ENHANCED LOCALIZATION COVERAGE WITH NON-REGENERATIVE UWB RELAYS

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ABSTRACT

Real-time locating systems (RTLS) enable a number of new important applications. Their performance is mainly limited by wireless propagation impairments. This paper puts forth the idea to enhance coverage and accuracy of RTLS in the presence of severe non line-of-sight propagation conditions using low complexity non-regenerative ultra-wide bandwidth relays. A maximum likelihood position estimator is derived and the feasibility of relay-based positioning scheme is demonstrated.

1. INTRODUCTION

Real-time locating systems (RTLS) are extremely important for current and future applications [1]. They are usually composed of nodes (*tags*) attached to or embedded in objects, and of reference nodes (*anchors*) that communicate with these tags through wireless signals to determine their locations. High-accuracy positioning can be obtained through the ultrawide bandwidth (UWB) technology [2]. In fact UWB technology [3] offers the potential of achieving high ranging accuracy through signal time-of-arrival (TOA) measurements due to its ability to resolve multipath [4].

Unfortunately, the presence of obstacles in real environments generates non line-of-sight (NLOS) propagation conditions that can make ranging challenging, leading to a limitation of the coverage area of the localization system. The typical solution to deal with severe NLOS conditions is to increase the number of anchors with higher infrastructure and deployment costs and complexity due to the necessity of keeping anchors tightly time synchronized when time-based positioning approaches are adopted. Therefore there is the need of low cost and flexible solutions to increase area coverage for RTLSs.

Communication networks coverage can be increased using regenerative relays, namely detect & forward (DF) [5]. Extensive literature is available dealing with relays in ad hoc wireless networks for communication reliability enhancement but fews focus on the use of relays for localization. In [6] the problem of locating and tracking passive point scatterers or regenerative relays is investigated using UWB signals. UWB positioning with a single anchor is proposed in [7] where the knowledge of the room geometry is exploited to map the signal reflections in the room walls onto a set of virtual anchors used for estimating the position of the tag. This requires an accurate electromagnetic knowledge of the environment. In [8] the adoption of cooperating regenerative relays is proposed to reduce the number of transmissions, thus overcoming the overhead and scaling inefficiencies of conventional two-way ranging approaches. Unfortunately, regenerative relays for localization have almost the same complexity of anchors since not only data transmission but also signal TOA estimation (ranging) have to be implemented. Therefore, issues related to cost, the need of power supply and tight synchronization among relays still remain as a drawback.

We consider a low complexity alternative solution to regenerative relays that is the employment of *non-regenerative relays* for localization coverage enhancement, where neither modulator nor demodulator sections are present in the relay and the signal is only repeated. Non-regenerative relays can be active, namely *amplify & forward (AF)*, or completely passive, we call them *just forward (JF)* (also referred to as *cold repeaters*). In JF relays no signal amplification is present. Note that non-regenerative relays are well known in communication networks [10]; JF relays have been adopted as gap fillers in broadcast systems since several years ago and, more recently, in Wi-Fi networks to cover shadowed areas especially in indoor environments. In [9] an UWB AF relay based on pulse delay is proposed with the purpose to extend the communication coverage. JF relays are usually composed of a couple of interconnected directive antennas and take advantage of antenna gains to mitigate the additional path loss caused by obstacles [10]. Non-regenerative relay based systems present in the literature are oriented to improve the communication coverage and reliability and no similar solutions have been proposed for positioning.

In this paper we propose a RTLS for high-accuracy localization and tracking using UWB signals employing anchors

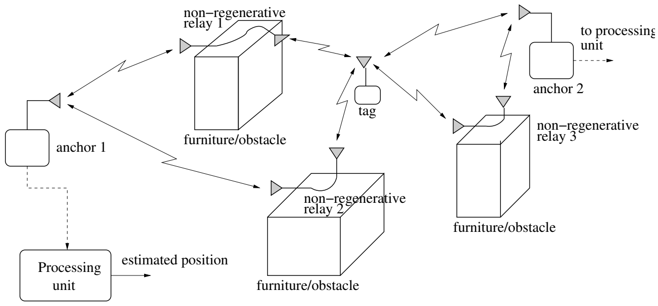

Fig. 1. Example of localization system employing non-regenerative relays.

and a set of non-regenerative UWB relays (AF or JF) deployed in fixed known positions. The purpose of the relays is to repeat the signal exchange between anchors and tags and hence to enhance the localization and identification of the tags, even in the presence of obstacles and severe NLOS propagation conditions. Then we design a maximum likelihood (ML) position estimator to show the feasibility and assess the performance of the proposed method.

