U.C.A.N.'s Ultra Wide Band System: MAC and Routing protocols

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***Abstract*—The European funded project U.C.A.N. (Ultra wide-band Concepts for Ad-hoc Networks) is in the process of designing and implementing an Ultra Wide Band (UWB) Impulse Radio (IR) single band communication system. This paper presents the MAC and routing protocols which are currently developed in U.C.A.N. project. Application scenarios for UWB systems are presented. The MAC protocol is an adaptation to UWB from the IEEE 802.15.3 draft standard for narrow-band WPANs. It uses the inherent ranging capability of UWB as a basis for advanced relaying and routing. Some MAC implementation issues on the demonstrator are described. Finally routing metrics and algorithm for the future system are detailed.**

***Index Terms*— UWB, MAC, Routing, Ad-hoc networks.**

I. Introduction

Ultra Wide Band (UWB) [1] is a type of spread spectrum wireless transmission system that has instantaneous fractional bandwidth of at least 25%, or alternatively 500 MHz bandwidth or more, as defined by the American Federal Communications Commission (FCC) [2]. The standardisation body IEEE is actively working towards a common standard around UWB technology [3]; a first set of proposals have been submitted in March 2003 [4]. Europe is also getting active in the field of UWB, via standardisation (ETSI, European Telecommunications Standard Institute) and regulation (CEPT, Conférence Européenne des administrations des Postes et des Télécommunications) bodies, and via EC (European Commission) funded projects.

There are basically two ways (in term of bandwidth occupation) to implement a UWB system: a single band approach, and a multiband approach. While U.C.A.N. does study the advantages of the multiband philosophy on a theoretical level, the demonstration platform to be realised will follow the single band model, implementing Impulse Radio (IR) [5], [6], as opposed to Direct Sequence Spread Spectrum (DS-SS) technique [7]. In DS-SS the bit is spread into a sequence of chips, and the chip rate is directly related to the bandwidth (roughly the inverse of the chip rate). In IR the bandwidth is decoupled from the chip rate by the introduction of an idle period after transmitting a pulse (short waveform concentrating energy followed by period of transmitting no energy). The period between two consecutive pulses is called in this case Pulse Repetition Period (PRP). The advantage of IR over DS-SS [8] is very high bandwidth (and associated processing gain), in addition to lower chip rate (and hence lower complexity).

The major components of an IR based UWB physical (PHY) layer are, on the transmit side:
- a channel coder (for Forward Error Correction (FEC));
- a modulator (transforming bits into digital symbols);
- a pseudo noise (PN) code generator (to randomise the PRP and the pulse polarity);
- a pulse generator (transforming digital symbols into analog signals);
- an antenna (shaping and radiating the analog signals).

On the receive side, the corresponding blocks are:
- an antenna (collecting received energy and shaping the analog signals);
- a demodulator (transforming analog waveforms into digital symbols);
- a synchronisation block (providing the same time reference for the receiver as used by the transmitter);
- optionally a template signal generator (providing template signals for correlation based receivers or filter coefficients for matched filter based receivers), and optionally a channel estimator (feeding the template signal generator);
- a PN code generator (to align the receiver processes to the randomized PRP and pulse polarity of the transmitter);
- a channel decoder (implementing FEC).

Fig. 1 depicts the PHY layer block diagram, as conceived within the U.C.A.N. project.

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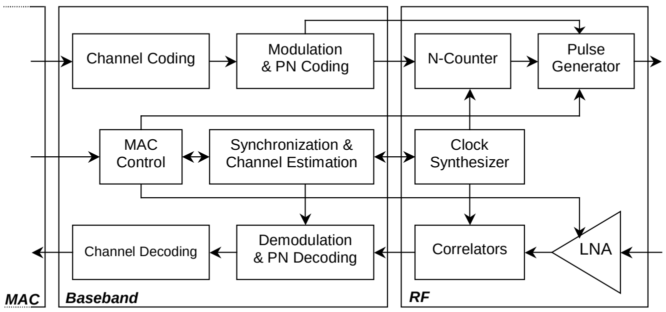

Fig. 1: U.C.A.N.'s PHY layer block diagram.

The object of this paper is to present the MAC and routing protocol development within the U.C.A.N. project. Section II describes the application scenarios. Section III presents U.C.A.N. MAC architecture and shows the differences with IEEE 802.15.3 MAC. Finally, section IV describes the relaying and routing strategies adopted for U.C.A.N. scenarios.

