An Intuitive Prioritised Medium Access Scheme for Tracking Applications in UWB LDR-LT Networks

M. Maman, B. Denis, L. Ouvry
CEA-Leti Minatec
17 rue des Martyrs, 38054 Grenoble, France
E-mail: mickael.maman@cea.fr, benoit.denis@cea.fr, laurent.ouvry@cea.fr

Abstract—In this paper, we describe an adaption of prioritised medium access techniques for high-precision real-time tracking applications in Ultra Wideband (UWB) Low Data Rate (LDR) wireless networks. In comparison with classical Time Division Multiple Access (TDMA) schemes, the proposed uncoordinated distributed prioritised solution is compliant with critical tracking requirements in large-scale networks. More particularly, the described protocol tends to favor high-speed targets as regards to the success rate of ranging packets issued at anchor nodes, as well as to the refreshment rate and the precision of range measurements. Finally, the performance of this solution is evaluated in comparison with TDMA schemes.

Index Terms—Prioritised Medium Access, Ranging, Target Tracking, Ultra Wideband

I. INTRODUCTION

The necessity to fuse both communication and radiolocation functionalities in Wireless Personal Area Networks (WPAN) and Wireless Sensor Networks (WSN), which is mostly driven by the emergence of demanding applications (e.g. logistics, house automation, people or goods monitoring), imposes to overcome new technical challenges.

One obvious issue consists in selecting a relevant physical layer that can deliver precise radiolocation metrics. As an example, the Impulse Radio-Ultra Wideband (IR-UWB) technology (e.g. [1]) in Location and Tracking (LDR-LT) applications (e.g. [2]-[4]) benefits from fine resolution capabilities for precise range measurements, relying on Time Of Arrival (TOA) estimation and cooperative $n$-Way ranging transactions.

Another crucial aspect concerns the design of a Medium Access Control (MAC) layer that can properly support the tracking functionality under mobility. Unlike low-precision tracking services, e.g. based on RFID systems, precise tracking indeed requires that a sufficient number of accurate range measurements is periodically performed with respect to anchor nodes. The available refreshment rate and accuracy of such measurements are traditionally identified as critical parameters as target speed increases (e.g. [5], [6]).

Regarding MAC design in LDR-LT networks, recent attempts have proposed to adapt communication protocols (e.g. [2], [7], [8]) mostly for ranging purposes in static or low mobility scenarios. On the contrary, more advanced protocols, such as those inspired by Game Theory or Dutch Auctions, exhibit interesting intrinsic features in the tracking context (e.g. [10]).

This paper presents one particular adaptation of uncoordinated prioritised medium access schemes for high-precision target tracking in UWB LDR-LT networks. The main idea is that each target can locally set a priority level for the transmission of ranging responses back to anchor nodes. One intuitive rule for priority setting is based on the experienced speed or traveled distance between consecutive updates of the target positions. Consequently, this protocol naturally tends to favor high-speed targets in terms of collision probability and ranging accuracy. In addition, as scalability clearly represents a major issue for LDR-LT systems, we show that the proposed scheme is also compliant with large-scale and dense networks. Finally, the retained solution can theoretically support different levels of connectivity with respect to anchors, while adequately benefiting from the fine properties of uncoordinated prioritised access schemes, what is also required in large-scale networks.

The paper is organized as follows. Part II provides a general description of the new prioritised access scheme and overviews several possible embodiments. In Part III, we give an example of intuitive priority setting that could be relevant in the tracking context. Then in Part IV, we derive the analytical expression of the standard deviation of residual ranging errors in the particular case of acknowledged schemes. In Part V, results obtained in canonical scenarios are provided. On this occasion, performance is illustrated in terms of collision rate, refreshment rate and ranging precision. This section also includes a brief comparison with classical TDMA through further simulations. Finally, Part VI concludes the paper.

