UWB AD-HOC NETWORKS

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ABSTRACT

In this paper we propose a new strategy for path selection in a UWB based ad-hoc network which, by minimizing a power-dependent global cost function, can potentially lead to an optimal network organization characterized by low emitted power levels and high network performance.

1. INTRODUCTION

Ultra Wide Band (UWB) radio is a widely used technique in radar applications. In the past few years, however, UWB has also received increasing attention for its broader applicability to wireless communication systems. In particular, a multiuser access scheme for UWB has been proposed by Scholtz and Win [1] in which users are diversified by time-hopping codes. In this scheme, system performance is monitored and evaluated by the multiuser interference noise which, in turn, can be reduced by appropriate coding strategies [2]. As a result, UWB has the potential for allowing simultaneous communication between a large number of users at high bit rates. Additionally, the high temporal resolution inherent to UWB provides robustness against multipath fading hence is particularly attractive for indoor LAN applications.

UWB is also capable of recovering positional information with high precision. This property has been extensively exploited in radar applications, and is appealing for cellular systems as well. In fact, position data can lead to better organization of telecommunication networks, for instance through better resource management and routing. At the same time, positioning can also help lower power levels by using directivity.

UWB signals, however, are spread over very large bandwidths (from a few Hz to several GHz) and therefore unavoidably overlap with [ho tolto others] narrow-band services. As a consequence, it is reasonable to expect that regulatory bodies will impose severe limitations on UWB power density to avoid interference provoked by this technique onto coexisting narrow-band systems. In order to reap all the benefits of UWB technology, it is therefore mandatory to take into account power considerations when designing UWB systems, all the way from the single-emitter level to the system level.

A conceptual framework for the design of a high-capacity UWB systems that is robust and leverages positioning information while abiding power constraints was introduced in [3]. Here, we further refine the framework and simulate the underlying model to derive general guidelines for ad-hoc networks based on UWB technology. In particular, we define strategies for setting up connections by optimizing a power-dependent cost function. The resulting power-saving strategy can lead to multi-hops communication paths even between two terminals that are within reach of each other (physical visibility). We compare the results obtained using the proposed strategies against those derived using traditional routing algorithms.

The paper is organized as follows. Section II reviews the principles of UWB transmission. Section III describes the proposed guidelines for ad-hoc network organization. Section IV contains the simulation data and results and Section V discusses and further extends these results.

2. REVIEW OF UWB TRANSMISSION PRINCIPLES

UWB radio is a carrier-less spread spectrum technique based on the transmission of very short (subnanosecond) pulses which are emitted in periodic sequences. As outlined in [1], N_s pulses are used for each transmitted symbol. The adopted modulation is a binary PPM. The transmitted signal is:

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

where $g(t)$ represents the pulse, T_f the basic time interval between two consecutive pulses, and $T_b = N_s \cdot T_f$ is the bit duration. Information bits are

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coded in the sequence of b_k's. Multiple access is achieved by using time-hopping codes and, for multi-user communication, the transmitted signal is:

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

where $1/T_c$ is the chip rate, and c_j is an element of the code word with $0 \le c_j \le N_h$ and $N_h \cdot T_c < T_f$. Equation 1 shows that the time hopping code provides an additional shift of c_jT_c. When the number of users is N_u and the noise $n(t)$ is additive, the signal at the receiver becomes:

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

where index k refers to user k. 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 this case, the correlation receiver is again the optimum choice, and the Signal to Noise Ratio SNR at the receiver can be written as follows:

$$\begin{aligned} SNR &= \frac{P}{N_s\sigma_a^2(N_u-1)+\sigma_{rec}^2} = \\ &= \frac{(N_s m_p)^2}{N_s\sigma_a^2(N_u-1)+\sigma_{rec}^2} \end{aligned} \qquad (2)$$

where P is the average power of the useful signal, σ_{rec}^2 is the power of the thermal noise, σ_a^2 is the power of the interference resulting from one user, and m_p is the signal at the correlator's output during the interval T_f. Equation 2 shows that global system performance depends on the amount of multi-user interference, which in turn is determined by the correlation properties of the time-hopping codes. Most often, pseudo-random codes are used, due to their good cross-correlation properties. Pseudo-random codes, however, are not easily addressed. Recently, new code constructions overcoming this problem have been proposed [2].

The fine time resolution available with UWB allows also high precision ranging: with pulse duration shorter that one nanosecond, two terminals can determine their distance within a few inches. An even better 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 their relative positions can be reconstructed (better than the one achievable with GPS, especially in indoor applications) with no additional hardware requirements.