II. U.C.A.N. SCENARIOS

The UWB radio technology can be a feasible solution for almost all network scenarios, starting from the simplest situation in which this technology is adopted in a mixed wired-wireless environment, with only radio resource control issues, to the hardest in which UWB is the base for a fully distributed, self-organizing, large scale ad-hoc network.

In task 4.1, the U.C.A.N. network architecture study is considering different types of networks scenarios that we can characterize in three (simplified) models:

- short range computer communication, e.g. linking domestic appliances to local PC as a super Bluetooth scenario, usually referred as WPAN applications,
- Hot spot coverage and network backbone interconnection in which PDAs could communicate by using UWB techniques ,
- clusters of ad-hoc networks, potentially composed of large populations of nodes covering very large areas, possibly using self–organising techniques for message hopping through the entire net.

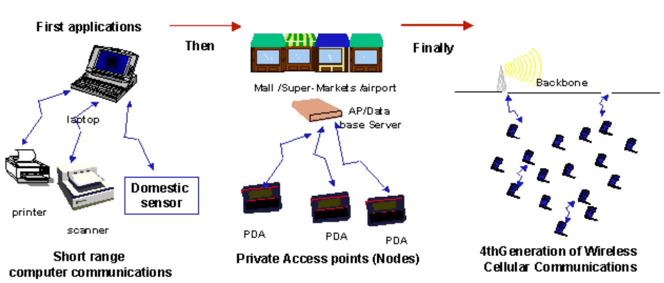

Fig. 2: U.C.A.N. application scenarios

Even if the ultimate scenario for an UWB ad-hoc network is the third scenario above listed, however several ad-hoc network scenarios can be considered for UWB-based networks. Key factors in the realization of these scenarios are: transmission power levels allowed for UWB devices, sustainable bit-rates, reliable and efficient localization algorithms, and scalable routing algorithms.

As a general guideline, the UWB network applications we can consider include, in increasing order of complexity, the following network scenarios:

1. Networks of fixed terminals at fixed known positions such as those that could be employed in a conference room (for peer to peer communication), in a car, or in a building. Typical ranges would be for terminals a few meters apart, and networks in the 100m range. The hypothesis of known positions obviously requires a previous planning of terminals disposition, but it avoids the adoption of localization algorithms.
2. Networks of fixed terminals initially deployed at locations that are not known with any precision. This scenario can be applied to several real-life applications, such as small range networks in scientific labs, conference rooms, and other environments in which a planned disposition is not possible. This is the case, for instance, of sensors deployed in some areas for surveillance purpose (underground parking), or a blanket of sensors dropped over a wide area (fire detection in a forest). This detection and surveillance applications require robust (immunity to fading/outages) and rapid (on the fly/no spectrum assignment) wireless networking in various complex environments such as urban areas or indoor conditions. In this scenario a cost function has to be defined and has to be used in MAC and routing protocols, but fast location updates are not necessary, because positions of terminals are considered fixed over long times.
3. Networks of terminals with moderate mobility in the same ranges as before or on larger scale. In a first step, we can imagine a scenario with electrical cars in an exhibition. These cars are used to move in a large exhibition and have an embedded camera. Cars are abandoned by users when they have finished to use. Every evening, at the end of the exhibition, an operator is able to locate the vehicles (with UWB communications) and, thanks to the camera, can bring the cars back to the parking area with a remote control.
For instance sensors are embedded in cars, capable of communicating from car to car, from cars to fixed sensors embedded in the road or along the side of the road, and/or from cars to the fixed land network. In this scenario frequent topology variations are supposed, which require dedicated location-update procedures to keep localization information up-to-date; The degree of correctness of localization information will heavily impact MAC and routing algorithms, and therefore the overall network performances.
4. Local ad-hoc wireless networks. In this scenario full mobility is supposed, for instance with hikers walking in forest or in snowy mountains. Fast adapting algorithms are required, both for localization and routing. The basic application of this scenario is voice communication between the different users of the group. An important auxiliary function is mutual positioning specially when members of the group are lost in the fog or under snow.

5. Large-scale ad-hoc network architecture for wireless/mobile telephony and data communication.

The requirements for this scenario are similar to those described for the previous ones, but the large scale extension leads to a higher number of users and therefore scalability becomes a key issue for all adopted algorithms. Some base stations are necessary to connect users who are distant or to connect users to a fixed network but for close users, relaying is sufficient.

III. MAC ARCHITECTURE IN U.C.A.N.

The selected applications in U.C.A.N. project are short (WPAN) and medium (WLAN) range applications. This choice influenced greatly the U.C.A.N. MAC architecture.

