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Power-aware design of MAC and routing for UWB networks

(Invited Paper)

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***Abstract*— Ultra Wide Band (UWB) radio is considered as a valuable candidate for the deployment of large-scale, low data rate networks, thanks to its large bandwidth allowing for a high number of simultaneous communications. The specific characteristics of UWB, such as ranging capability and severe power limitations, call however for innovative solutions not only at the physical layer, but also at MAC and network layers as well. In this paper an integrated strategy for MAC and routing in UWB networks is proposed, which combines the multiple access capabilities and the ranging information provided by this transmission technique. The strategy exploits the distance information for reducing the power emission in the network, leading to a longer network lifetime and low Multi User Interference (MUI), thanks to the combination of a distance-based routing metric with a location-aware routing protocol, enabled by the adoption of a distributed positioning protocol. The effectiveness of the proposed solution is evaluated by means of simulations.**

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 Local Area Network (LAN) applications. UWB is also capable of recovering distance information with great precision. Distance and position data can lead to better organization of wireless networks, for instance through better resource management and routing. 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.

In the last few years, the increasing interest in applications based on the deployment of ad hoc networks triggered significant research efforts on the introduction of the energy-awareness concept in the design of Medium Access Control (MAC) and routing protocols. Ad hoc networks, in fact, are considered as a viable solution for scenarios in which fixed infrastructure, and consequently unlimited power sources, are not available. In such scenarios, an efficient management of the limited power supply available in each terminal is thus a key element for achieving acceptable network lifetimes. This is particularly true for sensor networks, for which long battery duration is one of the basic requirements, given the typical size of such networks (up to thousands of terminals).

This work presents a power-efficient, location-aware solution for MAC and routing in UWB networks, and shows how the distance information made available by the UWB technology can be exploited to achieve low power levels and increased network lifetime on the long term, while assuring an adequate network performance (in terms of data throughput) on the short term. The results obtained by computer simulations propose UWB as a valuable solution for low data rate, location-aware networks.

The paper is organized as follows. Section II presents an overview of existing power-efficient MAC solutions, while Section III reviews location-aware routing protocols. Section IV presents the solution proposed for low data rate UWB networks, based on the combination of three key elements: a random access MAC protocol with dedicated procedures for distance estimation, a distributed positioning algorithm for retrieving position information, and a location-aware routing protocol capable of exploiting such information for optimizing network performance in terms of power-efficiency. Section V presents simulation results for the proposed solution, and Section VI draws conclusions.

II. Power-aware MAC protocols

CSMA-CA protocols are by far the most common approach adopted in narrowband wireless LANs. These protocols suffer however of several drawbacks in terms of power consumption: packet collisions, which cause a waste of power due to retransmission, terminals blocked in idle state by active transmissions, and overhearing, i.e. terminals consuming power in the reception of packets for which they are not the intended destination. Several protocols aiming at the solution of such drawbacks were proposed. Among them it is worth mentioning the Power-Aware Multiple Access protocol with Signalling for ad-hoc networks (PAMAS) [4]. This protocol combines the CSMA approach with the out-of-band principle, in order to minimize the time a terminal spends in idle state without neither transmitting nor receiving. The protocol foresees in fact a control channel on which the handshake between transmitter and receiver takes place, and a data channel on which data

packets are exchanged. The control channel allows terminals to determine when they can safely switch to sleep mode, thus saving power, without affecting data throughput or end-to-end delay. The main idea behind PAMAS is that if a node detects the channel as busy, it goes in sleep mode rather than waste power in idle mode without being able of exchanging data packets. The protocol defines dedicated handshakes which allow terminals to determine for how long they can keep the radio interface switched off. Simulations show that this approach leads to a power save of up to 70% compared to the standard MACA protocol. It should however be noted that part of the dramatic advantage shown by PAMAS over the MACA protocol is intrinsically due to the assumption of adopting a CSMA-CA approach at the MAC level. PAMAS exploits in fact the presence of "pause" periods in the terminal lifetime, due to busy channel or lost contention, to save energy without affecting delay and throughput.
If an alternative solution, for example Aloha without Carrier Sensing, is adopted, the adaptability of a PAMAS-like approach should be object of further investigation.

