Effect of power-efficient routing in UWB wireless mobile networks

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ABSTRACT

In this paper an UWB-specific, power-efficient routing strategy is described. The proposed method is based on the ranging capabilities offered by UWB. It is shown that emitted power levels as well as multiuser interference are significantly reduced. The new routing metric is analyzed against a traditional metric based on the number of hops for various transmission ranges, i.e. network connectivity conditions. A strategy capable of adapting to variable network connectivity conditions is finally proposed.

I. INTRODUCTION

Ultra Wide Band (UWB) radio has the potential of allowing simultaneous communication of a large number of users at high bit rates [1,2]. In addition, the high temporal resolution inherent to UWB provides robustness against multipath fading and is particularly attractive for indoor LAN applications. UWB is also capable of recovering positional information with great precision. Position data can lead to better organization of wireless networks, for instance through better resource management and routing, and lower power levels 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 [3]. It is therefore necessary to take into account power considerations when designing UWB systems.

A method for setting up connections by optimizing a power-dependent cost function was described in [4,5,6]. The proposed strategy was compared against traditional routing in a scenario characterized by fixed terminals and full network connectivity. Results showed that the power-saving strategy leads to multi-hop communication paths between terminals within reach of each other (physical visibility) and by this way increases network performance [5].

In this paper, the above strategy is re-evaluated in a more realistic network scenario, which includes mobility, variable network connectivity obtained by varying transmission range, and presence of multiuser interference noise.

The paper is organized as follows. Section II establishes the transmission principles. Section III describes the power–related cost function. Section IV defines the reference scenario and the routing algorithm. Section V describes the interference model. Section VI contains the simulation data and results, and Section VII the conclusions.

II. UWB REVIEW

There are several ways of generating an UWB signal. A recent definition given by the FCC [3] indicates in fact that any signal with either fractional bandwidth greater than 0.2 or bandwidth higher than 500 MHz falls into the UWB category. We consider here the most common version of UWB based on the transmission of very short (picosecond) pulses emitted in periodic sequences, in an impulse radio fashion. In order to increase robustness of transmission and control single pulse energy, N_s pulses are used for each transmitted symbol. Modulation is binary PPM. The transmitted signal is expressed by:

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} g\left(t - jT_s - b_i\tau\right) \qquad (1)$$

where $g(t)$ is the pulse, T_s the basic time interval between two consecutive pulses, and $T_b = N_s \cdot T_s$ is the bit duration. Information bits are coded in the sequence of b_k's. Multiple access is achieved by using time-hopping codes and, for multi-user communication with N_u users, and in the presence of additive noise, the transmitted signal writes:

$$s_{rec}(t) = \sum_{k=1}^{N_u} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} g\left(t - jT_s - c_j^{(k)}T_c - b_i^{(k)}\tau\right) + n(t)$$
(2)

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 $N_h \cdot T_c < T_s$. Equation 2 shows that the time-hopping code provides an additional shift of $c_j T_c$.

The optimal receiver for a single communication (with data composed of independent random variables) in an

AWGN environment is the correlation receiver described in [1]. The AWGN model is a good approximation also in a multi-user environment, when the number of users is large and the Central Limit theorem can be applied. In the case of low number of devices however the Gaussian approximation must be investigated further [7]. This scenario is most suitable to UWB systems and therefore interference modeling is a critical issue for UWB network design.

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. An even higher precision can be achieved by tailoring pulse shapes, leading to well-behaved autocorrelation functions. From the set of precise pairwise distances of a collection of terminals, a complete 3D map of relative terminal positions can be reconstructed in a more precise way than what achievable with GPS, in particular for indoor applications, with no additional hardware requirements.

