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Positioning accuracy in Ultra Wide Band Low Data Rate networks of uncoordinated terminals

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***Abstract*—The 802.15.4a standard can open the way to the deployment of innovative position-based applications for Low Data Rate (LDR) networks, thanks to the accurate ranging information provided by the selected Ultra Wide Band (UWB) physical layer (PHY). In order to take full advantage of the UWB PHY capabilities, however, the standard, now under definition within the IEEE, will require innovative, UWB specific solutions for medium access.**

In our previous work we proposed the (UWB)^2 MAC protocol for UWB LDR systems, based on a multichannel Aloha approach, and we evaluated its performance in presence of Multi User Interference (MUI) and multipath-affected channels.

In this work we determine the accuracy of position information achievable by a distributed positioning protocol in an UWB LDR network adopting the 802.15.4a PHY and the (UWB)^2 MAC. The analysis takes into account number of nodes, MUI, ranging errors and channel characteristics. Simulation results show that the (UWB)^2 MAC protocol can support distributed positioning with high accuracy, even in presence of NLOS propagation conditions and high number of nodes.

***Index Terms*—MAC, Positioning, UWB**

I. Introduction

The goal of the new 802.15.4a standard for Low Data Rate (LDR) networks, currently under definition within the IEEE, is to provide joint communications and high accuracy positioning in future sensor networks [1]. To this aim, the IEEE 802.15 Task Group 4a (802.15.TG4a) decided to adopt an Impulse Radio Ultra Wide Band (IR-UWB) physical layer, capable of providing the accurate ranging information required for accurate positioning [2].

The next step towards the release of 802.15.4a is the definition of the Medium Access Control (MAC) layer. Although in fact backward compatibility with the parent IEEE 802.15.4 standard is deemed as a desirable feature, a revision of the legacy MAC layer is required in order to take into account two factors:

- The need for supporting ranging at the MAC layer by means of dedicated procedures;
- The opportunity of taking advantage of the specific features of the new UWB physical layer.

In this view, we proposed in [3] a MAC protocol for LDR UWB networks, named Uncoordinated Baseborn Wireless medium access control for UWB networks (UWB)^2. This protocol is based on specific features of IR-UWB. Furthermore, it enables optimization of network algorithms by evaluating and storing distances, and by making them available to positioning and routing algorithms. In [4] performance analysis of the (UWB)^2 protocol for AWGN channels showed the validity of the approach. The analysis was extended in [5], where both signal characteristics and channel models specific of the IEEE 802.15.4a standard were taken into account. The results presented in [5] confirm that (UWB)^2 is a suitable solution for access in future 802.15.4a LDR networks.

In this work we evaluate the performance of a specific application in a network adopting the 802.15.4a physical layer and the (UWB)^2 MAC. Since positioning is the main goal of the future standard, a positioning protocol was the natural choice for such application. As a consequence, we selected and implemented the Self Positioning Algorithm, (SPA) originally proposed in [6]. This protocol was selected since it does not require any specific infrastructure, and can thus operate in the general scenario of a network without predefined anchor nodes.

We analyzed by simulation both the positioning error and the percentage of nodes sharing the same reference system. The analysis was carried out as a function of number of nodes and channel propagation scenarios. MUI and ranging error were taken into account as well; ranging error, in particular, was modeled following the approach proposed in [7] for UWB ranging error in both LOS and NLOS propagation conditions.

The paper is organized as follows. Section II presents goals and characteristics of the IEEE 802.15.4a standard. Section III reviews the (UWB)^2 MAC. Section IV introduces the SPA algorithm and describes the modifications introduced to the original protocol in our implementation. Section V describes the assumptions taken on the physical layer in the simulation analysis and presents simulation results. Finally, Section VI draws conclusions.

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II. THE IEEE 802.15.4A STANDARD

A. Application scenarios

Low data rate and low cost networks for mixed indoor/outdoor communications are nowadays of great interest in sensor and ad-hoc networking. The interest towards LDR networks led in 2003 to the definition of the IEEE 802.15.4 standard for low rate, low complexity and low power wireless networks [8]. The 802.15.4 standard also forms the basis of the ZigBee technology, providing a comprehensive solution for LDR networking, from physical layer to applications [9].

