A position based routing strategy for UWB networks

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Abstract - **In this paper a position based routing strategy which exploits the high precision ranging capabilities offered by Ultra-wide Band (UWB) is presented. It is shown that if a position-aware routing protocol and a power-aware routing metric based on ranging measurements are adopted, emitted power levels as well as multi-user interference are significantly reduced. The position-aware strategy is compared with standard solutions based on the minimization of the number of hops and on-demand routing. Results are presented for various transmission ranges, i.e. network connectivity conditions. Both power efficiency and routing performance are taken into account in the analysis and trade-offs between these two features are finally discussed.**

Keywords – Ultra-wide Band, Positioning, Power-aware routing metric, Location Aided Routing.

I. INTRODUCTION

Ultra Wide Band (UWB) radio has the potential of allowing simultaneous communication of a large number of users at high bit rates [1]. In addition, the high temporal resolution inherent to UWB provides robustness against multipath fading and is particularly attractive for indoor WLAN applications. UWB is also capable of collecting positional information with great precision. Position data can lead to better organization of wireless networks, for instance through position-aware resource management and routing. Lower power levels can also be achieved by using directivity.

UWB signals spread however over very large bandwidths and overlap with narrow-band services. As a consequence, regulatory bodies impose severe limitations on UWB power density in order to avoid interference provoked by UWB onto coexisting narrow-band systems [2]. Power considerations are therefore mandatory in the design of UWB systems.

A method for setting up connections by optimizing a power-dependent cost function was described in [3,4]. Early simulation results showed that the power-aware metric leads to multi-hop communication paths between terminals within reach of each other (physical visibility), and increased network performance [4]. Such results were confirmed in a realistic network scenario with mobility, variable network connectivity, and presence of multi-user interference noise (MUI) in [5].

In this work the effect of combination of the power-aware routing metric with a position-aware routing protocol is investigated. The adopted scenario is as in [5], but with improved model for MUI.

The paper is organized as follows. Section II reviews the transmission principles. Section III describes the power-related cost function. Section IV and V describe the assumptions on distributed positioning and MAC protocols, respectively, while Section VI describes the MUI model. The routing algorithm is presented in Section VII. The reference scenario and results of simulations are presented in Section VIII, and conclusions are included in Section IX.

II. UWB DEFINITION

The FCC regulation [2] indicates that any signal with either fractional bandwidth greater than 0.2 or bandwidth higher than 500 MHz falls into the UWB category.

We consider in this work the most common version of UWB based on the transmission of very short (picosecond) pulses emitted in periodic sequences, in an Impulse Radio (IR) fashion. In order to mitigate the spectral lines introduced in the power spectral density by periodic sequences, Time Hopping (TH) codes, which introduce a variable delay on each transmitted pulse, are used. Consider N_u users, binary PPM modulation, and additive noise; The transmitted signal writes:

$$s_{rec}(t)=\sum_{k=1}^{N_u}\sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} g\left(t-jT_s-c_j^{(k)}T_c-b_i^{(k)}\tau\right)+n(t)$$
(1)

where index k refers to user k, $1/T_c$ is the chip rate, and c_j is an element of the code word with $0 \le c_j \le N_h$ and $N_h * T_c < T_s$. Equation (1) shows that the TH code provides an additional shift of $c_j * T_c$. N_s is the number of pulses per bit, so that the bit period T_b is given by $T_b = N_s * T_s$.

As stated in the Introduction, the fine time resolution available with UWB allows high precision ranging. With pulse duration shorter that one nanosecond, two terminals can determine their distance within a few inches. From the set of precise pair-wise distances of a collection of terminals, a complete map of relative terminal positions can be reconstructed in a more precise way than with GPS, with no additional hardware requirements. Also note that indoor position-aware applications are banned with GPS due to penetration limitation while they are enabled with UWB.

