code: each terminal has a unique code for receiving, and the transmitter tunes on the code of the intended receiver for transmitting a packet.

3. Transmitter code: each terminal has an unique code for transmitting, and the receiver tunes on the code of the transmitter for receiving a packet.

4. Hybrid: a combination of the above schemes.

The $(UWB)^2$ protocol applies the multi-code concept to the specific case of a TH-IR UWB system. $(UWB)^2$ adopts a Hybrid scheme based on the combination of a common control channel, provided by a Common TH code, with dedicated data channels associated to Transmitter TH codes. The adoption of a Hybrid scheme can be motivated as follows:

1. It simplifies the receiver structure, since data transmissions (and corresponding TH codes) are first communicated on the control channel;

2. It provides a common channel for broadcasting. This is a key property for the operation of higher layers protocols. Broadcast messages are for example required for routing and distributed positioning protocols.

Note that the use of a Common code at the beginning of each transmission also allows an easy transition to the adoption of a Common code solution, whenever the bit rate and the offered traffic are low enough to allow the generated MUI noise to be managed in each receiver with the UWB processing gain alone. As regards code assignment, a unique association between MAC ID and Transmitter Code can be obtained by adopting, for example, the algorithm described in [16] which avoids implementing a distributed code assignment protocol.

$(UWB)^2$ was designed for distributed networks dedicated to low data rate applications; as a consequence, synchronization between transmitter and receiver may not be available at the beginning of packet transmission because of clock drifts in each terminal during inactivity periods. A synchronization trailer long enough to guarantee the requested synchronization probability is thus added to each packet. The length of the trailer depends on current network conditions, and is provided to the MAC by the synchronization logic.

A DATA MACPDU is transferred by means of the following handshake procedure:

1. A terminal T willing to transmit a DATA MACPDU to a terminal R transmits a Link Establish (LE) PDU on the common channel TH-0. The LE PDU contains the MAC ID of both terminals T and R, and the information needed by terminal R to determine the dedicated DATA TH code that will be used for the transmission of the DATA PDU.

2. The terminal R replies with a Link Confirm (LC) response PDU, that notifies to terminal T the correct reception of the LE PDU.

3. After receiving the LC PDU, T switches to the TH code declared in the LE PDU and transmits the DATA PDU; terminal T may optionally include in the DATA PDU a request for an explicit ACK of the correct reception of the PDU by R.

4. Terminal R, after the reception of the DATA PDU, confirms the reception if an acknowledgment was required by T.

Note that when the packet to be transmitted is constituted by a broadcast packet (e.g. a routing control packet), the MAC will adopt a simplified transmission procedure, where the DATA PDU that encapsulates the packet is directly transmitted on the Common TH-Code, without performing the LE/LC exchange. Given the broadcast nature of such PDU, in fact, the transmission of a LC PDU by each of the interested receivers must be avoided. Furthermore, for this kind of PDUs no ACKs are required, in order to avoid the transmission of an ACK PDU by each neighbor of T receiving the broadcast PDU. A broadcast ID known to all terminals is set as Receiver ID in these PDUs in order to inform neighbors of the broadcast nature of the transmission.

Such simplified procedure provides a lower protection of broadcast PDUs from interference; on the other hand, it makes possible for the upper layers to have a straightforward mean to communicate broadcast information. Furthermore, the potential loss of a control broadcast packet is usually much less critical than the loss of a DATA packet since updated control information is usually retransmitted either on a periodic basis or within a short time.

The handshake procedure described above is fundamental for communication purposes, since it allows transmitter and receiver to exchange information on the dedicated TH-code to be used for DATA transmission.

In the view of allowing distributed positioning and location-aware routing, however, $(UWB)^2$ also uses the handshake procedure for collecting distance information between transmitter and receiver during the exchange of control packets, as shown in fig. 2.
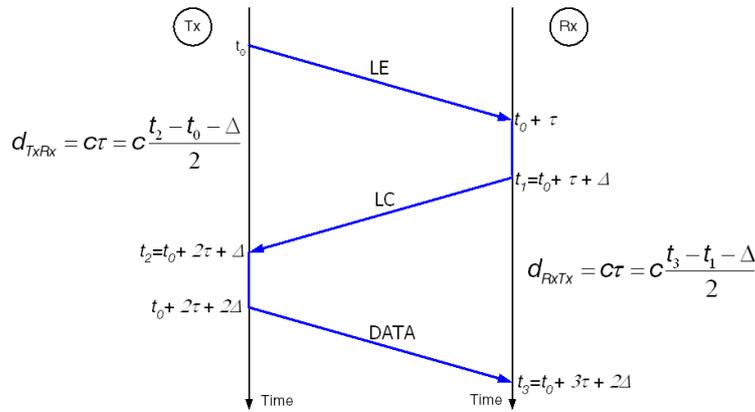

Figure 2: Procedure for bidirectional distance estimation in $(UWB)^2$.