Both IEEE 802.15.4 and ZigBee have however an intrinsic limitation regarding an important requirement of future low data rate systems, that is the limited possibility of locating objects and individuals by means of distributed, infrastructure-independent positioning algorithms.

The introduction of positioning in low data rate networks is actually one of the main goals of the recently formed IEEE 802.15.4a Task Group [1]. In particular, the 802.15.4a systems are expected to provide accurate position information in both indoor and outdoor environments. The support for ranging provided by the 802.15.4a standard will allow the assessment of a large set of application scenarios that are precluded to existing, non location aware low data rate networks, such those compliant to the original 802.15.4 standard.

Based on the response to the Call for Applications launched in November 2005 in order to identify potential application scenarios for the new standard, the main 802.15.4a application areas are the following [2]:

- Industrial Inventory Control;
- Home Sensing, Control and Media Delivery;
- Logistics;
- Industrial Process Control and Maintenance;
- Safety/Health Monitoring;
- Personnel Security.

Applications falling in any of the above areas can be grouped, in terms of technical requirements, in the four scenarios presented in Table I.

TABLE I
APPLICATION SCENARIOS FOR THE IEEE 802.15.4A STANDARD

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of nodes	10-100	100s – 1000s	100s	10 – 50
Anchor nodes	Yes	Yes	Yes/No	Yes
Environment	Indoor/Outdoor	Indoor/Outdoor	Indoor/Outdoor	Indoor
Topology	Peer-to-peer / Centralized	Centralized	Peer-to-peer	Peer-to-peer
Mobility	Yes	No	Yes	Yes
Speed	< 3 m/s	-	< 10 m/s	1 m/s
Range	100 m	100 m	30 m	30 m
Application rate	< 10 kb/s	< 10 kb/s	10 – 100 kb/s	< 10 kb/s
Positioning Accuracy	30 cm	30 cm	30 cm	10 cm
Reliability	High	Medium	High	Medium
Example application	Locating people	Locating assets	Ad-hoc / sensor networking	Home intelligence

Table I shows that the expected transmission ranges are in the order of several tens of meters despite the strong power limitations imposed to UWB systems, thanks to the fact that the transmission rate of 802.15.4a devices will be in the order of 1 Mb/s, as further illustrated in the next subsection, providing a description of the physical layer of the 802.15.4a standard.

B. PHY characteristics

The definition of the physical layer of the new standard is almost completed [10]. Starting from the original 26 proposals for the PHY of the new standard, a down-selection procedure within the 802.15.4a TG led to the final decision of keeping two alternative physical layers [2], [10]:

- A narrowband PHY based on a chirp signal at 2.4 GHz, which will not provide ranging capability;
- An UWB PHY which will provide both ranging and communications capability.

In the following we will focus on the UWB PHY.

The UWB PHY selected for the standard will operate in either of the two following bands:

- A Low Frequency Band (LFB) in the range 3.2 – 4.7 GHz;
- A High Frequency Band (HFB) in the range 5.9 – 10.3 GHz.

The two bands will be divided in overlapping channels, and one channel in the LFB will be mandatory for all devices compliant to the standard, in order to assure interoperability between all future 802.15.4a devices.

The selected UWB signal is an impulsive signal, with pulses of duration up to 2 ns. The modulation scheme will depend on the receiver structure:

- Non-coherent receivers: the selected scheme will be a Pulse Position Modulation (PPM) with one bit per symbol;
- Coherent receivers: the selected modulation will be a combination of PPM and PAM, with two bits per symbol.

The signal adopted in the LFB will be characterized by a -3 dB bandwidth of 494 MHz, although larger signal bandwidths, up to 1.5 GHz, will be allowed in both bands in order to allow for increased rate and ranging accuracy.

Both the single link peak transmission rate and the targeted aggregate network throughput will be in the order of 1 Mbit/s, while the expected radio coverage will be in the order of 30 meters or more, depending on the selected link bit rate.

Ranging support will be part of the PHY definition, and specific preambles for ranging purpose will be defined in the standard, in order to allow high accuracy distance estimation. Ranging will be based on Time Of Arrival (TOA), with an expected ranging accuracy well below 1 m for SNR > 10 dB.