As far as power is concerned, we adopt the emission limits defined by FCC [3] (maximum average EIRP power of -41.3 dBm/MHz for emissions in the 0 – 0.96 GHz and 3.1 - 10.6 GHz bands, lowered down to -75.3 dBm/MHz in the 960 – 2.1 GHz band) as a reference in the definition of potential network scenarios. Such low limits were motivated by the need for meeting coexistence requirements with GPS receivers [8]. The implication is most likely an organization of the network resembling one of the two following scenarios:

- Short range – High bit rate
- Long range – Low bit rate

III. COST FUNCTION

As proposed in [4], 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 the sum of two components as follows:

$$c = \delta C_0 d^{\alpha} + C_1 R d^{\alpha}$$
$$where\ \delta = \begin{cases} 0 & \text{if nodes of the link already share an active link} \\ 1 & \text{otherwise} \end{cases} \qquad (3)$$

The first component 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. SCENARIO

We consider an ad-hoc network composed by N mobile terminals. All terminals are supposed to have same properties, which can be summarized as follows: high precision ranging capability, limited transmission range R_{TX}, maximum achievable bit rate B_{MAX}. As regards mobility, each terminal changes its speed and direction every T_{MOB} seconds with probability ($1-P_{INERTIA}$). Different mobility scenarios, from static to highly dynamic, can be obtained by varying T_{MOB} and $P_{INERTIA}$.

Each terminal generates connection requests to other terminals in the network, following a Poisson distribution with average value λ. All connection requests use a fixed bit rate (50kbits/sec).

In order to find a path connecting source and destination, a pure on-demand, flooding-based routing protocol is adopted. The choice of adopting a simple flooding-based approach is motivated by the intention of focusing the analysis on the effect of the link cost function described above; The combined effect of cost function and specific routing protocols (e.g. location based protocols as LAR [9]) will be object of future work.

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

1. A connection request is generated in the source terminal S. The connection is in the Requested status.
2. The source terminal S broadcasts Route ReQuest (RRQ) packets to its neighbors.
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 S neighbors.
4. When the destination terminal D receives the first RRQ packet a RRQ validity timeout is set. The connection is in the Found status.
5. When the RRQ validity timeout expires Terminal D chooses the best path. The choice is made based on the path cost information contained in each RRQ packet coming from the source. Note that each received RRQ packet is relative to a different path, since no duplicated RRQ forwarding is allowed.
6. Terminal D sends back a Route RePly (RRP) packet to the source S, using the selected best path in backward direction.
7. Source terminal S receives the RRP packet. The connection is in the Confirmed status.

8. S starts sending DATA packets to D along the best path. When the first DATA packet reaches D, the connection is in the Active status.

A connection can be aborted during set-up due to packet corruption by thermal and interference 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 by means of RouteReConstruction (RRC) broadcast packets.

V. INTERFERENCE MODEL

Multiuser interference introduces a major limitation in UWB ad-hoc networks. This effect was included in our analysis and a real time evaluation of interference noise was introduced in the simulator. In real world a given receiver j considers a packet as correct depending on a bit-per-bit decision. The outcome of this decision is determined by the received power, the thermal noise at the receiver and the interference noise power in the receiver location. In our simulator the result of the decision is approximated by evaluating the average SNR for a packet transmitted from terminal i to terminal j:

$$SNR_{ij} = \frac{\frac{P_i}{\beta_{ij}^2}}{N_0 B_{ij} + \sum_{k=1}^{N_p} \left(\frac{P_k}{\beta_{kj}^2} \cdot \alpha_k \cdot c_k \right)} \qquad (4)$$

where:

- P_i is the average power used by terminal *i* to transmit the information packet;
- β_{ij} is the attenuation between terminals *i* and *j*, depending on wavelength and distance d_{ij} between terminals;
- N_0 is the thermal noise power spectral density;
- B_{ij} is the bit rate used by terminal i to transmit the information packet;
- N_p is the number of colliding packets;
- P_k is the average power used to transmit the *k*-th colliding packet;
- β_{kj} is the attenuation between terminal transmitting the *k*-th colliding packet and terminal *j*, depending on wavelength and distance d_{kj} between terminals;
- 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.

If SNR_{ij} is over a given threshold the packet is assumed to be correct, otherwise it is discarded. This description of the relationship between SNR, packet collisions and bit error rate (BER) is adopted to avoid the use of Gaussian approximation hypothesis. A more detailed description of the effect of collisions on BER requires additional hypotheses on both multiuser interference and channel models, and will be object of future work.

In Eq.4 the signal duty cycle c_k serves as a weight for the interference noise power. By this way the low collision probability guaranteed by impulse radio UWB is taken into account. The low duration of transmitted pulses significantly reduces in fact the probability of pulse collisions.