The protocol foresees in fact a known delay Δ between the reception of a PDU and the transmission of the next one, and thus allows both transmitter and receiver to evaluate the round trip time. More in detail, the transmitter T will be able to determine the distance from the receiver after the reception of the LC packet, while the receiver R will obtain the distance information after the reception of the DATA PDU.

Thanks to the ranging procedure described above, the $(UWB)^2$ MAC can provide the input required by a distributed positioning protocol, i.e. distance information between each pair of terminals in physical connectivity.

The most general solution for a distributed positioning protocol is to be anchor-free, that is no position information is available at network start, as in the Self Positioning Algorithm (SPA) [4]; in this paper we thus combined $(UWB)^2$ with the SPA.

4   Performance analysis

The performance of a distributed positioning algorithm can in general be defined in terms of its effectiveness in building a global coordinate system and providing each terminal with its position in the network. Performance is mainly determined by:

1. network connectivity degree, that is the average number of neighbors in physical reach within one hop;

2. ranging accuracy.

The network connectivity degree depends on the power available at each terminal, that is the transmission range of a terminal, and on the density of nodes in the network.

The ranging accuracy, on the other hand, derives from the adopted transmission technique.

In order to evaluate the effect of both network connectivity and ranging accuracy on positioning accuracy, we simulated a network of 20 mobile terminals distributed in an area of $80x80m^2$ adopting the $(UWB)^2$ MAC and the SPA positioning algorithm.

A first set of simulation investigated the effect of network connectivity as a function of transmission range. Simulations were performed with varying transmission ranges, from 20 meters (low network connectivity) up to 60 meters (high network connectivity), and assuming perfect ranging, i.e. no error in distance estimation.

Results of simulations are shown in Fig. 3, which reports the percentage of terminals that were able to evaluate their own position, as a function of the transmission range.
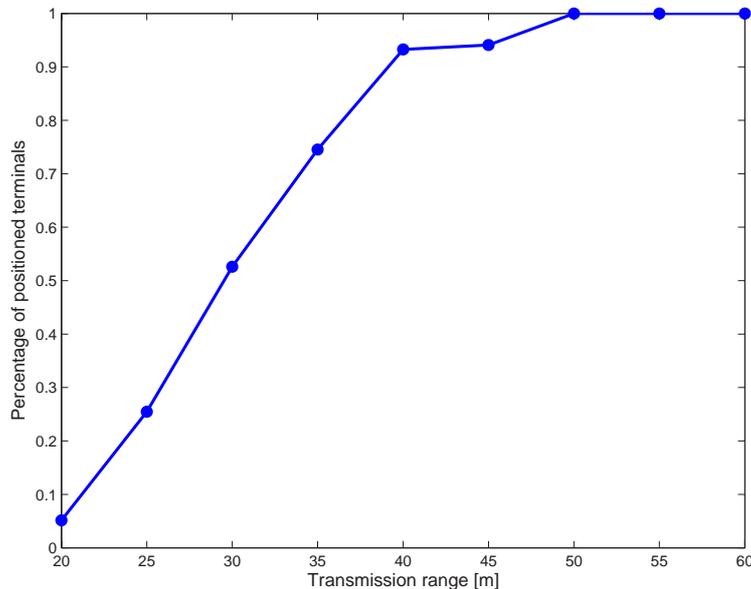

Figure 3: Percentage of terminals sharing the same coordinate system as a function of the transmission range.

Figure 3 shows that for medium to high network connectivity degrees (i.e. transmission range above 40 meters) a large number of terminals are able to position themselves, and use thus this information to optimize resource management and routing.

We then analyzed the effect of the density of nodes. The density was varied by varying the number of terminals while keeping constant the network area size. Figure 4 shows the percentage of positioned terminals as a function of the number of terminals, i.e. density, for three different values of the transmission range (40, 50, and 60 m). We can predict the performance of the positioning protocol as terminals run out of energy by reading the data of fig. 4 from right to left.