2. SYSTEM MODEL

We consider a RTLS (see Fig. 1) with an infrastructure composed of N_{A} anchors in known positions $\mathbf{p}_n^{(\text{A})}$, for $n = 1, 2, \ldots, N_{\text{A}}$, a set of N_{R} non-regenerative unidirectional relays in known positions $\mathbf{p}_i^{(\text{R})}$, for $i = 1, 2, \ldots, N_{\text{R}}$, and a generic tag in unknown position $\mathbf{p}$ to be determined. Anchors are considered to be synchronized.

2.1. Non-Regenerative UWB Relays

The JF UWB relay is composed of a directional high gain antenna, an electrical cable and a second directional or omni-directional antenna. The relay partially compensates the additional path loss caused by the two-hop link because of the directional properties of the antenna.

The AF UWB relay can be implemented in several ways. Unidirectional relays are sufficient when operating in a RTLS with one-way ranging protocols, whereas more complex relays are necessary in case of two-way ranging protocols [2]. The mutual coupling between antennas must be controlled through proper isolation and deployment to avoid unstable loop caused by positive feedbacks. This effect might cause a limitation on the maximum tolerable signal amplification level.

2.2. Signal Model

Tags emit UWB pulses that can be received by one or more anchors through a direct path in line-of-sight (LOS) and multipath due to reflections from walls and obstacles. Pulses can be modulated according to a time-hopping sequence and/or a bipolar sequence to make the transmitted signal unique of that specific tag and allowing the coexistence of multiple tags in the same scenario [3]. Here, without loss of generality, we consider the transmitted ranging packet composed of N_{s} amplitude modulated pulses as follows[1]

$$s(t) = \sum_{k=0}^{N_{\text{s}}-1} a_k \, p(t - kT_{\text{f}} - t_0) \tag{1}$$

where T_{f} is the pulse repetition period, and t_0 is the time offset of the tag's internal clock with respect to that of the anchors.[2]

The transmitted pulses are received by anchors and eventually repeated by one or more relays. Therefore the received signal at the mth anchor takes the form

$$r_m(t) = s_m(t) + \sum_{i=0}^{N_{\text{R}}} n_{i,m}(t) \tag{2}$$

where $n_{i,m}(t)$, for $i = 1, \ldots N_{\text{R}}$, is the thermal noise, with one-side power spectral density (PSD) $N_{i,m}$, due to the ith relay as seen by the mth anchor due to the tag-anchor propagation, and $n_{0,m}(t)$ is the thermal noise due to the anchor with PSD $N_{0,m}$. We consider $N_{0,m} = N_0$, $\forall m$. The useful term $s_m(t)$ is given by

$$\begin{aligned} s_m(t) = {} & w\left(\mathbf{p}, \mathbf{p}_m^{(\text{A})}\right) g_{0,m}\left(t - \tau\left(\mathbf{p}, \mathbf{p}_m^{(\text{A})}\right) - t_0\right) \\ & + \sum_{i=1}^{N_{\text{R}}} w\left(\mathbf{p}, \mathbf{p}_i^{(\text{R})}\right) \sqrt{G_i}\, w\left(\mathbf{p}_i^{(\text{R})}, \mathbf{p}_m^{(\text{A})}\right) \\ & \times g_{i,m}\left(t - \tau\left(\mathbf{p}, \mathbf{p}_i^{(\text{R})}\right) - \delta^{(\text{R})} - t_0 - \tau\left(\mathbf{p}_i^{(\text{R})}, \mathbf{p}_m^{(\text{A})}\right)\right) \end{aligned} \tag{3}$$