We were conducted by the following reasons in the U.C.A.N. applications selection. First of all the current regulation issued by the FCC is quite restrictive and allows a reduced maximum range for UWB systems. Moreover the UWB standardization process at IEEE is oriented on WPAN applications, which is also a consequence from the regulation. Lastly, U.C.A.N. project aims at demonstrating some UWB concepts on a platform with a few nodes, excluding large scale applications. Thus the MAC developed and demonstrated in U.C.A.N. is specially suited for WPAN, and it is able to cope with both asynchronous data transfers and multimedia applications with QoS.

WPANs are small scale networks called Piconets, with a reduced number of users (e.g. up to 10 per piconet). Several independent WPANs may have to coexist in the same area without interfering, so a mean of separating them has to be taken into account. IEEE 802.15.3 proposes that several frequency channels be used for coexistence of narrow-band WPANs. However, in a single wide band UWB system, this concept is not applicable. In these systems, other techniques such as the time hopping (TH) code division, are more suitable.

MAC protocol is centrally coordinated, with a PicoNet Coordinator (PNC) which synchronizes the devices (DEVs) and allocates the resources. Even if the MAC protocol is a centralized one, the topology is ad-hoc and communications are in peer to peer mode. The PNC can be chosen dynamically, i.e. it is auto-claimed each time a new piconet is created. It partially follows from the constraint that the same hardware must be used for all DEVs. With this protocol, main part of the processing power is concentrated in the PNC's hands. However if the PNC disappears, another station can take on its role, which is an advantage over static centralized management.

A combination of TDMA (intra-piconet) and TH-CDMA (inter-piconet) was chosen because of targeted applications. In particular, voice and video cannot cope with too large transmission delays and jitter, which eliminates collision-based access protocols like CSMA/CA.

The chosen MAC is based an adaptation of the 802.15.3 MAC draft standard [9] to UWB physical layer, with additional ranging and relaying features. The same terminology as in 802.15.3 has been adopted for clarity. We first give an overview of IEEE 802.15.3 and then describe the U.C.A.N. specific MAC protocol.

A. *IEEE 802.15.3 MAC protocol*

IEEE 802.15.3 timing within a piconet is based on the superframe, which is illustrated in Fig. 3.

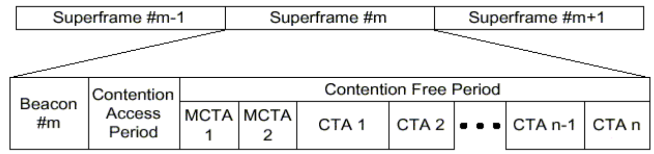

Fig. 3: 802.15.3 superframe format

The superframe is composed of three parts: a beacon, a Contention Access Period (CAP) and a Contention Free Period (CFP). The beacon frame is sent by the PNC at the beginning of every superframe. It is used to time-synchronize all DEVs to the PNC's clock, to set the superframe timing allocations, as well as to communicate management information for the piconet. The Contention Access Period (CAP) is used to communicate commands and non-stream asynchronous data. During CAP, DEVs access the channel using CSMA/CA and a backoff procedure. PNC divides the CFP into channel time allocation (CTA) slots. CFP is used for asynchronous and isochronous data streams. Standard does not precise the algorithm that PNC uses to allocate channel time.

Channel access in the CFP is based on a TDMA method. Each CTA has guaranteed start time and duration within the CFP. Management time slots (MCTAs) are CTAs that the PNC assigns for communication between the DEVs and the PNC. These slots are used by DEVs to send their channel time requirements and exchange other control messages with the PNC. Association MCTAs are used for unassociated DEVs to send to the PNC the request to associate to the piconet. In open MCTAs any DEV that is already associated to the piconet can attempt to send a command frame to the PNC.

Slotted Aloha is used to access open and association MCTAs, while the access mechanism for regular MCTAs, i.e. neither open nor association MCTAs, is TDMA.

B. *U.C.A.N. MAC protocol*

Adaptations to IEEE 802.15.3 were introduced for the following reasons: 1) IEEE 802.15.3 is originally intended for narrowband 2.4GHz WPAN, and was very likely to need adaptations for UWB WPAN, 2) U.C.A.N. platform may impose some restrictions, and 3) U.C.A.N. is also investigating some possible MAC enhancements that will take into account the inherent advantages of the UWB technology, not currently addressed in IEEE 802.15.3. U.C.A.N. MAC introduces procedures for enabling UWB ranging and relaying.

