

# MAC Performances for Localization and Tracking in Wireless Sensor Networks

Davide Macagnano, Giuseppe Destino, Flavio Esposito, Giuseppe Abreu

Centre for Wireless Communications

University of Oulu

P.O.Box 4500FIN-90014

macagnan@ee.oulu.fi, destino@ee.oulu.fi, flavio@ee.oulu.fi, giuseppe@ee.oulu.fi

**Abstract**—Time delay rather than throughput, is a constraint of greater importance in tracking systems. In particular, the maximum access delay permissible by the application is strongly related to the dynamics of tracked objects. The purpose of this article is to study the performance of a new media access control (MAC) technology specifically suited for LDR UWB systems [3] under the point of view of a tracking application. Specifically, the time delay necessary to collect the ranging information in both, star and meshed topology networks, have been studied as function of the number of mobiles in the network.

More importantly, we propose two new ranging packet to be used inside the aforementioned MAC, in order to achieve in both the network topologies, a clear advantage compared to the current solution.

## I. INTRODUCTION

The rapid development of wireless sensor networks (WSNs) and the increasingly low cost of embedded computational power, creates conditions for many new WSN applications. Amongst others, one of especial relevance is localization and tracking (LT).

Knowledge of the location of sensors can be employed, for instance, to improve the robustness and to reduce the power consumption in WSNs through routing optimization [1], not to mention that localization and tracking functionalities are themselves often required in many WSN applications such as surveillance systems [2].

Amongst many new technologies, ultra wide band (UWB) is definitely one of the most promising for localization and tracking, thanks to its ability to minimize the interference to other services and to its sub-centimeter ranging resolution. Under this motivation, the Integrated Project PULSERS (for Pervasive Ultra-wideband Low Spectral Energy Radio Systems) was launched by European Commission in order to promote the investigation of UWB studies, with one Work Package dedicated to the study of low data rate (LDR) systems with integrated localization and tracking capabilities.

An important outcome of the first phase of PULSERS, concluded in December 2006, was the design of a new media access control (MAC) technology specifically suited for LDR UWB systems [3]. Inspired by the the IEEE 802.15.4 standard, this new MAC architecture was developed for local area

networks (LANs) with low data-rate and a low power consumption. PULSERS' MAC differs from the former, however, in many aspects. Of special relevance to LT applications is the fact that three guaranteed time slots (GTS) have been reserved inside the contention-free period (CFP) of its super-frame (SF), in order to incorporate and ensure ranging capabilities. The data transmission rate achievable with this MAC has been widely studied in [4] where throughputs reached under different conditions have been investigated.

For tracking systems, however, time delay is a constraint of greater importance than throughput. In particular, the maximum access delay permissible by the application is strongly related to the dynamics of tracked objects. In this article the performance of the new LDR PULSERS' MAC architecture is studied under the point of view of a LT application.

Since the primarily application of concern is tracking, we focus on a star topology, as described in [3], with the centralized tracking algorithm described in [6]. In particular, the performance assessment is based on the time delay necessary to collect the anchor-to-target ranging information required by that algorithm.

The limits for the actual ranging procedure has dealing with dynamic scenarios are out-lighted. After the discussion of few basic improvements that can be made, a new ranging technique, suitable to solve dynamic contexts is proposed through the introduction of new ranging packet.

Concerning the localization problem, making reference [5], networks characterized by meshed topologies are considered. Under this assumption, the time delay necessary to collect the anchor-to-target and the target-to-target ranging information has been investigated. It is shown how, through the introduction of a new ranging packet, the number of TS, and consequently the energy necessary to acquire full knowledge of the ranging, is minimized.

This has been done taking into consideration the MAC specifications [4], which imposes the existence of a coordinator device, namely the personal area network (PAN) coordinator. This same device is in charge of synchronizing all the other devices through the periodic retransmission of a beacon signal which bounds the SF structure.

## II. MAC OVERVIEW

As already recalled in section I, PULSERS' MAC is based on the IEEE 802.15.4 standard. Its main feature, at least under a LT point of view, is that it enables ranging amongst the devices in the network.

This is possible through the introduction in the SF of a ranging period (RNG), corresponding to the last three TS of the CFT.

Figure 1 shows the structure for the SF, bounded by two Beacon Intervals (BIs).

A SF structure is bounded by two successive Beacon Periods (BPs), which, amongst many other functionalities, are also in charge to allocate the TSs, and consequently the RNG slots to the designated devices. It is also assumed that all the nodes are able to listen the BPs, which means that they are all aware of the whether TSs allocation in the CFP.