III. THE $(UWB)^2$ MAC

The high temporal resolution of IR-UWB signals has the beneficial side effect of reinforcing robustness to MUI, in particular for low data rate applications [11]. As a consequence, access to the medium in low data rate UWB networks can be based on a most straightforward solution, that is Aloha [12], [3]. The adoption of an Aloha-like approach may also favor lowering costs, given that it does not rely on specific PHY functions, such as Carrier Sensing, and may thus be adapted, with no significant effort, to different PHYs.

According to the Aloha principle, devices transmit in an uncoordinated fashion. Thanks to resilience to MUI offered by impulse radio, correct reception in the presence of multiple simultaneous links is possible.

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.

These considerations led to the Uncoordinated, Wireless, Baseborn protocol for UWB ($(UWB)^2$) MAC protocol, based on the combination of ALOHA with TH-CDMA [3].

$(UWB)^2$ is a multi-channel MAC protocol, each channel corresponding to a different code. $(UWB)^2$ 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 prepare 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.

The $(UWB)^2$ MAC also includes a solution for the management of ranging information made available by the above procedure. Each terminal i maintains in fact 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.

IV. THE SELF POSITIONING ALGORITHM

A. *Brief description*

The Self-Positioning Algorithm (SPA) [6] has the goal of providing each node in the network with its own position in a common coordinate system. In absence of external reference points (*anchor nodes*) the nodes are only able to position themselves in a relative coordinate system; in some cases this information is however sufficient for enabling location-based optimizations, for example at the routing layer. It should be noted that the protocol can be easily adapted to the case where anchor nodes are available and provide an external reference system.

In this section we will only provide a brief introduction to the protocol, as a background for the performance analysis presented in Section V. A complete description of the algorithm can be found in [6].

The SPA algorithm is logically organized in two phases.

Phase 1 – During this phase each node attempts to build a node-centered coordinate system, called Local Coordinate System (LCS) centered on itself. In order to build its own LCS, each node i performs the following actions:

1. Detect its set of one-hop neighbors K_i; in the original definition of the protocol this phase is accomplished by using beacons, in order to maintain an up-to-date map of one-hop neighbors;
2. Evaluate the set of distances D_i from its neighbors K_i; it is assumed that the distance measurement from each one-hop neighbor is obtained by means of TOA estimation;
3. Send D_i and K_i to its one-hop neighbors.

As a consequence of the above steps, each node i will know directly its distances from all its one-hop neighbors, the IDs of its two-hop neighbors, and a subset of the distances from its one-hop neighbors to its two-hop neighbors.

The determination of the local coordinate system in a 2D scenario requires the selection of two additional terminals p, q in the K_i set. p and q must satisfy two requirements:

1. They must not lie on the same line with i;
2. Their distance d_{pq} must be known to i.

In the coordinate system defined by i, p and q, i can determine the position of each neighbor k for which the distances d_{pk} and d_{qk} are known.

Phase 2 – At the end of Phase 1, each node that was able to obtain enough ranging information to build a coordinate system occupies the position (0, 0) of its own LCS: in order to define a global network topology, all node-centered systems of coordinates must be linearly transformed in order to have a unique orientation (i.e. the same direction for x and y axes of all nodes) and thus converge to a Network Coordinate System (NCS). This is obtained by exchanging information between nodes in a peer-to-peer fashion: whenever a node receives information on the coordinate system of a neighbor, it decides if harmonizing its own coordinate system to the received one based on a predefined criterion, such as the node ID number.

B. *Enhancements to the SPA*

The SPA was originally proposed as a solution for providing coarse positioning information to be used by a position-based routing protocol in large scale ad-hoc networks. In the process of adapting this algorithm to the application scenarios foreseen within the 802.15.4a TG, several modifications and enhancements were introduced in the protocol:

- The original beacon-based solution for detecting one-hop neighbors was modified in order to take into account the characteristics of the underlying $(UWB)^2$ MAC protocol: in the protocol that we implemented, each terminal transmits a packet for neighbor discovery on the common channel defined in $(UWB)^2$; each terminal receiving such packet starts a ranging procedure as defined in [3] after a random delay, required to avoid systematic collisions of ranging packets on the control channel.