U.C.A.N. MAC does not use CSMA/CA channel access method. CCA (Clear Channel Assessment) is necessary for CSMA/CA method of channel access. In the case of UWB, CCA by energy detection is difficult with UWB-PHY because of very low power emissions. Since energy is spread in a large frequency bandwidth, this usually causes low energy at the receiver. In UWB the energy is not a good measurement due to wide band receiver. Indeed, the transmissions of others are perceived as noise.

This leads to the conclusion that CSMA/CA is hard with UWB. Therefore, U.C.A.N. MAC does not use CAP period within the superframe.

Similar to IEEE 802.15.3, timing within a U.C.A.N. piconet is based on the superframe divided into three zones:

- A beacon phase, emitted by the PNC to synchronize DEVs and broadcast information about the piconet characteristics and the resource attribution.
- An random access phase, composed of particular management CTAs (that we call Access CTAs) for which access is based on slotted aloha, and not CSMA/CA. As referred to IEEE 802.15.3, these management slots correspond to open and association MCTAs. Acknowledgements for this phase is done in the beacon of the next superframe.
- A phase during which DEVs are allocated CTAs by the PNC to transmit control or data frames.

The superframe structure is shown in Fig. 4.

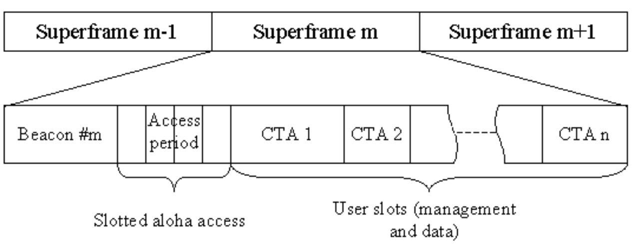

Fig. 4: U.C.A.N. superframe structure

All duration in the superframe (Beacon, Access Period, CTAs) are theoretically variable. For simplicity of implementation in U.C.A.N, the superframe has a fixed length of about 10 ms. The Access period has also a fixed duration of about 800 µs.

CTAs have variable length and are dynamically allocated by the PNC. There are two types of allocations: isochronous streams are allocated regular CTAs, whereas asynchronous streams are given CTAs on-demand. Four levels of service priority are defined. Simulations will show which is the best strategy for resource scheduling.

U.C.A.N. MAC defines several types of frame formats, namely control frames, data frames and measurement frames. Control frames are used for DEVs to communicate with the PNC, data frames are used in peer-to-peer communication between DEVs, while measurement frames are used in support of UWB ranging functionality. Long MAC Service Data Units (MSDUs) can be fragmented to improve frame error rate. Several types of acknowledgement (ACK) schemes can be used: no-ACK, immediate ACK or delayed ACK.

MAC level relaying has been added. Only a slight modification in the possible interpretations of resource request commands was necessary. It is useful for the PNC to know when a DEV wants to relay and allows it to allocate resource more efficiently. Priority is given to relaying streams over new streams, to avoid problems of "half-way blocking" when DEVs that need two hops to reach a destination are allocated resources only for the first hop. The relaying establishment algorithm in the demonstrator is a simplification of the routing algorithm explained in IV. Relaying cost is based only on distance, and the cost function can be written as:

$$C(x,z) = [d(x,y)]^2 + [d(y,z)]^2$$

C. Demonstrator implementation

U.C.A.N. MAC protocol is being developed on Motorola's ART platform. MAC implementation has two parts: the first one called MAC firmware (MAC S/W) is responsible for all the non-time critical functions; the second part is the MAC Hardware accelerator (MAC H/W), and is in charge of managing low-level time critical functions. MAC H/W is embedded in the FPGA. The most important time critical functions are: MSDU transmission including necessary operations to deliver associated MPDU to the PHY, beacon detection at the receiver side, MPDU reception and associated transformation to deliver MSDU to MAC firmware, fragmentation and defragmentation, and all associated control frames management including acknowledgement mechanism.

On the other hand, MAC Firmware is in charge of MAC management functions such as association, disassociation, or power control, preparation of MSDU to be transmitted and delivery to MAC H/W, preparation of requests for CTA allocation, consumption of received MSDU. In addition to that PNC is also in charge of the preparation and scheduling of superframes, and of piconet management.