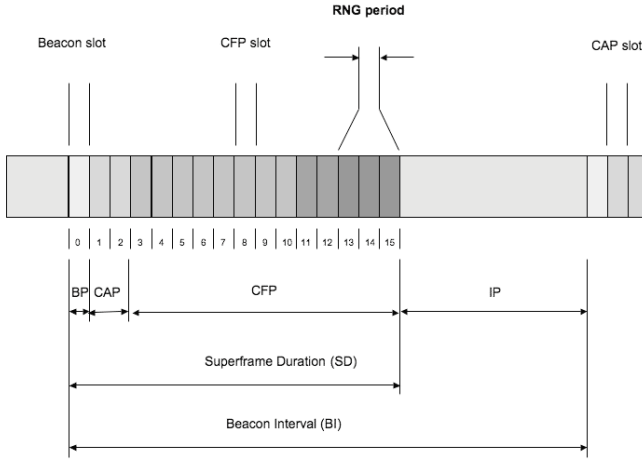


Fig. 1. Time delay expected from the different technique using PULSERS' MAC specifications.

The ranging, as explained in section III, is based on Time Of Arrival (TOA) estimates. This means, that in the case of Two Way Ranging (TwoWR) procedure, two Guaranteed Time Slots (GTS) in the RNG period will be needed. In the case of offset between the clocks of the devices, the Two Way Ranging scheme can be coupled with drift estimation/compensation using an additional TS. This technique will be referred as Three Way Ranging (ThreeWR) scheme.

The TwoWR technique involves two nodes performing a classical peer-to-peer ranging transaction. One node, after being designated by the PAN coordinator as a requester, transmits his request packet inside the assigned TS. Once that this packet is delivered, it will let the recipient node to estimate the TOA for the request. Then, after a known Time of Reply ( $T_R$ ), this same node will send back, inside the TS assigned by the PAN coordinator, its response to the requester node.

$T_R$  can be an immediate acknowledgment time or a fixed time. However, due to the hypothesis that the MAC only supports a single frame per slot, this option cannot be supported.

Therefore, in the case that adjacent TS are used for transferring request-reply packets,  $T_R$  will coincide with the time between the receiving of the request and the beginning of the next TS. Otherwise, it coincides with the number of TS which elapse between a request and its relative reply.

Once that the replay arrives to the requester, it measures the TOA on its own clock. Relying on its measurement and  $T_R$ , as shown by equation 1, this node is now able to estimate the distance between itself and the responder.

An enhancement to the TwoWR scheme consists in asking the responder to transmit an additional packet in order to estimate the clock drift between the two devices, and hence correct the TOA estimate (ThreeWR technique).

## III. RANGING TECHNIQUES

In this section a brief description on how to perform pairwise range measurements is given. A TwoWR scheme, already introduced in II, enables TOA estimates between two a priori asynchronous devices  $i$  and  $j$  as:

$$\tilde{\tau} = \frac{1}{2} \left( \tilde{T}_{i,1} - \tilde{T}_{i,0} - T_R \right), \quad (1)$$

where  $T_{i,0}$  and  $T_{i,1}$  are the the initial ranging request and response times at the node  $i$ . In a real system, the clock inaccuracies and its eventual offsets can affect the TOA estimates and consequently the range measurements. Rewriting the real time measurement as

$$T_{\text{Real}} = \frac{1}{\epsilon} T_{\text{Meas}}, \quad (2)$$

with  $\epsilon = 1 + \Delta$  as the actual relative clock frequency at a certain node, then the TOA estimate using a TwoWR scheme can be written as a function of the clock ratio

$$\gamma_{ij} = \frac{\epsilon_i}{\epsilon_j}, \quad (3)$$

as

$$\tilde{\tau}'_{ij} = \epsilon_i \tau_{ij} + \frac{T_R}{2} (\gamma_{ij} - 1) + \frac{\epsilon}{j} (u_i + u_j). \quad (4)$$

Therefore as shown in [8], once  $\Delta$  is considered as centered and uniformly distributed random variable, and  $u$  as a centered gaussian one, then the bias on the TOA for a TwoWR is:

$$E[\tilde{\tau}'_{ij}] - \tau_{ij} = \Delta_i \tau_{ij} + \frac{T_R}{2} (\gamma_{ij} - 1) \quad (5)$$

with variance

$$\text{Var}^{(2)}[\tilde{\tau}'_{ij}] = \frac{\epsilon_i^2}{2} \sigma_u^2 \quad (6)$$

where  $\sigma_u^2$  represents the noise term variance affecting the TOA measurements. It can be easily noticed from equation 5, how the bias is proportional to  $T_R$ .