As far as power is concerned, current limits for class B unintentional radiators in FCC Part 15 are used as a reference (500 μV/m at 3 m from the transmitter, for emissions over 960 MHz). Recent studies on the effect of UWB transmissions over GPS receivers [4], however, indicate that lower limits will be necessary to meet coexistence requirements. This will inevitably result in an organization of UWB networks based on small cells.

3. NETWORK ORGANIZATION

3.1. Network

The basic network component we have in mind consists of an ad-hoc set of n nodes with the following properties: (a) each node can physically reach any other node; (b) all nodes have the same functionalities; (c) the nodes are fixed; (d) connections between nodes have QoS requirements; (e) each node has a limited output bandwidth, which corresponds to the node resource.

The hypothesis that each node is in physical reach of all other nodes implies that nodes are positioned within the intersection of their coverage areas, as illustrated in Figure 1. The hypothesis that the nodes are in fixed positions leads to a network component consisting of a fixed number of nodes located at fixed positions. Mobility of the nodes will be introduced in future versions of the system.

3.2. Cluster

To each node i we associate a cluster of nodes (neighbours) centered on the node itself and included in the coverage area of node i. At the physical layer, each node knows the exact position of every other node in its cluster. This is easily achieved using UWB capabilities. In principle, the cluster may coincide with the coverage area of the node. The size of the cluster, however, may be smaller than the coverage area depending upon factors such as radio channel conditions and network load. The resource management module of a node also coordinates resource sharing between the node and its neighbours. Thus the motivation for the concept of cluster is also directly related to physical and MAC layer requirements. A complete study of the notion of cluster in relation to these complex motivations is beyond the scope of this paper. For all practical purposes, in the simulations to be presented here, the size of a cluster is best seen as an additional parameter that can be used to control the granularity of multi-hop strategies, since hops are allowed only between nodes that are members of a same cluster.

As far as routing is concerned, we suppose that during path search each node relies on forward and backward propagation of short messages within clusters across the entire network to ultimately collect a list of all available possible paths at time t, as well as their costs (see below). The cost and time associated with collecting this information is neglected. Thus for all practical purposes, we can assume that the routing module of a source node knows the exact position of all the other nodes in the network, although this information might not have been available at the physical layer module of the node.

3.3. Single link cost and global network cost

Each node in the network can play in turn one of the following roles: source node, intermediate node, and destination node. Node functionality depends upon the role it must play in the communication:

- as a source node it must be capable of setting up new connections i.e. it must have enough bandwidth;
- as a destination node it can theoretically accept an unlimited number of connections;
- as an intermediate node it must accept an incoming link only if it has enough bandwidth to set-up the corresponding outgoing link.

In the above view, a link between two nodes is *admissible* if the two nodes involved in the communication can comply with the requested functionality. A *admissible* path is formed by only *admissible* links.

As in the model proposed in [3], a communication cost is attached to each *admissible* path, and the cost of a path is the sum of the costs associated with the links it comprises. The cost of a link is expressed as the sum of two components as follows:

$$c = \delta C_0 d^{\alpha} + C_1 R d^{\alpha}$$

$$\text{where } \delta = \begin{cases} 0 & \textit{if nodes of the link already share an active link} \\ 1 & \textit{otherwise} \end{cases} \tag{3}$$

The first component takes into account the signalling cost of 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 the signalling cost is added. The second component takes into account the cost for transmitting data and depends upon the requested data rate R (QoS).

Both components are related to power consumption, and therefore depend upon the distance d between the two nodes. The parameter α is related to propagation characteristics of the channel and has commonly a value between 2 and 4. The constants C_0 and C_1 are used to weight the signalling and transmission components.

Here we also define the global network cost $NC(t)$ as the sum of all active connection costs at time t. $NC(t)$ must always be less than a maximum affordable value C_{max}. In this view, a *admissible* path p between i and j is *admissible* only if its cost $C_p(i,j)$ is such that:

$$NC(t) + C_p(i,j) \le C_{max} \tag{4}$$

If none of the *admissible* paths satisfies this condition, the new connection request is rejected.

3.4. Routing

By considering a maximum value for NC we introduce a constraint which may force the system to reject a single-hop connection between two nodes. Thus, multi-hop routes may be selected not only for routing purposes but also for limiting power consumption. The proposed algorithm, called Clustered-Multi-Hop or CMulti-Hop, examines the set of all possible paths given the cluster structure. Each hop must be to a node in the cluster and never to a node which, although reachable (within coverage area), is out of the cluster. All paths satisfying the global network cost condition (Equation 4) are recorded. A selection procedure examines then the recorded paths and chooses the path with lower cost. In case of two paths with same cost, the path with a lower number of hops is selected.