III. Location-aware routing protocols

In the last few years the availability of GPS technology caused an increasing interest in the research on routing protocols capable to exploit the location information in the path search procedures. In this section we briefly review the existing solutions, in order to highlight how these solutions fit to the case of a UWB network.

A. Location-aware Long-lived Route Selection in Wireless Ad Hoc Network

The Location-aware Long-lived Routing (LLR) protocol [5] belongs to the family of source-initiated, on-demand routing protocols. The protocol exploits location information in the choice of the best path between source and destination, aiming at the minimization of route failures and, as a consequence, of route reconstruction procedures. As in traditional source routing protocols, a source terminal S needing for a route to a destination broadcasts Route Discovery packets to its neighbors, which will forward packets until the destination is reached. In LLR, two additional information fields are included in each packet: terminal position and radio range. This information is used by each terminal receiving the packet to compute a position-related metric: the so called Normalized Movement Limit (NML) ([5]). The computed NML is added to the packet before forwarding it.
The NML is assumed as an indicator of link stability: the higher the NML value, the lower the probability of link failure due to terminal mobility. When the destination D receives several Route Discovery packets originated from the source S, it selects the route characterized by the highest NML, in order to minimize the probability of a route failure.

B. Distance Routing Effect Algorithm for Mobility (DREAM)

The DREAM algorithm [6] proposes the idea of using positional information to reduce the amount of routing overhead. The protocol combines both proactive and reactive approaches, by relying at the same time on periodic updates by each terminal for the dissemination of location information and on a flooding-like procedure for sending a packet to the targeted destination.
When a source terminal S starts the procedure in $t = t_1$ it is supposed to have the following information:

- Its own position (X_S, Y_S)
- The positions of its one-hop neighbors
- The position of the destination D, (X_D, Y_D), at a given time $t_0 < t_1$
- The maximum speed v of the destination, or at least a probability density function of such a speed, $p(v)$

The source uses such information to determine the direction in which packets should travel in order to reach the destination and, consequently, the geographical region in which the packets should be forwarded (forwarding region). The forwarding region is determined by the angle α, as defined in Figure 1. Once that α has been determined, the terminal checks if there is at least one neighbor in the forwarding region and, if this is the case, sends the packet. Each intermediate terminal, when receiving a packet, evaluates its own position with regard to the forwarding region defined by the source: only terminals which lie within the region are authorized to forward the packet.
As stated before, the procedure requires positional information regarding not only the source, but also its neighbors and the destination. This information is communicated through a distributed dissemination algorithm, which constitutes the proactive part of the protocol. Each terminal A periodically broadcasts update packets containing its own position; two kinds of update packets are defined in DREAM:

- *short lived packets*, used to update the location tables in A's neighbors, which are not allowed to reach distant parts of the network
- *long lived packets*, used to update the location tables in terminals which are not in direct connectivity with A, which are allowed to reach every node in the network

Note that the lifetime of each packet is defined in terms of physical distance reached from the terminal originating the packet: each terminal B receiving an update packet generated by terminal A checks both A's position (recorded in the packet) and its own position: if the distance $A - B$ is higher than the packet lifetime the packet is discarded, otherwise it is forwarded. Short lived and long lived packets are emitted by each terminal with different frequencies, taking into account the so-called distance effect, which is represented in Figure 1 and can be described as follows. Given a terminal A moving at speed v, and two terminals B and C which in $t = t_0$ are positioned at distances D_{AB} and $D_{AC} \gg D_{AB}$ from A respectively, terminal B will experience a faster variation of the forwarding region to destination A than terminal C, due to A's movement in the time interval $t_1 - t_0$ (i.e. the angle α_B will increase faster than the angle α_C to keep A in the forwarding region.) As a consequence, B will need much more frequent updates than C regarding A's position: such updates will be provided by means of short lived packets which will reach B without increasing the routing overhead all over the network. C will receive updates at lower frequency by means of long lived packets.