III. COST FUNCTION

As proposed in [3], a communication cost is attached to each path, and the cost of a path is the sum of the costs related to the links it comprises. The cost of a link is expressed as:

$$c = \delta C_0 d^{\alpha} + C_1 R d^{\alpha}$$
$$\text{where } \delta = \begin{cases} 0 & \text{if nodes of the link already share an active link} \\ 1 & \text{otherwise} \end{cases} \quad (2)$$

The first component of Eq. (2) takes into account the signalling cost for setting-up a new link. If two nodes already share an active link, $\delta = 0$ and there is no signalling cost. If two nodes do not share an active link, $\delta = 1$ and a signalling cost is added. The second component takes into account the cost for transmitting data, and depends upon the requested data rate R.

Both terms are related to power consumption, and therefore depend upon the distance d between two nodes. Note that the evaluation of such a distance relies on the precise ranging capabilities offered by the UWB technique. The parameter α is related to channel propagation characteristics and has commonly a value between 2 and 4. Constants C_0 and C_1 are used to weight the signalling and transmission components.

IV. DISTRIBUTED POSITIONING

The ranging capability offered by UWB can be exploited to build a network coordinate map, enabling thus position-aware functions in upper layers protocols, such as routing. Triangulation is a feasible way to build a network map starting from ranging measurements, if a sufficient network connectivity is provided. In particular, the algorithm proposed in [6] can provide such a network map. In the following we assume that the network coordinate system is available to all terminals after a transitory time. The overhead caused by the introduction of the distributed positioning protocol, and the robustness of such protocol to mobility and transmission errors will be object of future work.

V. MAC PROTOCOL

TH-IR provides a built-in CDMA multiple access mechanism, based on the adoption of a different TH code on each active link. In traditional CDMA networks with low processing gains a code distribution protocol is required in order to avoid excessive MUI. Oppositely, UWB is expected to provide a huge processing gain thanks to the low signal duty cycle, so that random selection of TH-codes can still guarantee a good performance. In the simulation a fully distributed MAC in which terminals select a random code and transmit packets in a Aloha fashion is hypothesized. The effect of random code selection is taken into account in the MUI model as described in the following section.

VI. MUI MODEL

The effect of MUI was included in our analysis and introduced in the simulator. A given receiver considers a packet as correct depending upon a bit-per-bit decision. The outcome of this decision is determined by the received power, the thermal noise at the receiver, and the MUI noise power in the receiver location. In our simulator the result of the decision is approximated by evaluating the average SNR for a packet as:

$$SNR = \frac{\frac{P}{\beta}}{N_0 B + \sum_{k=1}^{N_p}\left(\frac{P_k}{\beta_k}\cdot \alpha_k \cdot c_k\right)} \quad (3)$$

where:

- P is the average power used to transmit the useful packet;
- β is the power attenuation for the useful packet, depending on wavelength and distance;
- N_0 is the thermal noise power spectral density;
- B is the signal bandwidth corresponding to the rate used to transmit the useful packet, defined as $B = 1/T_b$;
- N_p is the number of colliding packets;
- P_k is the average power used to transmit the k-th colliding packet;
- β_k is the power attenuation for the k-th colliding packet, depending on wavelength and distance;
- α_k is the portion of the useful packet affected by collision provoked by the k-th interfering packet, expressed as a percentage of packet duration;
- c_k is the signal duty cycle for the k-th packet expressed as the ratio between pulse duration and pulse repetition period.

Note that c_k serves as a weight for the MUI power, modeling the low collision probability guaranteed by IR UWB. The low duration of transmitted pulses, in fact, significantly reduces the probability of pulse collisions.

Symbol Error Probability (SEP) is expressed by:

$$SEP = \frac{1}{2} erfc\left(\sqrt{\frac{SNR}{2}}\right) \quad (4)$$

Note that Eq. (4) is only valid if MUI is modeled as Gaussian noise. The validity of such approximation for UWB networks is discussed [7].