II. PRIORITISED ACCESS SCHEMES FOR TRACKING APPLICATIONS

A. General Scheme

As a first step of our investigation, we consider a simplified configuration comprising $N_A$ anchors that communicate with a set of $N_T$ mobile targets to be positioned. We also assume that $n$-Way Ranging transactions performed with respect to available anchors allow a tracking algorithm to collect range measurements based on TOA estimation and to compute mobile positions.

In the general scheme, the $N_A$ anchors share a common period of duration $T_o$ between possible updates of targets positions. Consecutive updates, which can hence occur at times $k T_o$, are based on the collection of up to $N_A$ range measurements $\hat{d}_{A,k}$ performed between target $i$ and available anchors $A$. During $T_o$ (called pseudo-period hereafter), anchors are expected to broadcast ranging requests at dedicated times to all the available targets in their respective neighborhood.
Response periods are systematically divided into $N_{p}$ pseudo-slots, so that targets can send their ranging response back to current requesting anchors and complete 2-Way ranging transactions.

Moreover, once a target is synchronized on (at least) one ranging request, it starts counting down (from an arbitrary high convinced value) and comparing its current counter to a priority level that is locally set. For evident power/time consumption considerations, it is preferable that a silent count down is realized locally by the targets based on their own clocks, so that Transmission/Reception modes can wake up only during selected pseudo-slots for delivering ranging responses. When the current count down reaches the local priority level, the target sends its response back to (at least) one requesting anchor. For each target, one priority level is set with respect to each available anchor or to a set of available anchors if the chosen rule depends on a macroscopic variable that can be valuable within the current pseudo-period whatever the considered anchor (e.g. traveled distance between two consecutive updates, target speed or position).

In addition, each pseudo-period $T_{p}$ should preferentially comprise the transmission of acknowledgements (ACKs) from anchors to responding targets, enabling to perform two consecutive 2-Way transactions and hence to correct raw range measurements. This correction of clock drift effects based on 3-Way schemes ([7], [9]) is discussed in section IV. This packet is also used to indicate if the ranging response is successful and/or to send specific information related to target status, such as its speed or traveled distance.

One further general statement is that the selection of two distinct priority levels (i.e. two distinct pseudo-slots) guarantees the successful reception of ranging responses. Thus, the smallest temporal granularity (i.e. the minimum pseudo-slot duration) must be carefully designed to prevent from collisions. This duration, called $T_{S}$, enables to encompass all the plausible Times of Flight (TOF) with respect to available anchors (considering network topology and geometry), synchronization (i.e. uncertainty on the beginning of each pseudo-slot at local clocks), clock uncertainties (e.g. clock drift), as well as packet durations.

B. Possible Embodiments

1) Broadcasted Requests and Responses: One first solution relies on the possibility to send ranging requests from different anchors within $T_{p}$ at the beginning of each period $T_{o}$, and to broadcast each ranging response to anchors, hence enabling to share and save time resources (Figure 1).

The broadcast of ranging responses/requests and the use of immediate ACKs from anchors called BRR-IA appear particularly relevant for larger networks under partial connectivity, where targets can only communicate with a partial set of anchors. Moreover, one target performs range measurements with respect to several anchors almost simultaneously and does not need to wait for several anchor periods before updating its position. This particularity prevents from the traditionally harmful dispersion of range measurements under mobility.

Another clear advantage is that one target, which can not get synchronized on a sufficient number of requests (typically 3 in the 2D plane), can take the decision to remain silent. Hence, targets that would not be able to update their position are discarded and do not contribute to collisions.

2) Broadcasted Acknowledgements: One possible enhancement to the BRR-IA scheme consists in delaying and broadcasting ACK from targets at the end of the overall period (Figure 2). This solution, called BRR-BA, is clearly optimized as regards to resources consumption.

Finally, note that the two described schemes could be advantageously coupled with a spatial reuse of resources, allowing several anchors to operate simultaneously.