A temporary hierarchy depending on the source terminal is used in each connection request. Consider a connection request from i to j. The algorithm starts by giving i the highest hierarchy degree (0), while neighbours of i are labelled with degree 1. During path search, a node can set-up a link only with nodes at lower hierarchy degree. There will be no links between i neighbours, because these share the same hierarchy degree. The algorithm repeats this procedure recursively, meaning that if j is in i's cluster (and therefore its degree is 1) all nodes which are in j's cluster **and are not in *i*'s cluster** will have degree 2, an so forth until all nodes have an assigned hierarchy degree. This procedure guarantees that there are no loops in the paths, while reducing the overall number of hops by preventing links between nodes which are both neighbours of the same node.

4. NETWORK SIMULATIONS

We developed a computer simulation for the model introduced in [3] with a few additional hypotheses:

- the connection requests are described by a Poisson model, i.e. the time between two consecutive requests follows a negative exponential distribution, with average value equal to1 s;
- the duration of the connections also follows a negative exponential distribution, with average 180 s;
- source and destination nodes are selected with a uniform distribution over all nodes.

The simulated topology corresponds to the case where the nodes are regularly distributed along a ring (ring lattice)—other topologies have also been studied but are not reported here. Likewise, we have varied cluster sizes but results here are reported only for clusters composed of five nodes, including the cluster head.

We compared the performance of the proposed algorithm with two other algorithms. The first, called Link-State, is the application of the CMulti-hop to the case of a cluster coinciding with the coverage area. The Djkstra algorithm [5] is used for path search. The Djkstra weighting coefficient of each link is given by Equation 3, which leads to greedy minimization of the cost function. The second is a Single-Hop algorithm which simply tries to connect the source and the destination nodes with a direct link. Both Link-State and Single-Hop operate under the constraints of NC. Our prediction was that, due to the cluster structure, the CMulti-Hop would combine these two strategies leading to both power limitation and reduction of the number of hops. The comparison of the three algorithms should permit to understand the tradeoffs between power saving and QoS in a UWB multihop low-interference network.

The three algorithms were tested and compared for a value of the signalling coefficient C_0 (Equation 3) equal to 0.7, which corresponds to a high-signalling cost environment, while varying the NC maximum value C_{max}. Other parameters were set as follows: $\alpha=2$, $C_1=1$, R randomly selected over an uniform distribution. In order to analyse the properties of the network, we derived the following quantities:

- average number of hops per connection (basically a QoS indicator);
- percentage of accepted requests (an important parameter in a limited-cost environment).

Simulation results are presented in Fig.2 and Fig.3 (average number of hops and percentage of accepted connection requests, respetively, as a function of NC maximum value C_{max}.) In both figures, C_{max} varies from an extremely low (20) to a very large value (35920).

Results show that in a high signalling-cost environment with a strong constraint on maximum cost (left side on both figures) the Single-Hop algorithm leads to a low percentage of accepted requests and allows only a small number of active connections. With the use of the Link-State algorithm, on the contrary, the number of accepted connections grows much faster for increasing C_{max}, and the average number of hops is high. Also note that with the assumed value of available bandwidth, there is a saturation effect due to the heavy use of local links, and the system converges to rejecting any connection request even for an unlimited C_{max}. We thus increased the available bandwidth at each node (HB curves in the figures) and verified that in this case the Link-State algorithm behaves in a saturation-free fashion, i.e. it fastly converges to 100% of accepted requests.

The CMulti-Hop algorithm leads to higher percentage values of accepted requests than both Single-Hop and Link-State. The saturation effect is still present but happens at higher percentages than the Link-State, with standard bandwidth values. As predicted, the cluster structure induces a reduction in the number of hops compared to the Link-State (see Fig.2) and limits local links usage. In summary, the CMulti-Hop algorithm leads to a lower average number of hops which is a positive fact under QoS constraints while guaranteeing a high percentage of accepted requests also in the case of limited available bandwidth at the node.