- In the original version of the algorithm the transmission of the D_i and K_i sets from a generic node i to its one-hop neighbors triggered an immediate update of distance and neighbor databases in each neighbor; this approach would lead to a high number of packets sent almost simultaneously in the same area of the network, causing a high number of packet collisions on the common channel. This behavior was modified in the implementation by forcing each node to introduce a random delay before sending its own update, thus avoiding systematic collisions.
- The SPA was originally defined as a mean for providing each node with its own position in a unique coordinate system, without providing the node with information on the position of all other nodes in the network. In most of the scenarios foreseen in 802.15.4a, however, the capability of a node to determine the position of other nodes is an important additional feature. As a consequence, in our version of the protocol, when a node i sends information on its LCS, it also sends position information about all known nodes. In this way, when a node receives a LCS and harmonizes its own coordinate system to the received one, it also learns about the position of nodes farther than two hops away, leading eventually to a full knowledge of the network map in all nodes in the network.

V. SIMULATION SETTINGS AND RESULTS

The performance of the SPA algorithm was analyzed in an indoor scenario, defined as a room of 15x15 m^2, as a function of the following parameters:

- node spatial density (determined by the number of nodes in the considered scenario);
- percentage of NLOS links in the network.

The second parameter, in particular, allowed us to determine the impact of the NLOS propagation, influencing both propagation and ranging error, on the positioning algorithm. It should be noted in fact that the presence of a high percentage of NLOS links leads not only to a larger ranging error on such links, but also to a higher packet loss probability, due to the higher path loss experienced by nodes that are in NLOS conditions.
In order to provide a realistic evaluation of the performance of the enhanced version of SPA in a UWB LDR system adopting the $(UWB)^2$ protocol, the analysis was carried out taking into account:

- impact of the channel, in terms of both propagation and interference modeling;
- physical layer characteristics compatible with the future UWB PHY of the 802.15.4a systems;
- ranging error.

Details on the settings for each of the above aspects are provided in the next subsection.

A. *Channel, physical layer and ranging error settings*

In order to model the impact of channel we adopted the first two channel scenarios defined within the 802.15.4a TG, that is CM1 and CM2, corresponding to indoor LOS and NLOS channel conditions, respectively [13].
The physical layer settings were derived from [10], and can be summarized as follows:

- IR-UWB with a band of 494 MHz centered at 3952 MHz (corresponding to Channel 2 of the future 802.15.4a channel scheme, see [10]);
- Average Pulse Repetition Frequency (PRF): 15.6 MHz;
- Pulses Per Symbol (PPS): 16;
- Modulation: PPM (non-coherent receiver);
- Bit rate: PRF/PPS = 965 Kb/s;
- TX power P_{TX}: fixed to FCC indoor limit [14], leading for the considered bandwidth to P_{TX} = 36.6 μW.

The ranging error model for LDR UWB signals was derived from [7], where the model previously proposed in [15] was adapted, based on the results of an UWB channel measurement campaign. The ranging error is given by the formula:

$$d - d^* = W_G \cdot G(0,\sigma) + W_E \cdot E(1/\lambda) \quad (1)$$

where:

- d is the real distance between transmitter and receiver;
- d^* is the estimated distance;
- $G(0,\sigma)$ is a Gaussian variable with mean 0 and standard deviation σ depending on the channel scenario;
- $E(1/\lambda)$ is an Exponential variable with mean 1/λ, depending on the channel scenario;
- W_G and W_E are weighting coefficients depending on the selected channel scenario.

Note that in [7] three different channel scenarios are defined: LOS, NLOS and $NLOS^2$. For sake of simplicity, however, in our analysis we only considered LOS and $NLOS^2$ channel conditions. The values of the parameters for the two scenarios are presented in Table II below:

TABLE II
RANGING ERROR PARAMETERS

Channel scenario	Gaussian Parameters	Exponential Parameters
LOS	W_G=1; σ=0.0068	W_E=0; λ=1
NLOS ($NLOS^2$)	W_G=0.26; σ=0.0129	W_E=0.74; λ=8.433

The authors furthermore propose in [7] an average ranging error model, which is obtained as a weighted combination of the three scenarios, with weights depending on the distance between transmitter and receiver. This model was not adopted in our analysis, since in our case scenarios were obtained as a combination of purely LOS and NLOS links. This allowed us to identify a link as either LOS or NLOS for both channel and ranging error models.