We assume for simplicity one pulse is used per bit, and thus Eq. (4) also provides the Bit Error Probability. Packet Error Probability (PEP) for a packet composed of L bits without error protection is thus :

$$PEP = 1 - (1 - SEP)^L \quad (5)$$

VII. ROUTING PROTOCOL

A simplified version of the Dynamic Source Routing protocol [8], referred to as DSR, is adopted.

The connection set-up procedure can be described as follows:

- Step 1. A connection request is generated in the source terminal S. The connection is in the Requested status.
- Step 2. The source terminal S broadcasts Route ReQuest (RRQ) packets to its neighbors.
- Step 3. Each Intermediate terminal I receiving a RRQ packet checks whether either other packets relative to the same path S-I have already been processed, or I is already in the path. If one of these two conditions is verified, the packet is discarded. In the opposite case the packet is updated by including I in the path, and by adding the cost of the last hop to the path cost, and forwarded to I neighbors.
- Step 4. When the destination terminal D receives the first RRQ packet a RRQ validity timeout is set. When the timeout expires Terminal D chooses the best path based on the path cost information contained in each received RRQ packet. Since no duplicated RRQ forwarding is allowed, each received RRQ packet is relative to a different path.
- Step 5. Terminal D sends back a Route RePly (RRP) packet to source S, using the selected best path in backward direction.
- Step 6. Source S receives the RRP packet. The connection evolves in the Found status.
- Step 7. S starts sending DATA packets to D along the best path. When the first DATA packet reaches D, the connection moves into the Active status.

A connection can be aborted during set-up due to packet corruption by thermal and MUI noise; It can also be interrupted after activation, due to lack of connectivity between terminals provoked by mobility. When such an event occurs, the link failure is signaled to the source S by means of RouteReConstruction (RRC) broadcast packets.

It should be noted that the path search phase (steps 2. and 3.) is highly power consuming due to flooding, and increases MUI noise for active links all over the network. Positioning information can mitigate this problem by allowing a directed flooding based on source and destination positions, as proposed in the Location Aided Routing (LAR) protocol [9]. Directed flooding is based on the definition of a Request Zone which includes source and destination positions. Terminals within the Request Zone only, are allowed to forward RRQ packets; Flooding in wrong direction is thus avoided. The Request Zone is defined by the source, based on its estimate of destination position. Mobility of terminals is taken into account by defining an Expected Zone which depends upon the last available position for destination and expected terminal speed. Figure 1 shows the Expected Zone and two possible definitions of the Request Zones, Conic and Rectangular.

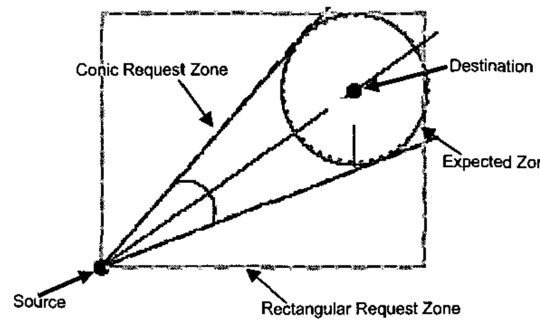

Figure 1 – Definition of Expected and Request Zones in the LAR protocol

A larger Request Zone would increase the probability of achieving a valid route to destination, at the cost of a higher number of RRQ packets. As a consequence, the shape of the Request Zone is the result of a trade-off between power efficiency in the path search procedure and percentage of Found connections. Due to power efficiency requirements in UWB networks, the Conic Request Zone was adopted in the simulations.

VIII. SIMULATION SCENARIO AND RESULTS

The combined effect of UWB specific routing metric and LAR protocol on network performance was analyzed in an ad-hoc network composed by N mobile terminals. All terminals have: 1) high precision ranging capability, 2) limited transmission range R_{TX}, 3) maximum achievable bit rate R_{MAX}. As regards mobility, each terminal changes its speed and direction every T_{MOB} seconds with probability (1-$Prob_{INERTIA}$). Different mobility scenarios, from static to highly dynamic, can be obtained by varying T_{MOB} and $Prob_{INERTIA}$.