In order to estimate the clock drift without any HW clock-tracking, a ThreeWR procedure can be used. It consists in

aTwoWR transaction coupled with the transmission of a further frame used to compute the relative clock drift estimation. Calling with  $T_D$  the time difference between a node  $j$  in the TX mode and a node  $i$  in the RX mode, the clock ratio  $\gamma_{ij}$  can be computed by the node  $i$  as the ratio between the measured duration and the theoretical one (i.e. expected one) as:

$$\tilde{\gamma}_{ij} = \gamma_{ij} + \frac{\epsilon_1}{T_D} (u_{i,0} - u_{i,1}), \quad (7)$$

where  $u_{i,0}$  and  $u_{i,1}$  are the uncertainties affecting the two measurements detection at the RX side. Now the clock drifts can be compensated from the TOA estimates as:

$$\tilde{\tau}_{ij} = \tilde{\tau}'_{ij} - \frac{T_R}{2} (\tilde{\gamma}_{ij} - 1). \quad (8)$$

In [8] is shown how through a ThreeWR technique the bias estimate can be written as

$$E[\tilde{\tau}_{ij}] - \tau_{ij} = \Delta_i \tau_{ij}, \quad (9)$$

with variance

$$\text{Var}^{(3)}[\tilde{\tau}_{ij}] = \frac{\epsilon_i^2}{2} \left( 1 + \left( \frac{T_R}{T_D} \right)^2 \right) \sigma_u^2 = \text{Var}^{(2)}[\tilde{\tau}_{ij}] + \left( \frac{T_R}{T_D} \right)^2 \sigma_u^2. \quad (10)$$

Comparing equations 5-6 with 9-10 it is clear how the ThreeWR scheme corrects the bias at expenses of an increase on the variance, proportional to  $(T_R/T_D)$ .

#### IV. RANGING ACQUISITION DATA DELAY FOR TRACKING

One of the first requirement for a tracking system is the ability to minimize the exchange of packets necessary to update the ranging information between two successive estimates of the node positions.

In section I, it was already introduced how the network topology in tracking scenario follows a star configuration. The delay between two consecutive updates of the all ranging is studied starting from the currently implemented on the MAC [3] named as the nominal solution. Its improvements are discussed in the following subsections. In the following,  $A$  and  $M$  refer to the number of anchor and mobile nodes respectively.

##### A. Nominal Case

It is the technique currently available and implies that each anchor node initiates specific ranging transactions with all the target nodes in the network. Once that the all the ranging are estimated, they still have to be relayed from the anchors to the central node (e.g. to the PNC), before applying the tracking algorithms. Looking at the number of TS, if a TwoWR technique is used, then the sum of two terms. The first one, equal to  $2AM$  refers to the anchor-to-target ranging while a second  $2AM$  will count for the relaying to the PNC.

##### B. Enhancement 1

The current ranging procedure can be improved aggregating the ranging measurements at the anchor nodes, and then relaying them to the PNC through a single packet. Compared to the previous case, the number of packets necessary to relay the ranging information to the PNC drops from  $2AM$  to  $2A$ .

The collection for all the anchor-to-target ranging into a single packet, requires the definition of a new ranging packet, which could be as the one shown in figure 2. Where RM1 refers to the ranging between the specific anchor which is relaying the packet to the PNC and the target one, and so on.



Fig. 2. Report Ranging Measurement (RRM) Packet Format for Enhanced mode 1.

##### C. Enhancement 2

A further reduction can be reached through the broadcasting the ranging requests sent by the anchors. Indeed, using what proposed above in addition to the aggregation for the ranging measurements collected at the anchor nodes, as proposed in IV-B, it is possible to decrease the TS necessary to send the requests to the target nodes.

Figure 3 shows the transactions between 3 requesting anchors, 2 target nodes and the PNC.