B. *Simulation results*

Fig. 1 presents the percent positioning error as a function of the number of nodes in the network, in a scenario where only LOS links are present between nodes. The percent positioning error is defined as follows:

$$Positioning\,Error\,(\%) = \frac{|Real\,distance - Estimated\,distance|}{Real\,distance} \quad (2)$$

For each node, the average error is determined by evaluating Eq. (2) considering in turn each of the nodes sharing the same coordinate system. According to this definition, the error can only be evaluated for nodes that were able to achieve a position in the NCS. As a consequence, the percentage of nodes that were able to obtain their position in the NCS should be taken into account in evaluating the relevance of the position error measure.

Results show that in the case of full LOS the positioning accuracy is always satisfactory. In these conditions in fact the UWB signal power (as determined by the signal bandwidth and the FCC limits) is high enough to provide full connectivity for all node densities, leading thus to the optimal conditions for the application of the SPA. It can be noted from Fig. 1 that as the node density increased the positioning error slightly increased as well.

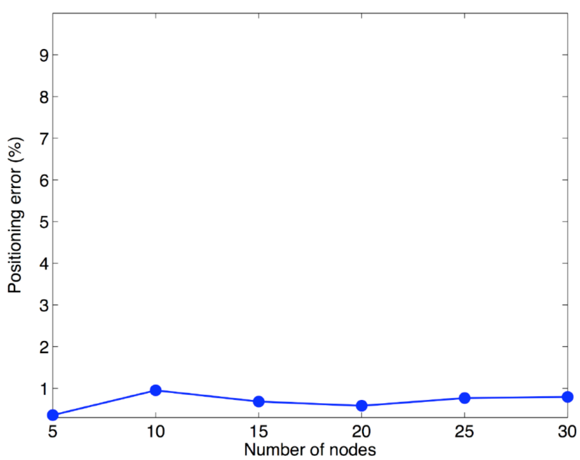

Fig. 1. Positioning error as a function of number of nodes for an indoor scenario in which all terminals are in LOS conditions.

This is due to the fact that a large number of nodes leads to a stronger interference, and thus a higher number of collisions, without any advantage in terms of accuracy: in all cases, however, the underlying $(UWB)^2$ MAC protocol guaranteed a very good resilience to interference, allowing for a positioning error below 1% in all cases. Furthermore, in all cases the percentage of nodes that were able to obtain their position in the NCS was higher than 99.8%.

Fig. 2 shows the positioning error in the same scenario, but assuming the worst case scenario of only NLOS links: in this case the path loss is much larger (with an exponent in the path loss variation with distance of 4.58, based on [13]), and the ranging errors are larger as well, according to the model described in (1). The results show that under these conditions the connectivity in the network is strongly reduced, leading to poor performance for low number of nodes. Furthermore, the larger ranging error leads to larger positioning errors, in the order of 15% for high node densities. Note that positioning error is very low for low node densities: this can be explained by considering Fig. 3, which shows the percentage of positioned nodes in the same simulations. In the case of 5 and 10 nodes only the 30% and 60% of the nodes were able to determine their position, respectively, and thus the corresponding position error could not be evaluated in a reliable way.

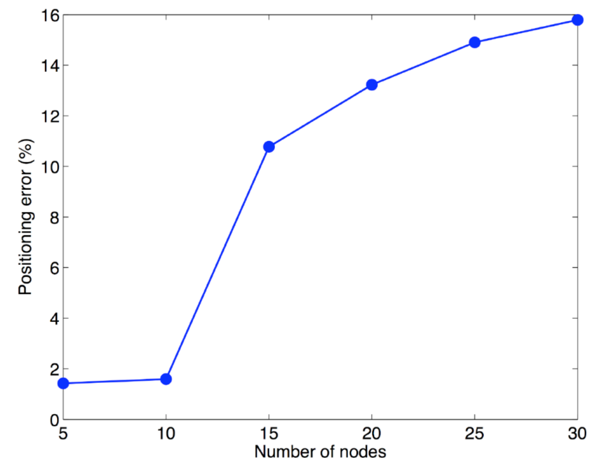

Fig. 2. Positioning error as a function of number of nodes for an indoor scenario in which all terminals are in NLOS conditions.