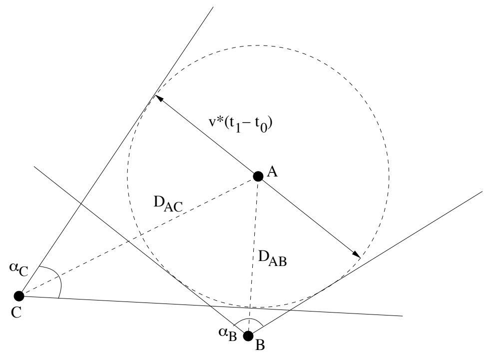

Fig. 1. Definition of forwarding zones and distance effect

It is evident that terminal speed plays an important role in such a protocol, and each terminal is expected to adapt the emission frequencies of both long lived and short lived packets to its own speed: as a consequence fixed terminals will use the lowest frequencies, while highly mobile terminals will send frequent updates.

C. Location Aided Routing (LAR)

The LAR protocol [7], [8] is a typical on-demand routing protocol. In order to find a route between source and destination terminal, it relies on a flooding-based Route Discovery procedure. The major drawback of a flooding-based on-demand protocol is constituted by the huge amount of routing overhead generated during path search procedures. The Location-Aided Routing exploits location information in order to reduce the amount of routing overhead, in a similar way to the DREAM algorithm described in section III-B. The basic location information required by LAR consists in:

- Source position
- Destination position
- Maximum terminal speed

Such information is exploited during the Route Discovery procedure in following way. Suppose that a terminal S starts a Route Discovery procedure to destination D at time $t = t_1$, and that the last information update regarding D's location was received by S in $t = t_0$. Based on the estimation of the maximum speed v of terminal D, S can evaluate the maximum distance traveled by D since the last location update. Such a distance is given by $d_{MAX} = v \cdot (t_1 - t_0)$. As a consequence, the current position occupied by D lies in a circular region of radius d_{MAX} centered on $(x_D(t_0), y_D(t_0))$, referred to as the *Expected zone*. The Expected zone indicates which zone of the network should be reached by Route Request packets. The key idea in LAR is to exploit this information to reduce the amount of Route Request packets flooding through the network, by allowing forwarding of packets generated by the source only in the direction of the Expected zone containing the destination. The region of the network in which forwarding is allowed is referred to as *Request zone*. An intermediate terminal is allowed to forward a Route Request packet only if it lies within the Request zone defined by the source of the connection request.

As most of the location-based routing protocols proposed so far in the literature, LAR assumes the adoption of GPS-enabled terminals. This allows each terminal to know its own position and speed. Nevertheless, as described in the previous section, the knowledge of the position of the destination is also required at the source in order to reduce routing overhead. This means that localization information must be disseminated through the network. Such dissemination is performed by piggybacking location information in all routing packets. LAR uses time stamps during Route related procedures in order to indicate how recent the piggybacked information is. Note however that, at least at the beginning of network operations, terminals will be forced to find routes in the absence of location information. In such a situation basic flooding is adopted.

D. From GPS to UWB positioning

The adoption of the UWB technology in place of GPS as the basis for retrieving position information opens new scenarios to location-based applications (such as indoor deployment), but also poses new challenges. It is reasonable to expect that significant modifications will be required for a GPS-based protocol to be applied in a UWB network. The main additional requirements posed by UWB-based positioning are as follows:

- Positioning is obtained by distributed processing of ranging measurements, thus potentially requiring a long time to spread positioning information all over the network. Furthermore, occasional large errors in position information due to lack of connectivity or unfavorable topology may occur. The routing algorithm must be then capable to find routes and establish connection even in conditions of positioning information incomplete or absent.
- Estimation of absolute terminal speeds is in general not available.