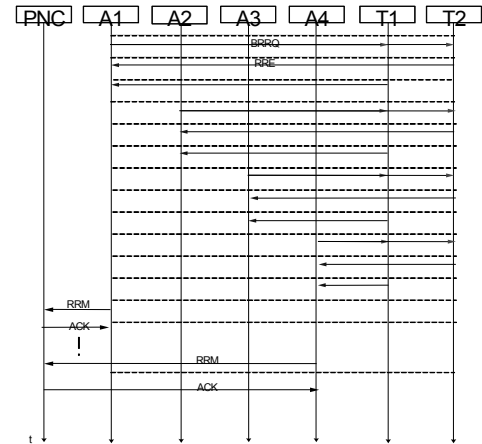


Fig. 3. Temporal diagram for "enhancement 3". Broadcasting for requests and responses used in addition to the data aggregation.

##### D. Enhancement 3

In this section a further minimization in the number of TS is proposed through the introduction of a new packet (BRRE) which allows broadcast and/or multicast ranging in response too. Following what depicted in Figure 4, and using the fact that the RNG TS are assigned to the devices by the PNC, it is possible to broadcast the target's replies to the anchors

using a ranging packet as the one shown in Figure 8. The BRRQ message will not differ much from the common RQ packet. The only difference will be in the destination address field, which has to include a broadcast and/or multicast address format, still to be defined.

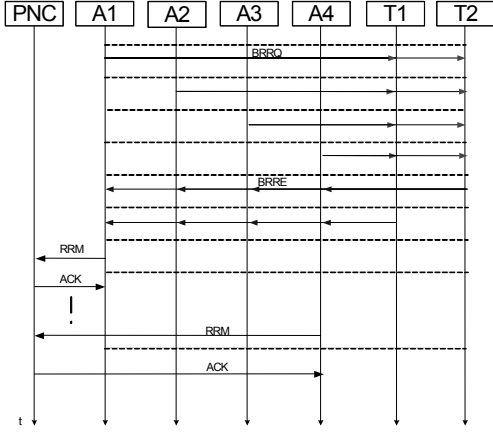


Fig. 4. Temporal diagram for "enhancement 3". Broadcasting for requests and responses used in addition to the data aggregation.

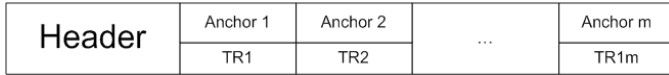


Fig. 5. Broadcast Ranging Response packet (BRRE) format.

Since all the requests are broadcasted before than the replies,  $T_R$  tends to grow as a function of target nodes  $M$ . Thus, adopting a TwoWR technique, equations 5-6 shows how the biases on the ranging estimates would be also  $M$  dependent.

This problem can be overcome through a ThreeWR procedure. Indeed equations 9-10 show that under this scheme, the estimates are unbiased but affected by a variance which corresponds to the one for the TwoWR, augmented by an additional term dependent on the ratio between  $T_R$  and  $T_D$ . Computing this ration, it can be noticed that ordering all the requests before than the replies, as shown in Figure 4, its value already drops below 1 for  $M = 5$  and converges to 0.5 when the node exceed 15.

Concluding, , as confirmed in section V, although being a less flexible strategy, our ranging packet, used with ThreeWR technique let to use the RNG TS more efficiently, at the only expense of a slight increase in the variance of the bias.

## V. COMPARISONS FOR STAR TOPOLOGIES

Table I shows, for both TwoWR and ThreeWR techniques, the number of TS required by the aforementioned enhancements procedures, in order to collect the anchor-to-target ranging information within the network.

TABLE I  
NUMBER OF TS REQUIRED BY THE DIFFERENT MAC STRATEGIES

	TwoWR	ThreeWR
Nominal	$2AM + 2AM$	$3AM + 2AM$
Enhancement 1	$2AM + 2A$	$3AM + 2A$
Enhancement 2	$A(1 + M) + 2A$	$A(1 + 2M) + 2A$
Enhancement 3	$A + M + 2A$	$A + 2M + 2A$

The gain achieved by this technique, can be appreciated from Figure 6. Here, considering as the SF length equal to 66.667 ms, as suggested by [3], the introduction of the BRRE packet, so as required by the "enhancement-3" method, even if adopted with a ThreeWR technique, overcomes all the other solutions.

Indeed, it is still possible, even in the case of a WSN containing 50 mobiles, to collect the ranging in less than one second, more than 6 time faster than the "nominal" mode.