where $\tau(\mathbf{p}_1, \mathbf{p}_2) \triangleq ||\mathbf{p}_1 - \mathbf{p}_2||/c$ is the time taken by the signal to reach position $\mathbf{p}_2$ from $\mathbf{p}_1$ being c the speed of light, G_i is the gain of the ith relay, and $\delta^{(\text{R})}$ is the delay introduced by the relay mainly caused by the presence of the electrical cable (and the amplifier in AF relays). Pulses $g_{i,m}(t)$, for $i = 1, 2, \ldots N_{\text{R}}$, are the channel responses to $s(t)$ related to the link $\{$tag $\rightarrow$ ith relay $\rightarrow$ mth anchor$\}$, whereas $g_{0,m}(t)$ are the channel responses to $s(t)$ related to the link $\{$tag $\rightarrow$ mth anchor$\}$. They account for multipath propagation effects and pulse distortion caused by antennas and circuits frequency selectivity. In this formulation multiple hop paths between relays are neglected, since they are expected to be strongly mitigated by directive antenna radiation patterns. The summation

[1]Through a proper design of the spreading sequence $\{a_k\}$ it is possible to reduce the multi-user interference in a multi-tag scenario. The analysis of multi-user interference is beyond the scope of this paper.

[2]t_0 is unknown to the anchors since, in general, tags and anchors nodes are not synchronous. However, in some system configurations tags can be partially synchronized through a dedicated conventional control channel (e.g., at 2.4 GHz or UHF). In such a case the initial uncertainty on t_0 can be significantly reduced.

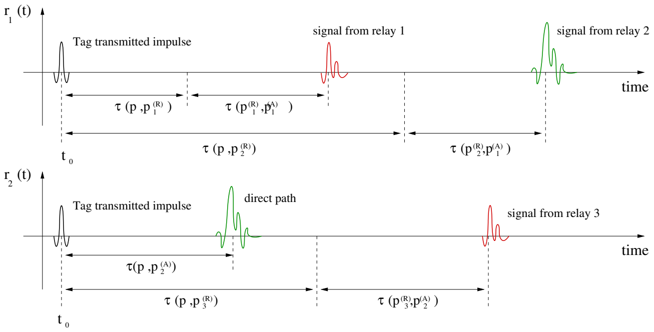

Fig. 2. Example of signal structure in a scenario adopting active tags. $\delta^{(\mathrm{R})} = 0$. $r_1(t)$ and $r_2(t)$ are the signals received by anchors 1 and 2, respectively.

in (3) accounts for all signals repeated by the relays, whereas the first term accounts for the direct path between the tag and the anchor.

When a path between generic positions $\mathbf{p}_1$ and $\mathbf{p}_2$ exists, the coefficient $w(\mathbf{p}_1, \mathbf{p}_2)$ accounts for the transmitted power, antenna gains, and path loss. Specially, it can be expressed as:

$$w(\mathbf{p}_1, \mathbf{p}_2) = \sqrt{\frac{1}{L(\mathbf{p}_1, \mathbf{p}_2)}} \tag{4}$$

where

$$L(\mathbf{p}_1, \mathbf{p}_2) = L_0 \, ||\mathbf{p}_1 - \mathbf{p}_2||^{\beta} \Psi(\mathbf{p}_1, \mathbf{p}_2) \tag{5}$$

is the intrinsic channel path loss, with path loss exponent β, and L_0 is the path loss at 1 meter. The term $\Psi(\mathbf{p}_1, \mathbf{p}_2)$ is a comprehensive coefficient that accounts for TX and RX antennas' radiation patterns.[3] In the absence of a path (severe NLOS propagation condition) $w(\mathbf{p}_1, \mathbf{p}_2) = 0$. Note that the information about radio visibility can be derived from the environment knowledge [11].