5. EXTENSIONS AND CONCLUSIONS

The peculiar characteristics of the UWB radio channel offer new solutions and opportunities for resource management and networking. The introduction of a cluster structure, based on localization information, in a wireless network allows us to develop a local routing algorithm which takes into account UWB requirements (high signalling cost, power limitation) and at the same time exploits UWB advantages such as precision ranging to evaluate link cost function. The proposed CMulti-Hop algorithm allows a high number of connections to be instaured while limiting the number of hops. Furthermore, its variable cluster size enables fine performance tuning. Thus CMulti-Hop appears to be a good solution for local level routing, which can be applied in combination with a more scalable routing protocol, for example AODV, for global level routing.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] M.Z. Win, R. A. Scholtz, "Ultra-Wide Bandwidth Time-Hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications," *IEEE Trans. Commun.*, vol. 58, no. 4, April 2000.

[2] M.S. Iacobucci, M.G. Di Benedetto "Time Hopping Codes in Impulse Radio Multiple Access Communication Systems," Proceedings of the International Workshop on 3G Infrastructure and Services, Athens, Greece, July 2-3, 2001, pp.171-175.

[3] M.G. Di Benedetto and P.Baldi "A model for self-organizing large-scale wireless networks, " invited paper, Proceedings of the International Workshop on 3G Infrastructure and Services, Athens, Greece, July 2-3, 2001, pp.210-213.

[4] NTIA Special Publication 01-45: Assessment of Compatibility between UltraWideBand (UWB) Systems and Global Positioning System (GPS) Receivers.

[5] Edsger W. Dijkstra. A note on two problem in connexion with graphs. *Numerische Mathematik*, 1:269–271, 1959.

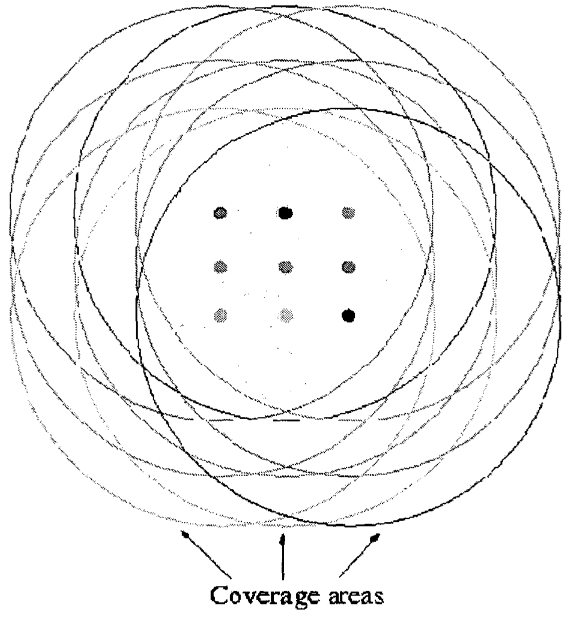

Fig. 1. Universe considered in the present paper, formed by the intersection of radio coverage areas of all UWB terminals.

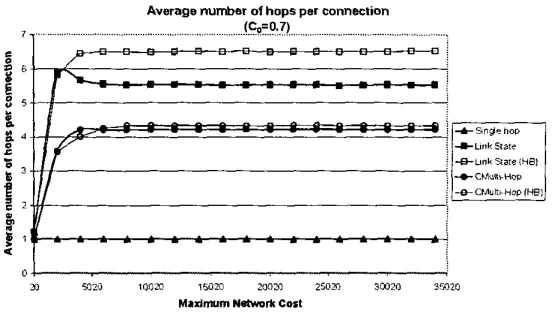

Fig. 2. Average number of hops per connection as a function of the maximum network cost value. Each curve characterized by a different dot shape corresponds to a different path selection strategy (Triangle: Single Hop, Square: Link State, Circle: Clustered Multi-Hop), while different dot colors correspond to different values of available bandwidth in each terminal (Black: standard bandwidth, White: high bandwidth).

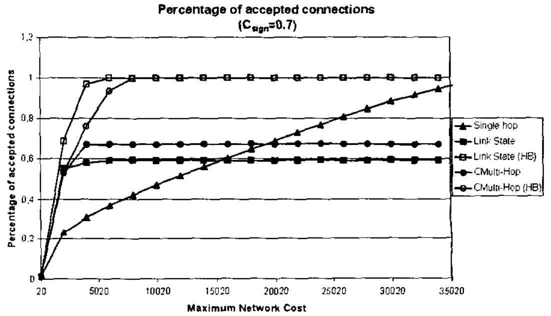

Fig. 3. Percentage of accepted connections as a function of the maximum network cost value. Each curve characterized by a different dot shape corresponds to a different path selection strategy (Triangle: Single Hop, Square: Link State, Circle: Clustered Multi-Hop), while different dot colors correspond to different values of available bandwidth in each terminal (Black: standard bandwidth, White: high bandwidth).