Each terminal generates connection requests to other terminals in the network, following a Poisson distribution with average value λ. All connection requests use the same bit rate within a single simulation.

Table 1 in next page shows the settings of relevant parameters for the entire set of simulations.

Routing protocols (DSR, LAR) were paired against different metrics (Hops, UWB Cost). Each pair was evaluated in terms of both routing performance (ratio between Found and Requested connections) and power efficiency (average number of RRQ packets per Found connection).

Two different transmission ranges (R_{TX}=40m, R_{TX}=80m) were considered. Both provide sufficient degree of network connectivity for the distributed positioning algorithm to work properly (see section IV). The two ranges however lead to low vs. high network connectivity degrees.

Parameter	Value
Number of Terminals N	10
Area size	80x80 m^2
Maximum bit rate R_{MAX}	1 Mb/s
Poisson distribution average value λ	0.2 s^{-1}
Connection bit rate	50 kb/s
Signal duty cycle	10^{-3}
Mobility interval T_{MOB}	0.5 s
Maximum speed	6 m/s
Inertia probability $Prob_{INERTIA}$	0.5
RRQ/RRP packet size	760 bits
RRC packet size	252 bits
DATA packet size	5000 bits
Link cost function coefficient C_0	0.5
Link cost function coefficient C_1	1

Table 1 – Simulation settings

Figure 2 shows the results corresponding to the low transmission range. As observed at steady state, the routing metric has little effect on routing performance (see white vs. black dots). Low network connectivity seems to reflect in a low system sensibility towards the selected routing metric. Although the UWB Cost metric seems to lead to slightly worse performance if combined to the LAR protocol, in fact, further investigations are required to determine the significativity of such results.

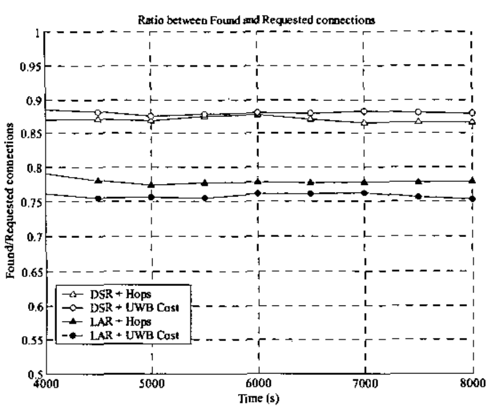

Figure 2 – Ratio between Found and Requested Connections as a function of time (R_{TX} = 40 m). Each curve characterized by a different dot shape corresponds to a different routing metric (Triangle: Hops – Circle: UWB Cost function), while different dot colors correspond to different routing protocols (Black: LAR – White: DSR)

Figure 2 also indicates that LAR leads to a lower percentage of Found connections, due to the restricted Request Zone together with low network connectivity which lead to path search failures. DSR is obviously not affected by this problem, since it uses standard flooding.

Figure 3 shows the average number of RRQ packets for the same transmission range. The LAR protocol significantly reduces the number of RRQ packets, thus leading to a reduction of power consumption and emitted power levels.

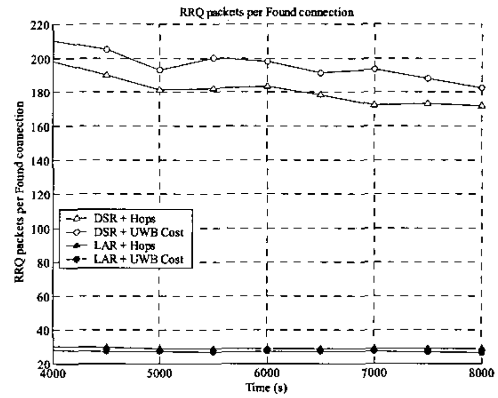

Figure 3 – Average number of RRQ packets per Found connection as a function of time (R_{TX} = 40 m). Each curve characterized by a different dot shape corresponds to a different routing metric (Triangle: Hops – Circle: UWB Cost function), while different dot colors correspond to different routing protocols (Black: LAR – White: DSR)

Figure 3 confirms that in the condition of a low network connectivity the routing metric has low effect on network performance (see white vs. black dots pairs in Fig. 3).