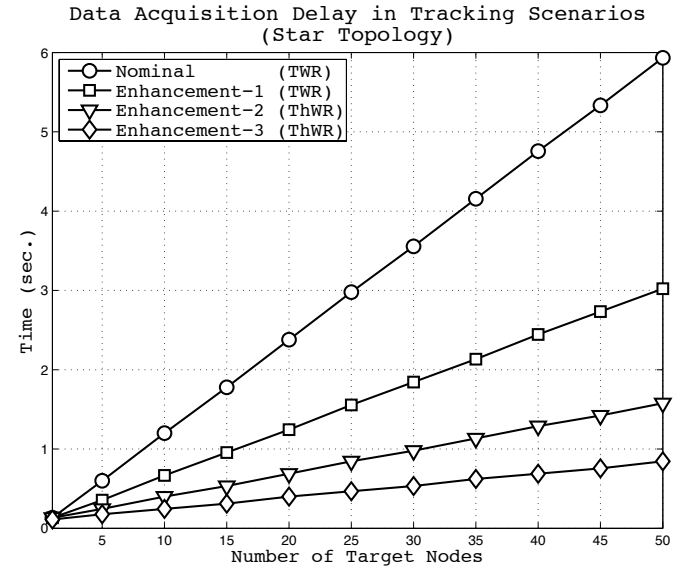


Fig. 6. Time delay for the different techniques proposed, with RNG equal to three GTS, a SF of 66.667 ms long and a scenario characterized by four anchor nodes.

## VI. RANGING ACQUISITION DATA DELAY FOR LOCALIZATION

As discussed in the previous section, under the tracking context the interest was focused on acquiring the ranging informations in the shortest time possible. Now that a pure localization application is considered, the scope changes. Assuming as allowed the ranging amongst different devices, the network assumes now a meshed topology.

Under this context, more interest is focused on the energy consumption necessary to collect the anchor-to-target and the target-to-target ranging, strongly related to the the number of packets to be sent through the network.

Although localization algorithms that do not require all the pairwise distance information [7], a fully connected meshed

topology is considered in order to find the upper bounds for the different scheduling technique proposed. Considering the difference in the network topology, it is still possible to apply the techniques discussed in section IV. The number of TS necessary to collect the ranging, due to the mutated connectivity, will differ from the one described in Table I, although the technique are still valid.

In order to minimize the number of packets, here below a new ranging procedure is proposed.

#### A. Enhancement 4

In subsection IV-C and IV-D it was shown how the usage of BRRQ and BRRE packets reduces the number of TS required to acquire the ranging information. A further optimization, particularly suitable to the localization context, can be obtain using a single broadcast ranging packet for both request and response. Figure 4 shows the transactions within the nodes in the network. This solution provides many advantages. First, the amount TS required is reduced, and more interesting, making use of the particular packet format shown in ??, all the nodes can acquire ranging information amongst all the devices in the network up to a 2-hop distance.

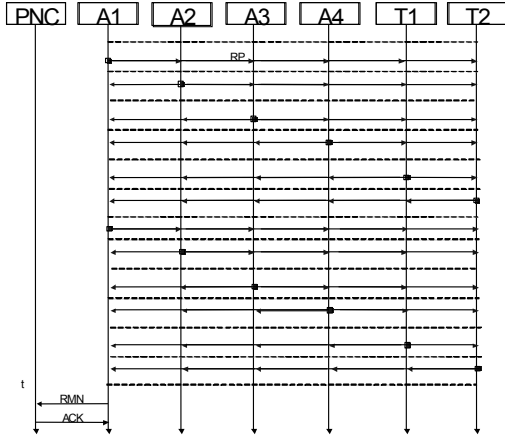


Fig. 7. Temporal diagram of the distance measurement acquisitions with a single broadcast ranging packet.

In using this scheduling technique, the formatting of the ranging packet (RP) is essential. In fact it needs to store both the time-stamp of the current packet transmission and all the time-stamps of the receiving packets after its previous transmission.

Header	Ttx	Node1	...	Nodem
		Trx1		Trxm

Fig. 8. Broadcast Ranging Response packet (BRRE) format.

## VII. COMPARISONS FOR MESHED TOPOLOGIES

Table II shows the TS necessary to collect the ranging information within the network as a function of the number of nodes, for both TwoWR and ThreeWR technique. As before,  $A$  refers to the number of anchors,  $M$  the number of mobiles while  $N$  their sum.