IV. Routing strategies for U.C.A.N. scenarios

The demonstration phase of U.C.A.N. will not permit to deploy a large number of UWB terminals, thus the routing study has been performed theoretically and through simulations. The research carried out within the U.C.A.N. project on routing strategies focused on two main aspects:

- Routing metric
- Routing algorithm

The combination of these two aspects leads to the complete definition of the routing protocol. Potential solutions for both of them have been developed within the U.C.A.N. project.

A. Routing metric

Traditional routing protocols for ad-hoc networks generally focus on procedure definitions (path search, information dissemination, error recovery). Low attention is dedicated to the definition of routing metric, which is assumed to coincide with number of hops; Few exceptions to this statement can be found [10].

Routing metric is a key aspect in the definition of routing protocol, as it deeply influences protocol performance. In fact, a metric correctly tailored for the characteristics of the network may lead to an optimization of routing, significantly increasing network performance.

In the case of a UWB network, the severe power limitations due to coexistence requirements lead to the conclusion that the key system parameter is emitted power. Following this assumption, a metric was defined which favors an efficient use of power, thus increasing coexistence capabilities [11][12]. At the same time, other aspects which influence network performance were taken into account in metric definition. Some of them are related to physical layer issues, as synchronization overhead and multi-user interference, while others regard network layer, as end-to-end delay, route quality and traffic balancing.

The routing metric is based on the introduction of an additive link cost function which is obtained as the sum of several terms taking into account the above aspects, with the general form:

$$C(x,y) = C(power) + C(setup) + C(interference) + C(quality) + C(delay)$$

The cost of a communication path is the sum of the cost of its links:

$$C(path) = \sum_{(x,y)\in path} C(x,y)$$

In general, there will be many possible communication paths between source and destination. The basic routing strategy will be to opt for the path with minimal cost. Note that the way such a path is individuated will depend on path search procedure, but this will not affect the definition of link and path costs.

The cost of a link varies in time and also depends on the parameters (e.g., requested rate) of the originating request from source terminal. As an example, the power term of the cost function *C(power)* is defined as:

$$C(power) = C_1 \cdot R(x,y) \cdot d^{\alpha}(x,y)$$

where R is the requested rate on the link, d is the distance between the two terminals and α a positive number depending on propagation characteristics (usually between 2 and 4). Note that such a definition is based on the ranging capability offered by the UWB technology.

A simplified version of the routing metric described above will form the base of the relaying function to be included in the U.C.A.N. demonstrator. Specifically, a metric based on distance between terminals in the piconet will be adopted to select the relaying terminal when no direct connectivity between source and destination is available.

B. Routing algorithm

The choice of routing algorithm takes into account two main criteria, partially in contrast between them:

- Exploitation of positioning information in routing: the capability of UWB to provide ranging information and, through distributed computing, positioning information has been considered a key aspect to be taken into account in the development of routing protocol. So a routing protocol capable of exploiting such information was selected.
- Independence of routing from positioning: even if positioning may significantly help routing, in the case of UWB network such information will not be available at all times: the need to build an initial positioning database at network setup and possible errors and lacks of information will eventually cause both ranging and positioning information to be unavailable in some or all terminals. Such terminals should be capable to perform routing as well, even without the advantages offered by positioning information.

Furthermore, a choice between proactive and reactive routing protocol had to be made. Location-aware protocols available in literature show that positioning information can be better exploited in the case of reactive protocols; Furthermore, even if network size foreseen in the U.C.A.N. project (10-100 terminals) is small enough to allow in most of cases both approaches, reactive protocols adapt better to the fast topology changes present in mobile ad-hoc networks.

Such considerations led to the choice of an on-demand routing protocol, in which positioning information is exploited to significantly reduce the protocol overhead, but is not essential for the execution of routing function. A similar protocol is the Location-Aided Routing protocol [13][14] which constitutes an interesting basis for the routing protocol to be adopted for the U.C.A.N. project.

The LAR protocol 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 fact, depending on source position and destination *expected* position a *Forwarding zone* is defined, and only terminals lying within this zone are allowed to forward request packets during the Route Discovery procedure.

In order to optimize the original protocol and adapt it to the U.C.A.N. scenario, two main modifications were required:

- In LAR, an intermediate terminal only forwards the first Route Request packet received for each connection request. If routing metric is no number of hops, such a forwarding strategy would generally discard packets which travel over paths at lower cost than the first one. In U.C.A.N., intermediate terminals are allowed to forward more than one packet related to the same request.
- In order to limit as much as possible power emissions, an optimized cone-shaped Request zone was selected, which guarantees the lowest number of emitted Route Requests packets during a Route Discovery procedure. Fig. 5 shows an example of cone-shaped Request zone.