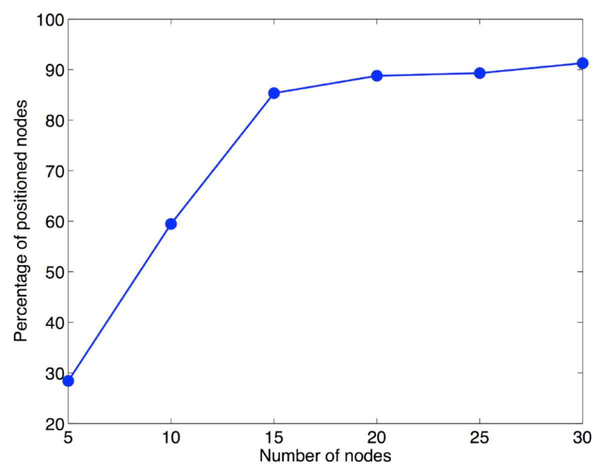

Fig. 3. Percentage of nodes sharing the same coordinate system as a function of number of nodes for an indoor scenario in which all terminals are in NLOS conditions.

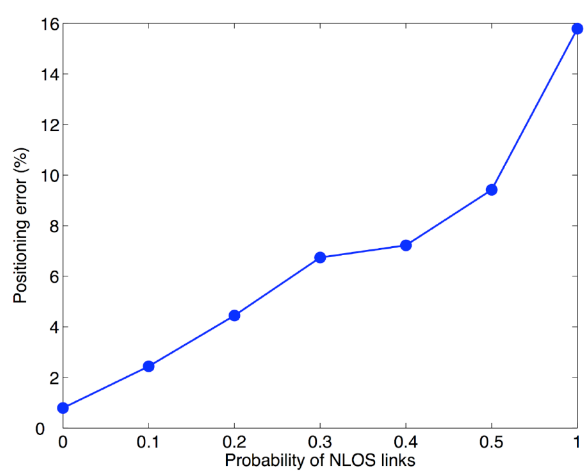

Fig. 4. Positioning error as a function of the percentage of NLOS links, for a scenario consisting in 30 nodes in an indoor environment.

In order to better understand the impact of the NLOS propagation conditions on the positioning accuracy of the SPA protocol, we focused on a high-density case, with 30 nodes in the indoor environment, and analyzed the performance in a more realistic scenario, where both LOS and NLOS links were present. The results are presented in Fig. 4 and Fig. 5 as a function of the percentage of NLOS links in the network. The two figures present the positioning error and the percentage of nodes sharing the same coordinate system, respectively.

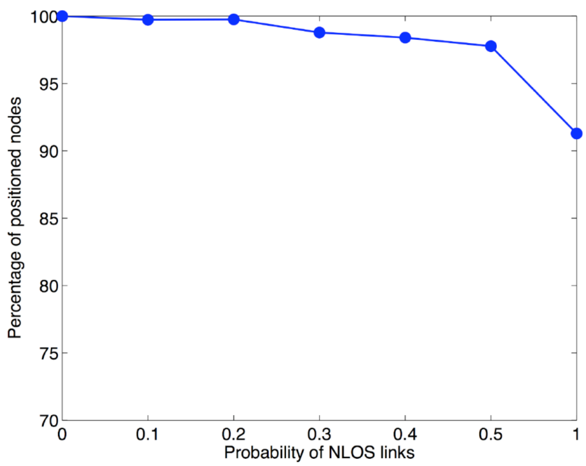

Fig. 5. Percentage of nodes sharing the same coordinate system as a function of the percentage of NLOS links, for a network of 30 nodes in an indoor scenario.

The results highlight that the positioning error remained below 5% even when up to the 20% of the links experienced NLOS propagation conditions. Above this threshold, the percentage of nodes that were able to join the positioning process decreased significantly (see Fig. 5), and at the same time the ranging error increased due to the larger number of NLOS links. The overall effect of these two phenomena was an increased positioning error that exceeded 15% when all the transmissions took place in NLOS conditions.

VI. Conclusions

In this work we analyzed the performance of a distributed positioning algorithm in a network of LDR UWB terminals adopting the 802.15.4a physical layer and the $(UWB)^2$ MAC. Performance analysis took into account channel characteristics, MUI and ranging errors. Simulation results indicate that the high ranging accuracy provided by Impulse Radio UWB can lead to high positioning accuracy even in the challenging case of a totally distributed, anchor-free positioning algorithm, such as the Self Positioning Algorithm. Furthermore, results highlight that the $(UWB)^2$ MAC protocol was able to sustain in all cases the broadcast traffic generated by the SPA algorithm, and constitutes thus a suitable basis for distributed protocols and applications in LDR UWB networks.

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