TABLE II

NUMBER OF TS REQUIRED BY THE DIFFERENT MAC STRATEGIES

	TwoWR	ThreeWR
<b>Nom.</b>	$2N^2 - 2N - A^2 + A$	$\frac{5}{2}(N^2 - N) - A^2 + A$
<b>En. 1</b>	$N^2 - A^2 + A - 2$	$\frac{(3N + 4)(N - 1) - 3(A^2 - A)}{2}$
<b>En. 2</b>	$\frac{(N^2 + 5N - A^2 + A - 4)}{2}$	$N^2 - A^2 + A + 2N - 2$
<b>En. 3</b>	$\frac{2N + 2(N - 1)}{2}$	$\frac{3N + 2(N - 1)}{2}$
<b>En. 4</b>	$2N + 2$	$3N + 2$

In figure 9 the time delay necessary to collect the ranging information within the network is plotted for all the five scheduling techniques under the MAC's specifications described in [3], which means a RNG period of three time slot and a SF length of 66.667 ms.

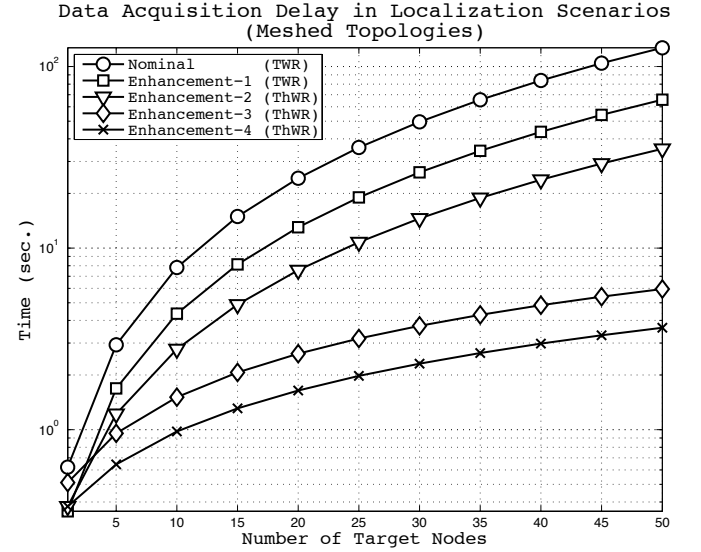


Fig. 9. Time delay for the different techniques proposed, with RNG equal to three GTS, a SF of 66.667 ms long and a scenario characterized by four anchor nodes.

## VIII. CONCLUSIONS

Two scheduling technique with the definition of the relative ranging packets, proposed in subsection IV-D and VI-A. It has been shown, how they overcome some of the limitations for the MAC layer described in [3]. In fact it has been show, how these procedures allow the collection of the ranging information in a time considerably shorter when compared to the scheduling technique currently available on the above mentioned MAC, and its enhancements too.

## REFERENCES

- [1] G. Kesidis, T. Konstantopoulos, and S. Phoah, "Surveillance coverage of sensor networks under a random mobility strategy," in *Proc. IEEE Sensors*, vol. 2, Oct. 22-24 2003, pp. 961 – 965.
- [2] A. Rao, S. Ratnasamy, C. Papadimitriou, S. Shenker, and I. Stoica, "Geographic routing without location information," in *Proc. ACM of the 9th Annual International Conference on Mobile Computing and Networking*, San Diego, CA, USA, Sep. 14 - 19 2003, pp. 96 – 108.
- [3] PULSERS Deliverable D53.2, "MAC and Networking Algorithms Specifications, Operating Code Specifications, test S/W specifications (MAC debug) [LDR-LT]", final version, Dec. 2005.
- [4] PULSERS Deliverable D53.2, "Selection of architecture for HDR and LDR-LT operational modes including simulation results", final version, Dec. 2005.
- [5] G. Destino and G. T. F. de Abreu, "Localization from imperfect and incomplete ranging," in *Proc. IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'06)*, Helsinki, Finland, Sep. 2006.
- [6] D. Macagnano and G. T. F. de Abreu, "Tracking multiple targets with multidimensional scaling," in *Wireless Personal Multimedia Communications*, San Diego, U.S.A., Sep. 17 - 20 2006.
- [7] G. Destino and G. T. F. de Abreu, "Sensor localization from wls optimization with close-form gradient and hessian," in *Proc. IEEE 49th Annual Globecom Conference (GLOBECOM'06)*, U.S.A., Nov. 27 - Dec. 1 2006.
- [8] PULSERS Deliverable D3a2.1, "LT system-PHY, MAC and Network layers", final version, Jan. 2007.