We expect that the adoption of a power-efficient link cost function to serve as a routing metric will reduce the effect of the interference, leading thus to higher network performance. In order to confirm this expectation, we compared a routing metric based on the cost function presented in section III (Minimum Cost) against a traditional routing metric based on minimization of the number of hops (Minimum Hop) .

Results of this analysis are presented in the next section.

VI. RESULTS

We consider N = 10 terminals randomly distributed in an area of 80x80 m^2. Table 1 shows the settings of relevant parameters for the entire set of simulations.

Parameter	**Value**
Maximum bit rate B_{MAX}	1 Mb/s
Connection request DATA rate	50 kb/s
Poisson distribution average value λ	0.2 s^{-1}
Signal duty cycle	10^{-3}
SNR threshold	12 dB
Mobility interval T_{MOB}	0.5 s
Maximum speed	6 m/s
Inertia probability $P_{INERTIA}$	0.5
RRQ packet size	760 bit
RRP packet size	760 bit
RRC packet size	252 bit
DATA packet size	5000 bit
Link cost function coefficient C_0	0.5
Link cost function coefficient C_1	1

Table 1 – Simulation settings

The routing metrics are compared for varying transmission ranges, i.e. for different degrees of network connectivity. We selected as performance indicator the ratio between Found and Requested connections.

In a weakly connected network (R_{TX} = 20 m) the Minimum Hop and Minimum Cost strategies lead to similar results. The weak connectivity dramatically limits system performance, independently of the selected routing metric (Fig. 1). The increase of network connectivity (R_{TX} = 40 m) improves network performance in terms of Found connections vs. Requested (Fig. 1). The advantage of using a power-efficient cost function seems negligible, due to the low influence of multiuser interference noise.

On the other hand the Minimum Cost strategy leads to a higher number of hops, as shown in Fig. 2. This effect increases when network connectivity increases (Fig. 2).

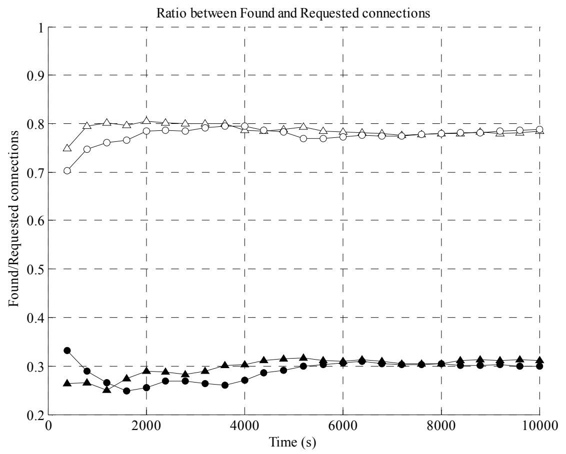

Figure 1 – Ratio between Found and Requested Connections as a function of time. Each curve characterized by a different dot shape corresponds to a different routing strategy (Triangle: Minimum Hop - Circle: Minimum Cost), while different dot colors correspond to different transmission ranges (Black: R_{TX} = 20 m - White: R_{TX} = 40 m)

For low network connectivity the Minimum Cost strategy increases the average number of hops, without any advantage in terms of percentage of Found connections.

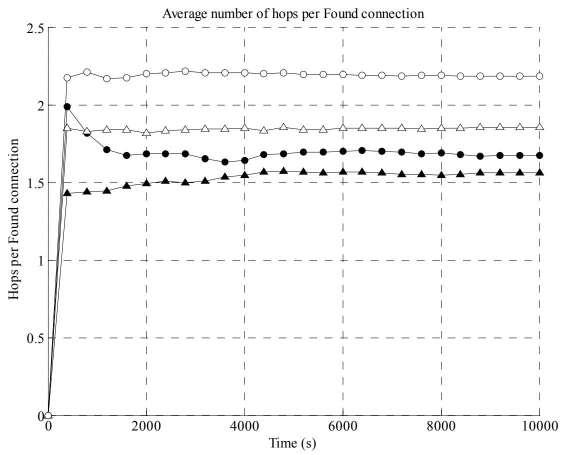

Figure 2 – Average number of hops per Found connection as a function of time. Each curve characterized by a different dot shape corresponds to a different routing strategy (Triangle: Minimum Hop - Circle: Minimum Cost), while different dot colors correspond to different transmission ranges (Black: R_{TX} = 20 m - White: R_{TX} = 40 m)

The case of higher network connectivity is shown in Fig. 3.