III. EXAMPLE OF SIMPLE PRIORITY SETTING

As it has been previously mentioned, a specific rule has to be defined locally to set the priority level $P_{i,k}$ in each node $i$ at step $k$. As an example, we propose a function that tends to favor high-speed targets, as follows:

$$ P_{i,k} = C_{i,k} + f_{i,k} = \lceil \frac{\tilde{D}_{i,k-1}}{\delta_{d}} \rceil + f_{i,k} $$  \hspace{1cm} (1) $$

where $C_{i,k}$ is a coarse-grain priority level at time $k$ chosen among $N_{p}$ values, $f_{i,k}$ is one realization of a discrete random variable corresponding to the fine-grain priority level (preventing from collisions for targets having similar coarse-grain priority levels), $\tilde{D}_{i,k-1}$ is an estimation of the distance traveled by the target since the last updates (e.g. available from its previous position updates) and $\delta_{d}$ is the value between two consecutive coarse-grain priority levels defined as $\delta_{d} = \frac{P_{\text{max}}}{N_{p}}$. 

![Figure 1. Prioritised access scheme with a BRR-IA scheme.](image1)

![Figure 2. Prioritised access scheme with a BRR-BA scheme.](image2)
with $D_{\text{max}} = v_{\text{max}} T_o$ the maximum observable distance traveled between two consecutive updates (considering the best refreshment period as $T_o$) and $s$ a scaling factor that enables to enlarge the maximum priority level for constant $D_{\text{max}}$.

As for the fine-grain priority level $f_{i,k}$, it can be uniformly drawn according to the following probability density function:

$$p(f_{i,k}) = p(f_i) = \frac{1}{n_p} \sum_{i=1}^{n_p} \delta\left(f_i - \left(\frac{i}{n_p} - \frac{1}{2}\right)\right)$$

(2)

where $n_p$ is the number of possible fine-grain positions.

Moreover, the maximum priority level $P_{\text{max}} = N_p + 1/2$ can be arbitrarily set as the priority obtained with $s = 1$ while experiencing a displacement amplitude $D$ that approaches $D_{\text{max}}$ (i.e. $D < D_{\text{max}}$) under the standard refreshment period $T_o$. Priority can hence be systematically bounded accordingly:

$$P_{i,k} = \min(C_{i,k} + f_{i,k}, P_{\text{max}})$$

(3)

Nevertheless, if $s = 1$ and if the coarse-grain granularity is systematically set depending on the latest displacement amplitude (i.e. without any memory of past events), then the $\min(.)$ operator in the previous expression is useless.

Finally, even if the total number $N_R$ of addressable pseudo-slots for ranging responses is constrained by $N_R = N_p n_p = \text{cst}$, the strength can be put on the deterministic or random flavor of priority levels, by properly adjusting $N_p$ and $n_p$ parameters.

IV. RANGING ACCURACY WITH ACKNOWLEDGED RANGING TRANSACTIONS

A. General Model

In this section, we provide the expression of the standard deviation of range measurements under both schemes, as a function of protocol durations and the uncertainty terms affecting TOA estimates. Under these schemes, the ranging response can be used as the request of a second 2-Way ranging transaction. According to [9], raw TOF measurements $\bar{\tau}_A$ (resp. $\bar{\tau}_T$) issued at an anchor $A$ (resp. a target $T$) from 2-Way ranging transactions can be expressed as follows:

$$\bar{\tau}_A = \varepsilon_A \tau + \left(\frac{\varepsilon_A}{\varepsilon_T} - 1\right) \frac{T_T}{2} + \frac{\varepsilon_A}{2} (n_{T1} + n_A)$$

(4)

$$\bar{\tau}_T = \varepsilon_T \tau + \left(\frac{\varepsilon_T}{\varepsilon_A} - 1\right) \frac{T_A}{2} + \frac{\varepsilon_T}{2} (n_A + n_{T2})$$

(5)

where $\varepsilon_A$ and $\varepsilon_T$ respectively refer to the relative frequency of anchor’s and target’s clocks, $\tau$ refers to the actual TOF, $T_T$ is the response time at the target (i.e. the time elapsed between the reception of the ranging request and the emission of the ranging response), $T_A$ is the response time at the anchor (i.e. the time elapsed between the reception of the ranging response and the emission of the ACK) and $n_{T1}$ (resp. $n_A$, $n_{T2}$) is a centered noise term affecting the TOA of the ranging request (resp. ranging response, ACK) estimated at the target (resp. target and anchor) with a standard deviation $\sigma_T$.