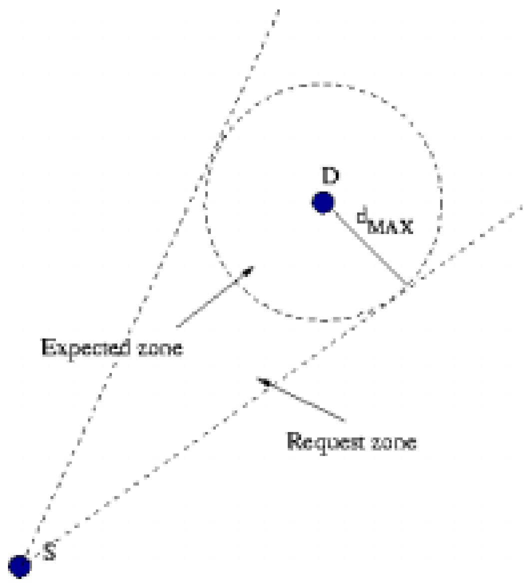

Fig. 5: Cone-shaped Request zone in LAR

V. Conclusion

The present paper has described the main characteristics of U.C.A.N. scenarios, MAC and routing algorithms. It was shown that the adaptation of 802.15.3 standard for 2.4GHz narrowband WPAN required only minor changes to cope with UWB-PHY. Moreover MAC layer can be enhanced by adding a low-level relaying function and using the UWB ranging capability. Some hints about MAC implementation were also given. Finally, principles of the location-aided routing protocol were derived, and its optimization for U.C.A.N. scenarios was explained.

References

[1] M. Pezzin, J. Keignart, N. Daniele, S. de Rivaz, B. Denis, D. Morche, Ph. Rouzet, R. Cattenoz, N. Rinaldi, "Ultra Wideband: the radio link of the future?", *Annales des Télécommunications*, 58, nr. 3-4, March-April 2003.

[2] FCC, ET Docket 98-153, "FIRST REPORT AND ORDER: Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems", Adopted: February 14, 2002, Released: April 22, 2002.

[3] IEEE P802.15-03/03r5, "P802.15.3a Alt PHY Selection Criteria", December 2002.

[4] http://grouper.ieee.org/groups/802/15/pub/2003/Mar03/.

[5] M.Z. Win, R.A. Scholtz, "Impulse Radio: How it Works", *IEEE Communications Letters*, February 1998.

[6] M.Z. Win, R.A. Scholtz, "Ultra-wide Bandwidth Time-hopping Spread-Spectrum Impulse Radio for Wireless Multiple-Access Communications", *IEEE Transactions on Communications*, April 2000, vol. 17, issue 5, pp. 824-836.

[7] J. Foerster, "The Performance of a Direct-Sequence Spread Ultra-Wideband System in the Presence of Multipath, Narrowband Interference, and Multiuser Interference", *IEEE Conference on Ultra Wideband Systems and Technology*, 2002.

[8] V.S. Somayazulu, "Multiple Access Performance in UWB Systems Using Time Hopping vs. Direct Sequence Spreading", *IEEE Wireless Communications and Networking Conference*, March 2002, vol. 2, pp. 522-525.

[9] IEEE Draft P802.15.3/D15, "Part 15: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPAN)", Oct. 2002.

[10] C.-K. Toh, "A Novel Distributed Routing Protocol To Support Ad-Hoc Mobile Computing," Proc. 1996 IEEE 15th Annual Int'l Phoenix Conf. Comp. And Commun., March 1996, pp. 480-486.

[11] L. De Nardis, P. Baldi and M.-G. Di Benedetto, "UWB Ad-Hoc Networks" Ultra Wide Band Systems and Technologies 2002, Baltimora, May 15-17, 2002, pp. 219 -223.

[12] P. Baldi, L. De Nardis and M.-G. Di Benedetto, "Modeling and Optimization of UWB Communication Networks Through a Flexible Cost Function," IEEE Journal on Selected Areas in Communications, Vol. 20, Issue 9, Dec. 2002, pp.1733 -1744

[13] Y.B. Ko and N.H.Vaidya, "Location aided routing in mobile ad hoc networks," Fourth annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom '98), 1998, pp. 66-75.

[14] Y.B. Ko and N.H.Vaidya, "Optimizations for location aided routing in mobile ad hoc networks," Technical Report 98-023, CS Dept, Texas A&M University, Nov. 1998.