For the sake of illustration, in Fig. 2 an example of signal structure received by anchors A and B in the scenario of Fig. 1 is depicted considering the presence of $N_{\mathrm{R}} = 3$ relays and $N_{\mathrm{A}} = 2$ anchors nodes and additive white Gaussian noise (AWGN) channels. As can be seen, the pulse emitted by the tag at time $t = t_0$ is received by relay 1 after $\tau\left(\mathbf{p}, \mathbf{p}_1^{(\mathrm{R})}\right)$ seconds and then repeated. The repeated signal arrives at anchor 1 after $\tau\left(\mathbf{p}, \mathbf{p}_1^{(\mathrm{R})}\right) + \tau\left(\mathbf{p}_1^{(\mathrm{R})}, \mathbf{p}_1^{(\mathrm{A})}\right)$ seconds. Note that the delay $\tau\left(\mathbf{p}_1^{(\mathrm{R})}, \mathbf{p}_1^{(\mathrm{A})}\right)$ is known since the positions of anchors and relays are a priori known. However, for certain geometrical configurations and multipath propagation, signal ambiguities (overlapping) could occur with possible performance degradation.

[3] Antenna frequency selectivity is included in the channel response $g_{i,m}(t)$.

3. MAXIMUM LIKELIHOOD LOCALIZATION

The signals received by each anchor are collected at a central processing unit, which proceeds in estimating the position of each tag. Here a ML approach is devised to estimate the tag's position considering perfect channel state information (CSI), that is, a perfect knowledge of $g_{i,m}(t)$ and $w(\cdot, \cdot)$. The purpose is to assess the feasibility of the proposed architecture and provide benchmarks for more practical positions estimators. The likelihood function related to the position $\mathbf{p}$ of the tag and time instant t_0 is

$$\Lambda(\mathbf{p}, t_0) = \prod_{m=1}^{N_{\mathrm{A}}} \exp\left\{ \frac{1}{N_m} \int_T [r_m(t) - s_m(t; \mathbf{p}, t_0)]^2 dt \right\} \tag{6}$$

where T is the observation interval that has to be chosen for accommodating all the useful signal echoes, $N_m = N_0 + \sum_{i=1}^{N_{\mathrm{R}}} N_{i,m}$ represents the overall noise PSD at each anchor, and where we have made explicit the dependence of $s_m(t)$ on the position $\mathbf{p}$ and t_0. Taking the logarithm and discarding all the terms that does not bring contribution for the maximization with respect to $\mathbf{p}$ and t_0, the log-likelihood function results in

$$l(\mathbf{p}, t_0) = \sum_{m=1}^{N_{\mathrm{A}}} \frac{2}{N_m} \int_T r_m(t) \, s_m(t; \mathbf{p}, t_0) \, dt - \sum_{m=1}^{N_{\mathrm{A}}} \frac{1}{N_m} \int_T s_m^2(t; \mathbf{p}, t_0) \, dt \, . \tag{7}$$

The last integral in (7) returns the energy of $s_m(t; \mathbf{p}, t_0)$, namely $E_m(\mathbf{p})$, which does not depend on t_0 but only on $\mathbf{p}$. The ML position estimate $\hat{\mathbf{p}}$ of the tag is given by

$$\hat{\mathbf{p}} = \arg \max_{(\mathbf{p}, t_0)} l(\mathbf{p}, t_0) \, . \tag{8}$$

In particular, by replacing (2) and (3) in (7) we obtain

$$\begin{aligned} l(\mathbf{p}, t_0) = \sum_{m=1}^{N_{\mathrm{A}}} \Bigg\{ \frac{2}{N_m} \Bigg[& \sum_{i=1}^{N_{\mathrm{R}}} w(\mathbf{p}, \mathbf{p}_i^{(\mathrm{R})}) \sqrt{G_i} \, w(\mathbf{p}_i^{(\mathrm{R})}, \mathbf{p}_m^{(\mathrm{A})}) \\ & \times \chi_{i,m} \left(\tau\left(\mathbf{p}, \mathbf{p}_i^{(\mathrm{R})}\right) + \tau\left(\mathbf{p}_i^{(\mathrm{R})}, \mathbf{p}_m^{(\mathrm{A})}\right) + \delta^{(\mathrm{R})} + t_0 \right) \\ & + w(\mathbf{p}, \mathbf{p}_m^{(\mathrm{A})}) \, \chi_{0,m} \left(\tau\left(\mathbf{p}, \mathbf{p}_m^{(\mathrm{A})}\right) + t_0 \right) \Bigg] - \frac{E_m(\mathbf{p})}{N_m} \Bigg\} \end{aligned} \tag{9}$$