From the two previous estimates $\bar{\tau}_A$ and $\bar{\tau}_T$, the relative clock ratio can be estimated as follows:

$$\left(\frac{\varepsilon_A}{\varepsilon_T} - 1\right) e = \frac{2(\bar{\tau}_A - \bar{\tau}_T)}{T_A + T_T}$$

(6)

Finally, the estimated TOF can be corrected according to:

$$\bar{\tau}_C = \bar{\tau}_A - \left(\frac{\varepsilon_A}{\varepsilon_T} - 1\right) \frac{T_T}{2}$$

(7)

After straightforward manipulations, it can be proved that the resulting corrected estimate is unbiased, but still affected by a centered noise term with the following standard deviation:

$$\sigma_T = \frac{\sigma_n}{\sqrt{2}} \sqrt{1 + \left(1 - \frac{T_T}{T_T + T_A}\right)^2 + \left(\frac{T_T}{T_T + T_A}\right)^2}$$

(8)

Based on Eq. (8), the ranging performance of both schemes will be characterized here through the evaluation of the standard deviation of corrected range measurements $\sigma_d = c \sigma_T$ (with $c$ the speed of light).

Finally, for the BRR-IA scheme, $T_A \approx T_3 = \text{cst}$ with respect to the first requesting anchor whatever the priority level and the monotony of the standard deviation function is then naturally favorable to high-speed targets. On the contrary for the BRR-BA scheme, $T_A + T_C \approx T_o - 2T_T = T_o - 2N_a T_3 = \text{cst}$ with respect to the first requesting anchor, leading to unordered standard deviations as a function of target speed. Thus, a new priority setting will be proposed to mitigate this effect in IV-B.

B. Re-ordering of Ranging Standard Deviations for Delayed/Broadcasted Acknowledgements

As pointed out in a previous section, BRR-BA is optimized in terms of resource consumption but less advantageous as regards to ranging performance. Indeed, the standard deviation of range measurements is no more a monotonic function of target speed for typical $T_T$ and $T_A$ values. More specifically, medium-speed targets are exaggeratedly favored in comparison with higher-speed targets. To overcome this problem, we propose to modify the priority setting in Eq. (1), by adding a new random term after defining the priority level:

$$P_{i,k} = p_{i,k} P_{i,k} + (1 - p_{i,k}) (2P_{\text{max}} - P_{i,k} + 1/n_p)$$

(9)

where $p_{i,k} \in \{0, 1\}$ is a uniformly distributed discrete random variable reflecting a “polarity” uncertainty when choosing the addressable pseudo-slot for the transmission of a ranging response. In comparison with BRR-BA, this scheme, called Flipped BRR-BA, practically leads to multiply by 2 the number of addressable pseudo-slots as $N_R = 2N_p n_p$ if $N_p n_p = \text{cst}$, or equivalently, to divide $N_R$ by 2 (and artificially multiply $n_p$ by the same factor) if $N_R$ remains constant.

V. RESULTS

In this section, we point out the main advantages and drawbacks of the described protocol solutions. For the sake of simplicity, we still consider that $N_t$ targets can communicate with $N_a$ anchors (i.e. under full connectivity). Without loss of generality, we also assume that anchors are perfectly synchronized, and that targets share exactly the same common count down value. In other words, we just consider that $T_3$ enables to tolerate timing uncertainties so that the previous assumptions are still valid.
A. Achievable Refreshment Rate and Ranging Performance

Performance is characterized here in terms of suffered collision rate, achievable refreshment period and dispersion of range measurements, as a function of target speed. One target (with the arbitrary index $i = 1$) has constant 2D speed $v_{1,k} = v_1$ and $N_t - 1$ competing targets with 2D speeds (also constant over the observation period $T_{obs}$), which follow a Rayleigh distribution with standard deviation $\sigma_n \approx 1\text{m.s}^{-1}$ (to satisfy $v_1 \leq v_{\text{max}}$). Finally, at the initialization, we consider that each target starts with known $\tilde{D}_{i,0}$ (e.g. just like in a steady-state regime with no collision).