Results for high network connectivity are shown in Fig. 4. No striking difference between the two routing metrics is indicated, although the adoption of UWB Cost metric led to a slight improvement of performance with both LAR and DSR protocols.

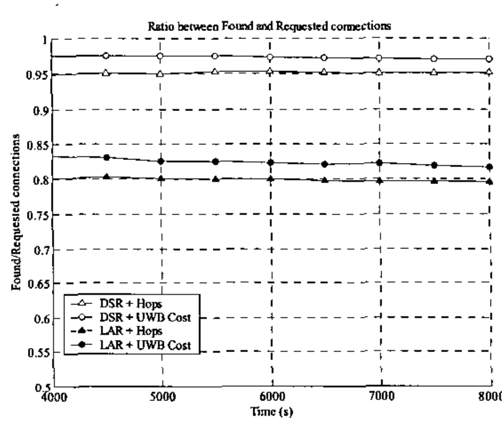

Figure 4 – Ratio between Found and Requested Connections as a function of time (R_{TX} = 80 m). Each curve characterized by a different dot shape corresponds to a different routing metric (Triangle: Hops – Circle: UWB Cost function), while different dot colors correspond to different routing protocols (Black: LAR – White: DSR)

The higher performance increase obtained in the case of LAR combined with the UWB Cost Function when the network connectivity increases could be due to the higher probability of finding a path within the Request zone. Further simulations are however required to confirm this interpretation.

Note that also in the case of high network connectivity the LAR protocol leads to a lower percentage of Found connections due to path search failures. This loss is however balanced by an increased efficiency in power management, as shown in Fig. 5. Figure 5 indicates that the introduction of LAR reduces by several orders of magnitude the number of RRQ packets required to set up a connection, leading thus to a significant power saving in each terminal.

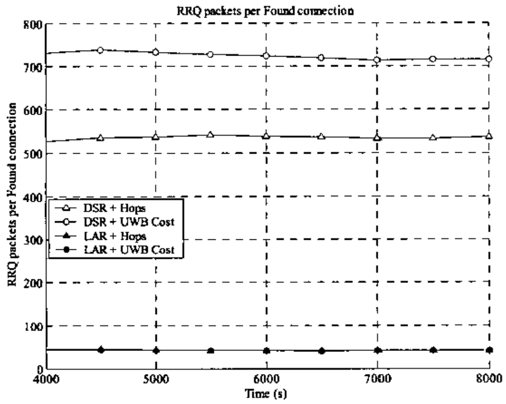

Figure 5 – Average number of RRQ packets per Found connection as a function of time (R_{TX} = 80 m). Each curve characterized by a different dot shape corresponds to a different routing metric (Triangle: Hops – Circle: UWB Cost function), while different dot colors correspond to different routing protocols (Black: LAR – White: DSR)

IX. CONCLUSIONS

Results reported in section VIII show that the adoption of position-aware routing strategies significantly improves the efficiency in power management for UWB networks, by optimizing the path selection procedure. The above strategy however achieves a lower routing performance due to a higher percentage of path search failures. Note that, as highlighted in section VII, a trade-off between performance and power efficiency can be achieved by adopting different shapes for the Request Zone.

The overhead caused by the distributed positioning protocol was not taken into account, and will be incorporated in future developments of this work.

Further investigations are required to better evaluate if the power-aware metric based on the UWB ranging capability can lead to significant increase in performance thanks to MUI mitigation. Furthermore, future work will investigate if the flexibility provided by the complete UWB Cost function proposed in [4] can enable a more accurate tuning of routing performance versus power efficiency, assuring optimal network performance in different network scenarios, and enabling QoS routing based on the selection of different routing metrics for different traffic classes.

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