where the inner summation accounts for the paths related to relays contribution and the second term accounts for the direct reader-tag path. In (9) we have defined the correlation term

$$\chi_{i,m}(\xi) \triangleq \int_T r_m(t) \, g_{i,m}(t - \xi) \, dt \, , \tag{10}$$

and the energy term

$$E_m(\mathbf{p}) \triangleq \int_T s_m^2(t; \mathbf{p}, t_0) \, dt \, . \tag{11}$$

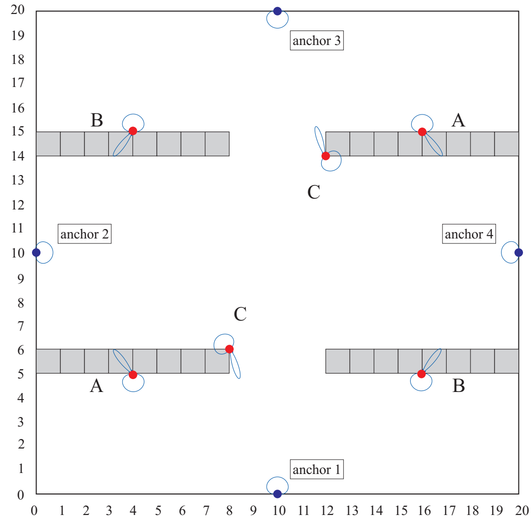

Fig. 3. The scenario considered in the numerical results. Blu points refer to anchors. Red points (A,B,C) refer to relay nodes. In both cases the antenna radiation pattern and orientation are reported. Obstacles are depicted in grey.

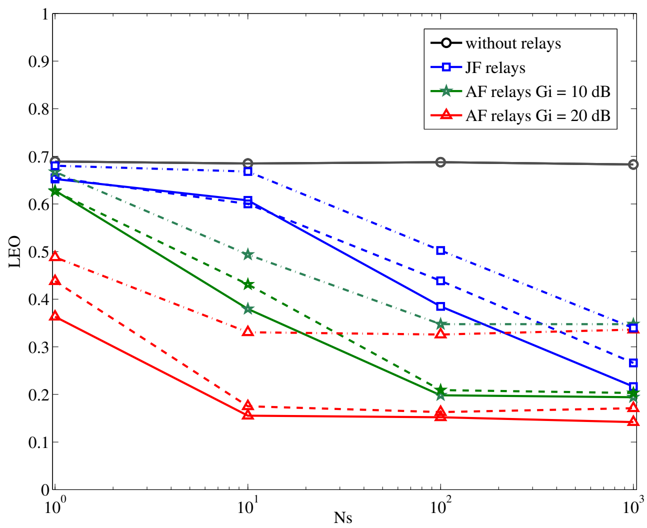

Fig. 4. LEO considering the simulation scenario of Fig. 3. Continuous lines (–) refer to 6 relays (A,B,C). Dashed lines (- -) refer to 4 relays (A,C). Dot-dashed lines (· -) refer to 4 relays (A,B).

Remark: The proposed architecture based on non-regenerative relays is not limited to the ML position estimate described above. In [12] non coherent estimators are investigated to relax the assumptions on knowledge of the pulse shape or of the relation between tag position and received energy (i.e., partial CSI).

4. CASE STUDY

We now evaluate the performance of the relay-based localization scheme adopting the ML estimation technique. In particular a IEEE 802.15.4a compliant transmission in considered, with root raised cosine (RRC) pulses centered at frequency $f_0 = 4$ GHz, roll-off factor $\eta = 0.6$, and a pulse width parameter $\tau = 1$ ns. Tags are equipped with an omnidirectional antenna with gain $G_\mathrm{T} = 0$ dBi, and with transmitting power compliant to the FCC emission limit in the $3-5$ GHz band. Anchors have noise figure $F = 7$ dB[4] and are equipped with a weak directional antenna presenting a maximum gain $G_\mathrm{A} = 5$ dBi and a half power beam width (HPBW) of 150 degrees. Relay nodes are equipped with the same kind of antenna oriented towards the part of the environment to be covered, and with a directional antenna presenting a maximum gain $G_\mathrm{R} = 10$ dBi and a HPBW of 20 degrees for the relay-reader link.