1) Immediate ACKs: The following BRR-IA curves characterize the performance with $N_t = 40$, $N_p = 5$, $n_p = 6$, $N_R = 30$, $T_s = 500\mu$s, $T_o = 77\text{ms}$, $v_{\text{max}} = 5\text{m.s}^{-1}$ over $T_{obs} = 3s$.

Figures 3 and 4 illustrate respectively the evolution of the collision rate for Target 1’s response message and the standard deviation of corrected range measurements for the BRR-IA scheme, considering $T_A \approx T_s$ and $\sigma_n = 3\text{ns}$, as a function of Target 1’s speed $v_1$. As it can be noticed, collision probabilities and ranging performance are properly ordered as a function of $v_1$, although the corresponding standard deviations appear to be less dispersed as a function of speed.

![Fig. 3. Collision Probabilities for Target 1’s Ranging Response, as a function of $v_1$](Image)

![Fig. 4. Mean standard deviations of unbiased corrected range measurements at Target 1, as a function of $v_1$](Image)

Fig. 5 shows the corresponding achievable refreshment rate for BRR-IA over $T_{obs}$, as a function of $v_1$. Again, high-speed targets are properly favored here.

2) Delayed/Broadcasted ACKs: In this subsection, we evaluate the performance of BRR-BA, with the same parameters as in BRR-IA, excluding the new pseudo-period duration $T_s = 19\text{ms}$. As expected, on Figure 3, the experienced instantaneous collision rate per pseudo-period as function of speed is exactly the same as with BRR-IA. Figure 4 and Figure 5 show respectively the standard deviations of corrected range measurements considering $T_A \approx T_o - T_s - T_F + T_F$ and $\sigma_n = 3\text{ns}$, and the achievable refreshment rate as a function of $v_1$.

B. Impact of Target Number and Coarse-priority Levels

We evaluate the impact of the number of targets $N_t$ and the number of coarse-priority levels $N_p$ for BRR-IA and BRR-BA (with $n_p = N_R/N_p$), and Flipped BRR-BA (with $n_p = 0.5N_R/N_p$).

Figures 6 and 7 show respectively the evolution of the collision rate and the average refreshment period obtained with the 3 prioritised schemes, as a function of $N_t$ and $v_1$, with $N_p=5$, $N_o=4$, $v_{\text{max}} = 5\text{m.s}^{-1}$ and $T_s = 500\mu$s (under $N_R = 30 = \text{cst}$). The standard deviation of corrected range measurements as a function of $N_t$ is not shown here because one advantage with the prioritised access is that the standard deviation of range measurements does not depend on $N_t$.
Figures 8 to 10 show similar curves and the evolution of the standard deviation of corrected range measurements, as a function of $N_P$ (under $N_T = 30 = cst$) and $v_1$, with $N_t = 40$, $N_0 = 4$, $v_{\text{max}} = 5 \text{m/s}^2$ and $T_S = 500 \mu\text{s}$.