In the case of the DREAM protocol both selection of routes and dissemination of information rely on positioning to work properly: in particular, the proactive dissemination algorithm exploits the capability of a terminal to determine its physical distance from terminals which are not reachable, in order to evaluate if an update packet is still valid. If location information is not available or subject to errors, the effect of such errors is thus amplified by both the proactive and reactive part of the protocol. Furthermore, lack of speed information poses an additional issue on the correct behavior of the protocol.

Oppositely, LAR protocol inherently offers a backup solution when no positioning information is available. In fact, in the case of absence of information regarding the position of the destination, the protocol switches to a basic flooding scheme, resembling a Dynamic Source Routing protocol. In this case the lack of positioning information results in a reduced efficiency of the protocol.

LLR can be adapted to a UWB-based positioning system with minor changes, but the protocol is inherently tailored for scenarios characterized by terminal mobility (in which route stability is the main concern), and does not offer major advantages in terms of power efficiency in networks composed of still or slowly mobile terminals.

The above considerations led to the choice of adopting LAR as the routing protocol for the integrated power-efficient and location-aware solution presented in the next section.

IV. Joint power-efficient, location-aware MAC and routing

The design of a power-efficient solution requires a cross-layer approach which involves all layers from physical to network and above. In this section we will focus on the joint design of MAC and routing for terminals based on a UWB radio physical layer. As regards the MAC itself, Time Hopping - Impulse Radio (TH-IR) provides a built-in CDMA multiple access mechanism, based on the adoption of a different TH code on each active link [1], [2]. The adoption of a multiple code MAC has been first proposed for traditional CDMA networks. In such networks, however, the low achievable processing gains require a code distribution protocol in order to avoid excessive Multi User Interference (MUI) by assuring that each link uses a different code [9]. Oppositely, UWB is expected to provide a huge processing gain thanks to the low signal duty cycle: as an example, an UWB signal characterized by a pulse duration T_p equal to 100 ps and a Pulse Repetition Period T_s of 1 μs has a duty cycle of $T_p/T_s = 10^{-4}$. Since a low duty cycle corresponds to a low probability of collision between pulses, it can be reasonably expected that a random selection of TH-codes still guarantees a good performance. Based on this assumption, a MAC tailored for UWB low data rate networks was proposed in [10], in which terminals transmit packets in a Aloha fashion on transmitter-specific codes, without any code distribution protocol. Simulation results confirmed that the Aloha based approach is a suitable solution for low data rate scenarios, where pulse collisions can be considered a rare event. The Aloha approach, as noted in section II, does not allow to adopt a PAMAS-like approach to increase power efficiency. Nevertheless, the adoption of a power-saving algorithm, allowing terminals which are not involved in any active communication to move to a sleep mode, can lead to a significant reduction of power consumption. Since the adoption of long sleep periods could lead to unacceptable delays in reaching a sleeping terminal, the algorithm should be carefully designed in order to achieve a trade-off between power saving and latency in the set-up of new connections. The MAC in [10] enables the exploitation of UWB-based positioning in upper layers by defining a dedicated procedure for ranging. The ranging information provided by the MAC is used in a twofold manner:

1) It allows the definition of a power-aware metric, as described in [11], [12]
2) It constitutes the input for a distributed positioning protocol which determines a relative network map.

Note that the protocol must be capable of building the map starting from scratch, and without predefined anchor nodes. Such a protocol is proposed in [13]. In this protocol each terminal starts a local positioning procedure assuming the role of center of the local coordinate system and attempting to determine the position of its neighbors in this coordinate system. At the same time, terminals exchange information in order to harmonize the local coordinate systems and converge to a network coordinate system. The relative position map obtained by means of the positioning protocol finally constitutes the basis for the application of a location based routing. As anticipated in section III we chose to adopt LAR as a routing protocol.