Finally we analyzed the effect of the accuracy in ranging in the specific case of a highly connected network (transmission range = 60 m). Three different cases were taken into account,
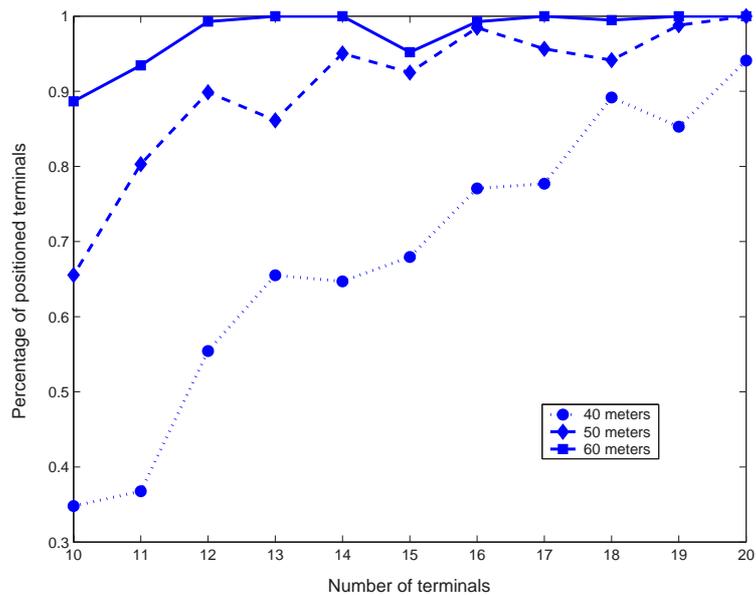
Figure 4: Percentage terminals sharing the same coordinate system as a function of the number of terminals for three values of transmission range (circles: range = 40 m, diamonds: range = 50 m, squares: range = 60 m).

characterized by a ranging error with uniform distribution in the intervals [-0.1m, 0.1m], [-1m, 1m], [-10m, 10m].

Figure 5 shows the percentage of positioning error as a function of ranging error.
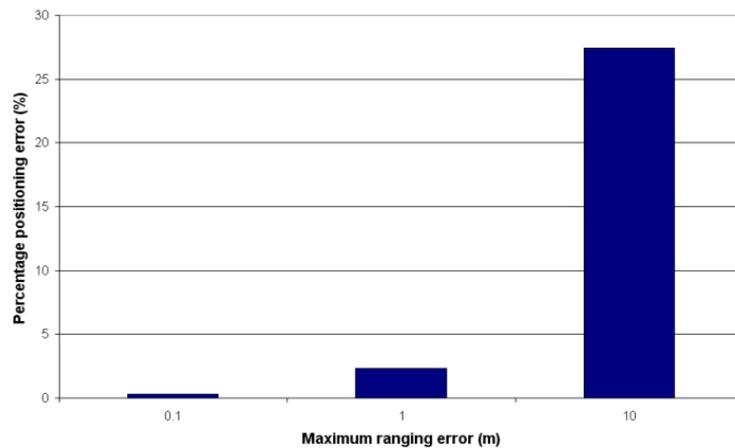

Figure 5: Percentage positioning error as a function of ranging error.

Figure 5 shows in fact that ranging errors in the order of 0.1 m (case 1) and 1 m (case 2) lead to satisfactory performance (errors in positioning below 5%) while the third case (ranging errors in the order of 10 meters) is not compatible with applications requiring accurate positioning. The ranging accuracy provided by UWB appears thus as an indispensable feature when high accurate positioning is required by the application layer.

5 Conclusions

In this paper, a solution for joint communication, distributed ranging and positioning for application in UWB sensor networks was proposed. The proposed solution is based on the adoption of the $(UWB)^2$ MAC protocol that performs ranging based on the exchange of control packets. The ranging information provided by the MAC is the input to the distributed positioning protocol (SPA). Performance was evaluated by simulation and measured as the percentage of positioned terminals as well as the percentage of positioning error, for varying network connectivity and ranging accuracy. Results show that the excellent ranging accuracy provided by UWB is an indispensable feature for applications requiring highly accurate positioning. Results also show that good network connectivity is an additional mandatory condition for designing robust location-aware protocols.

Acknowledgment

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