A dense multipath model is adopted for the tag-anchor and tag-relay channels considering an exponential power delay profile (PDP) with paths separated of 1.5 ns apart, each path with Nakagami fading (severity factor $m = 3$) except for the first path taken as deterministic according to the free-space path loss model ($\beta = 2$), and a rms delay spread of 3 ns.[5] Due to the high directivity of the relay antenna oriented in the anchor direction, an AWGN relay-anchor channel is considered. A sub-optimal version of the ML position estimation strategy (9) is used by considering in (10) the templates at the receiver $g_{i,m}(t)$ equal to $p(t)$; this is equivalent to the adoption of a filter matched to the first-path only, without taking advantage of the multipath energy as in a rake-like implementations.

Numerical results have been obtained with Monte Carlo simulations considering the tags uniformly distributed in the monitored area. As performance indicator we adopt the localization error outage (LEO), defined as the rate at which the localization error is greater than a given target error $e_\mathrm{th} = 50$ cm [11].

Figure 3 shows the layout of the scenario considered in simulations. It is a square cell of 20×20 meters (with obstacles). As worst case assumption, obstacles are intended to be completely blocking the signal propagation.

Figure 4 shows the LEO as function of the number of pulses per symbol N_s. Higher values of N_s lead to an increase of the signal-to-noise ratio (SNR), but at the expense of reduced localization rates and tracking performance degradation in the presence of tag movements. Black lines (○) refer to the absence of relay nodes: in this case, due to the blocking obstacles, the LEO is very high since only a fraction of the overall locations are in electromagnetic visibility with a sufficient number of anchors and hence can be localized. Specifically, about 70% of the spatial locations cannot be localized

[4] In the parameter and scenario set up considered it is $N_{i,m} \ll N_0$, and hence $N_{i,m}$ are neglected in the numerical results.

[5] This value is typical in LOS propagation conditions.

with the target position accuracy of $50\,\mathrm{cm}$ for any practical value of N_s (i.e., not larger than 1000). The effect of the relays is reported in colored curves, accounting for different numbers of relays and different deployment. The adoption of JF relays (blu curve with $\square$), allows a significative enhancement of the performance; in particular, by increasing the number of pulses per symbol N_s, thus the SNR, a coverage of 80% of the environment can be guaranteed with practical values of N_s. Further improvements can be achieved with the adoption of AF relays (green and red curves with $\star$ and $\triangle$, related to an amplification level $G_i = 10\,\mathrm{dB}$ and $G_i = 20\,\mathrm{dB}$, respectively). It is important to remark how the number of the relays and their deployment play a fundamental role in coverage and performance. In fact, the adoption of a reduced number of relays, e.g., 4 instead of 6, does not decrease substantially the coverage of the network if the deployment A,C is adopted, whereas different effects are visible in case of deployment A,B because the central part of the scenario still suffers from ambiguities due to the presence of only two anchors located one in front of the the other.

5. CONCLUSION

We have put forth the idea of UWB non-regenerative relays as a low complexity solution to increase the service coverage in high-definition RTLS based on UWB technique when operating in severe NLOS propagation conditions. The adoption of JF or AF relays increases the number of received signal components that, thanks to the a priori knowledge of relay positions, contribute in decreasing the possibility of ambiguities in ML estimators. Thus the relays act as additional anchors. Numerical results show that significant performance improvement can be achieved, even using simple passive JF relays, with respect the absence of relays. UWB non-regenerative relays can also be adopted to reduce the number of anchors with consequent reduction of the network infrastructure cost and complexity. The performance improvement obtained using ML algorithm suggests the possibility to design practical estimation procedures able to provide good performance with low complexity.

6. ACKNOWLEDGMENT

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