TABLE I
Simulation settings

Parameter	Value
λ	5 s
Target SNR	12 dB
Maximum speed	4 m/s
RRQ packet size	760 bits
RRP packet size	760 bits
DATA packet size	5000 bits
Initial energy per node	100 J
N	20
Transmission Range	50
Area size	$80x80\ m^2$
Propagation index α	4
R_{MAX}	1 Mb/s

V. Simulation results

The strategy defined in section IV was analyzed in an ad-hoc network composed by N UWB terminals. All terminals were characterized by 1) high precision ranging capability, 2) limited transmission range R_{TX}, 3) maximum data rate R_{MAX}, 4) limited energy. Each terminal generated connection requests to other terminals in the network, following a Poisson distribution with an average value of λ. Each simulation run was considered concluded when all terminals run out of energy. Table I shows the settings adopted for relevant system parameters for all simulations. MUI was taken into account following the MUI model defined in [12].

Figure 2 shows the results in terms of Found connections for the following four strategies:

a) Source routing (no location) with hop minimization
b) Source routing (no location) with cost minimization
c) Location aided routing with hop minimization
d) Location aided routing with cost minimization

Simulation results show that the combination of location aided routing with a power-aware cost function leads to the best results in terms of network lifetime, thanks to the reduction of power-consumption and of Multi-User Interference. Note that both location information and cost minimization contribute to the increase in network performance, as shown by the gap between performance of strategies c) and d), both based on LAR but with different routing metrics. Note that even if the selection of routes with higher number of hops could potentially lead to a higher number of lost packets, due to a higher packet error probability over multi-hop paths, this effect is negligible, thanks to the positive effect of reduced MUI which compensates for the higher number of hops in power-aware routes, as shown in Figure 3.

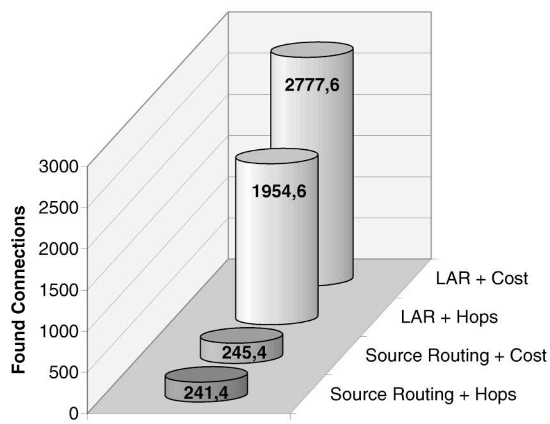

Fig. 2. Average number of Found connections

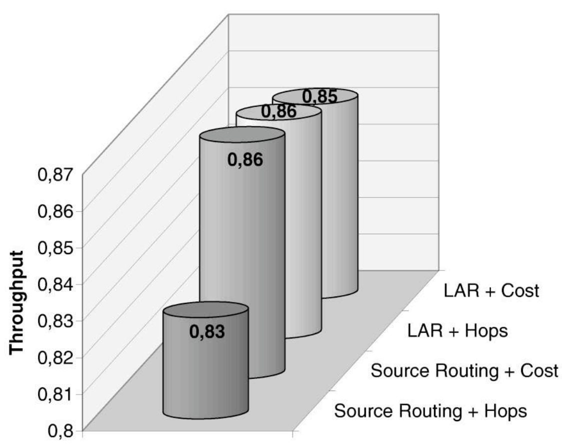

Fig. 3. Average Throughput

VI. Conclusion

In this work an integrated solution for MAC and routing in UWB ad-hoc networks was analyzed. The proposed MAC adopts an uncoordinated access to the medium, thanks to the high processing gain of UWB signals. Furthermore, a dedicated procedure in the MAC exploits the UWB ranging capability and provides distance information to the upper layers. Such information is then used in a twofold manner in order to achieve a high power efficiency: first, a distance-based routing metric is defined; second, the distance information is used by a distributed positioning algorithm for determining relative positions of terminals in the network. The distance-based routing metric, combined with a location-aware routing protocol using the results provided by the positioning protocol, reduce dramatically the power consumption, thus allowing for a higher number of communications, while maintaining unchanged the average throughput, thanks to the reduced MUI experienced by terminals in the network.

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