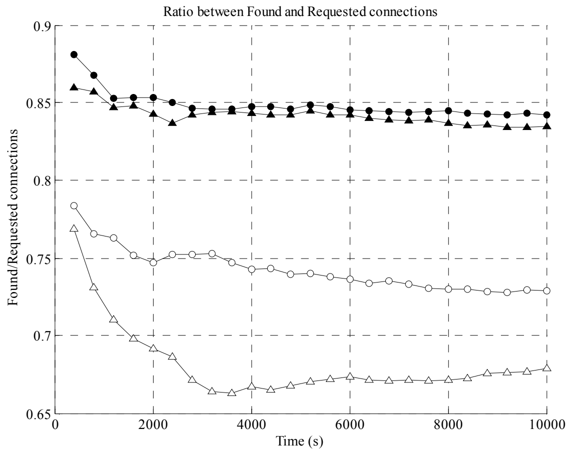

Figure 3 – Ratio between Found and Requested Connections as a function of time. Each curve characterized by a different dot shape corresponds to a different routing strategy (Triangle: Minimum Hop - Circle: Minimum Cost), while different dot colors correspond to different transmission ranges (Black: R_{TX} = 60 m, White: R_{TX} = 80 m.)

As shown in Fig.3 the improvement obtained by using the Minimum Cost is still negligible for medium network connectivity (R_{TX} = 60 m), while for high network connectivity (R_{TX} = 80 m) the Minimum Cost outperforms the Minimum Hop. This result can be explained by observing that the influence of multiuser interference on network performance increases as transmission range increases. Both strategies are affected by a higher interference (R_{TX} = 80 m) provoked by broadcast RRQ and RRC packets sent with higher power, leading to a lower number of Found connections. Nevertheless, the Minimum Cost strategy leads to a more robust system in a high-interference environment, since it adopts power-efficient (and, indirectly, interference-efficient) routes (Fig. 4).

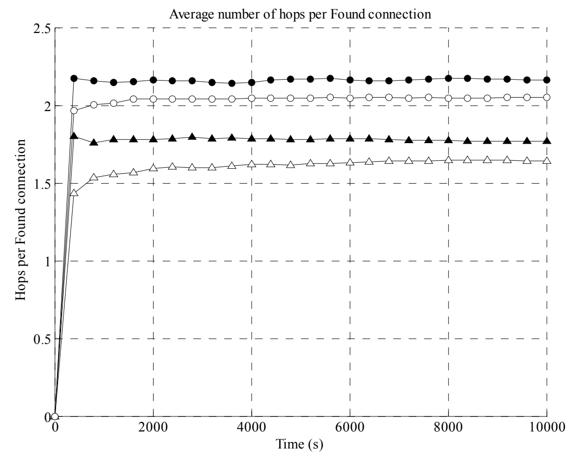

Figure 4 – Average number of hops per Found connection as a function of time. Each curve characterized by a different dot shape corresponds to a different routing strategy (Triangle: Minimum Hop - Circle: Minimum Cost), while different dot colors correspond to different

transmission ranges (Black: R_{TX} = 60 m - White: R_{TX} = 80 m.)

VII. CONCLUSIONS

Results reported in section VI show that network connectivity heavily influence system performance. Furthermore, the effect of network connectivity depends on the selected routing metric. In fact, the comparison between a traditional hop minimizing routing and a power-aware strategy shows that the two strategies behave differently for varying transmission ranges. In particular, the Minimum Cost strategy is not effective in the case of low network connectivity, since it increases the average number of hops with no advantage in system performance. Oppositely, when network connectivity grows, the Minimum Cost effectively reduces the effect of multiuser interference by increasing the percentage of found connections. This result suggests the adoption of a network adaptive routing strategy, allowing each terminal to modify the routing metric depending on the actual network connectivity. Such a state should be evaluated by the terminal itself (e.g. through the estimation of the average number of neighbors in a given time). Note that such an adaptive strategy could be achieved by including a network connectivity term in the link cost function, in analogy with the solution proposed in [6] for other network parameters such as interference, and node reliability.

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