![Fig. 8. Collision rate for Prioritised schemes as a function of $N_P$ and $v_1$](image)

![Fig. 9. Refreshment period over $T_{\text{obs}} = 1s$ for Prioritised schemes, as a function of $N_P$ and $v_1$](image)

![Fig. 10. Standard deviation of corrected range measurements for Prioritised schemes, as a function of $N_P$ and $v_1$](image)

C. Comparison with TDMA Schemes

In this section, we evaluate the global performance of BRR-BA for 3 priority distributions. In particular, we consider underlying Rayleigh (RD) and one-sided Gaussian (SGD) distributions of 2D speeds with the basic priority setting of Eq. (1) on the one hand, and a uniform distribution of random response times corresponding to a distributed ALOHA TDMA scheme on the other hand. For the latter, each target randomly chooses a pseudo-slot in the pseudo-superframe (PSF) of duration $T_o$ (with the same structure as on Figure 2) and transmits its ranging response in a pseudo-slot without paying attention to possible collisions. “Useful” pseudo-slots then refer to addressable pseudo-slots when the transmissions of ranging responses are successful. Finally, we set $N_P = 10$, $n_p = 3$, and $v_{\text{max}} = 5 \text{m/s}^{-1}$.

Figure 11 shows the number of useful pseudo-slots per PSF composing $N_R = N_PP = 30$ addressable positions overall. In this example, the best scheme is clearly based on an ALOHA TDMA approach for a network containing up to around $N_t = 86$ targets whereas beyond 86, the prioritised scheme enjoys better performance. Indeed, collisions are uniformly spread over slots whereas the prioritised scheme tends to concentrate collisions within low-priority pseudo-slots. Hence, the proposed scheme is relevant for large-scale networks and/or high-density networks. We insist on the fact that these results account for a global behaviour without target differentiation (i.e. over speeds), considering uniquely the overall number of successful communications per period. Anyway, one of the advantages of prioritised schemes relies on the possibility to choose locally in a distributed context which communications should have the highest probability of success, what is clearly not handled by ALOHA TDMA schemes.

![Fig. 11. Mean number of useful pseudo-slots over a 30-slot PSF, as a function of the target number $N_t$.](image)
high with BRR-BA for the first high-priority pseudo-slots, even under large numbers of targets \( N_t \), whereas TDMA schemes exhibit very low probabilities of success under similar conditions. This result is perfectly in line with classical concepts from Game Theory, as some nodes deliberately degrade their performance to favor more demanding nodes.

Figure 12. Probability of successful ranging responses as a function of the addressed pseudo-slot (slot index) and the number of competing targets \( N_t \).

Figure 13 shows the corresponding refreshment period. Our prioritised scheme offers a high refreshment rate to high-priority targets (i.e. with low slot index in the example) and a longer refreshment period to low-priority targets (i.e. almost static targets).

Finally, Figure 14 provides another comparison with TDMA with 30 pseudo-slots per PSF, for a SGD of coarse-grain priority levels. As an example, for a 80-target network, the refreshment rate for slot 1 (resp. slot 25) is 10 times higher (resp. 18 times lower) for the prioritised scheme than for TDMA.

VI. CONCLUSION

In this paper, we have described a prioritised access scheme for tracking applications in UWB LDR-LT networks. First of all, the proposed solution proves to enjoy fine robustness in large-scale or high density networks. Then, from a distributed perspective, one interesting property is that each target can determine \textit{a priori} its local importance and/or success rate with respect to other targets. It has been also shown that several performance indicators could be properly sorted (e.g. ranging standard deviations, collision refreshment rates) as a function of arbitrary criteria (e.g. target speed). Finally, the solution is also likely to offer fine flexibility as priority rules could be easily optimized depending on the retained criterion to favor, or on the initial distribution of target speeds.

In comparison with unprioritised solutions, such as decentralized or coordinated TDMA schemes, one of the most obvious drawbacks is that performance is globally degraded in terms of temporal occupation in small scale networks.

Complementing studies have been recently initiated to enhance the proposed scheme defining new priority functions for different distributions of speeds.

ACKNOWLEDGMENT

This work has been partly realized in the frame of the PULSERS II European Integrated Project (http://www.pulsers.eu). The authors would like to thank the partners involved in WP3a for their support, and especially the people from the Center for Wireless Communications (University of Oulu, Finland) and from the University of Karlsruhe (Germany).

REFERENCES