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Joint communications, ranging, and positioning in low bit rate Ultra Wide Band networks

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I. Introduction

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

Effective deployment of ad-hoc networks requires, however, to address a whole new set of design issues, ranging from hardware up to the application. Among new requirements one of the most challenging is introducing energy-awareness for extending the life of networks composed of terminals with limited power supply. Energy-awareness is particularly relevant for sensor networks. In such a context, knowing the spatial position of terminals can significantly improve energy management, by means, for example, of location-based routing protocols [1]. Position information is also crucial where data provided by sensors depend upon single sensor position, as for example in fire monitoring. The sensors are typically low-cost devices, and, therefore, the cost of equipping all sensors with Global Positioning System (GPS) cannot be afforded. Under these restrictions, sensors can build a map of positions by applying a distributed positioning protocol based on ranging information between terminals provided by a Medium Access Control (MAC) module.

Ultra Wide Band (UWB) radio has the appeal, among others, of measuring distances with high precision. Thanks to this feature, UWB has gained popularity world-wide, and has become a top candidate for location-aware ad-hoc and sensor networks [2]. Ranging is not, however, the only concern; network density is another factor to be considered. This is particularly true for networks where the set of active sensors varies in time due to sensors limited battery autonomy.

In this paper, we propose a UWB-tailored distributed MAC protocol which operates in combination with the distributed Self Positioning Algorithm (SPA) [3] in order to provide position information (Section II). We evaluate the performance of the proposed solution in terms of positioning accuracy as a function of ranging accuracy and network density (Section III). Section IV draws conclusions.

II. UWB ranging and positioning

UWB with its GHz-wide bandwidth is particularly suited for Time Of Arrival (TOA) ranging, as first proposed in [4]. The variance of the TOA estimation error $\sigma^2_{\hat{\tau}}$ is in fact related to bandwidth and to Signal to Noise Ratio (SNR) at the receiver, the lower limit for $\sigma^2_{\hat{\tau}}$ in presence of Additive White Gaussian Noise being given by the Cramer-Rao lower bound [5]. In the UWB case one can assume, as a case study, a pulse that fully exploits the emission masks released by the Federal Communications Commission (FCC) [6] in the frequency band [3.1 - 10.6] GHz, leading to: $\sigma^2_{\hat{\tau}} = 8.82 \cdot 10^{-39} s^2$, corresponding to a theoretical lower bound on distance estimation error $c\sigma_{\hat{\tau}} = 2.82 \cdot 10^{-11}$ m. Receiver hardware limitation as well as multipath and multi-user interference lead to a far lower ranging accuracy [7], in the order of tens of centimeters. According to [8] this ranging accuracy allows a positioning accuracy in the order of 50 centimeters.

In this paper, we assume that information data is organized in packets that are exchanged between nodes in an Aloha fashion, as defined in the low data-rate (LDR) UWB-tailored MAC named Uncoordinated, Wireless, Baseborn medium access for UWB communication networks $(UWB)^2$ [9].

$(UWB)^2$ adopts a physical layer using radiation of very short pulses that are modulated in position (PPM) by the information bits. The duty cycle of emitted signals depends thus on the ratio between the average interval between two consecutive pulses and the duration of a pulse. For low data rates, with bit rates of about 100 kb/s, this corresponds to signal duty cycles as low as 10^{-6}.

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

More specifically, $(UWB)^2$ uses a common control channel, provided by a Common TH code, for broadcasting routing and positioning packets. Dedicated data channels associated to Transmitters TH codes are used for data. Priorly to transmission TH codes can be transferred on the control channel. $(UWB)^2$ was designed for distributed low data rate networks. Synchronization between transmitter and receiver may not be available at the beginning of packet transmission because of clock drifts in each terminal during inactivity periods. A synchronization trailer long enough to guarantee the requested synchronization probability is thus added to each packet. In the view of allowing distributed positioning and location-aware routing, $(UWB)^2$ collects distance information between transmitters and receivers during the exchange of control packets. The $(UWB)^2$ MAC can provide the input required by a distributed positioning protocol, i.e. distance information between each pair of terminals in physical connectivity.

The most general solution for a distributed positioning protocol is to be anchor-free, that is no position information is available at network start, as in the SPA [3]. In this paper we thus combined $(UWB)^2$ with the SPA.

III. Performance analysis

The performance of a distributed positioning algorithm can be defined as the effectiveness in building a coordinate system and providing each terminal with its position in the network. Performance is mainly determined by: a) network connectivity degree, that is the average number of neighbors in one hop, b) ranging accuracy. The network connectivity degree depends on the power available at each terminal, that is the transmission range R_{TX}, and on the density of nodes in the network. The ranging accuracy, on the other hand, derives from the adopted transmission technique. In order to evaluate the effect of both network connectivity and ranging accuracy on positioning accuracy, we simulated a network of 20 mobile terminals distributed in an area of $80x80m^2$ adopting the $(UWB)^2$ MAC and the SPA positioning algorithm.

A first set of simulation investigated the effect of network connectivity as a function of R_{TX}. Simulations were performed with R_{TX} varying from 20 meters up to 60 meters, and assuming error-free ranging. Figure 1 reports the percentage of terminals that were able to evaluate their own position as a function of R_{TX}, and shows that for medium to high network connectivity degrees ($R_{TX} \geq 40$ m) a large number of terminals are able to position themselves, and use thus this information to optimize resource management and routing.

We then analyzed the effect of ranging errors in a highly connected network ($R_{TX} = 60$ m). Three different cases were taken into account, characterized by a ranging error with uniform distribution in the intervals [-0.1m, 0.1m], [-1m, 1m], [-10m, 10m]. Figure 2 shows the percentage of positioning error as a function of ranging error and highlights that ranging errors in the order of 0.1 m (case 1) and 1 m (case 2) lead to satisfactory performance (errors in positioning below 5%) while larger errors are not compatible with applications requiring accurate positioning. The ranging accuracy provided by UWB appears thus as an indispensable feature when high accurate positioning is required by the application layer.

IV. Conclusions

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

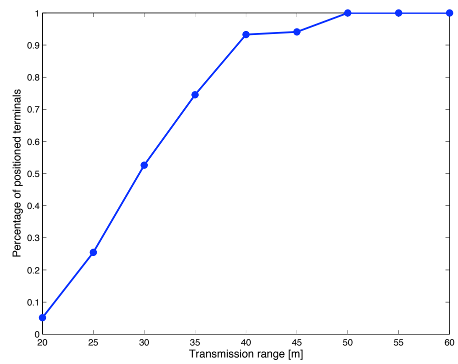

Fig. 1. Percentage of terminals sharing the same coordinate system as a function of the transmission range.

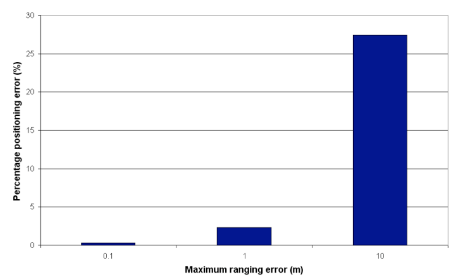

Fig. 2. Percentage positioning error as a function of ranging error.

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