IEEE International Conference on UWB, September 5 - 8 2005,
Zurich, Switzerland, pp. 758 - 763.

UWB MAC and Network Solutions for Low Data Rate with Location and Tracking Applications

Guerino Giancola[†], Ljubica Blazevic["], Isabelle Bucaille[□], Luca De Nardis[†], Maria-Gabriella Di Benedetto[†], Yves Durand[°],
Gwillerm Froc[*], Begoña Molinete Cuezva[‡], Jean-Benoît Pierrot[°], Pekka Pirinen[~], and Nils Rinaldi["].

[†] University of Rome La Sapienza, Italy. Email: {giancola,denardis,dibenedetto}@newyork.ing.uniroma1.it
["] ST Microlelectronics, Switzerland. Email: { ljubica.blazevic,nils.rinaldi }@st.com
[□] Thales Communications, France. Email: isabelle.bucaille@fr.thalesgroup.com
[°] CEA-Leti, France. Email: { durandyv,pierrotje } @ chartreuse.cea.fr
[*] Mitsubishi Electric, France, Email: froc@tcl.ite.mee.com
[‡] Robotiker Telecom, Spain. Email: bmolinete@robotiker.es
[~] University of Oulu, Finland. Email: pekka.pirinen@ee.oulu.fi

***Abstract*—The object of this paper is to present the main results achieved during the first fifteen months of the 6th framework European Union integrated research project PULSERS [1], regarding Ultra Wide Band (UWB) Medium Access Control (MAC) and network layer issues for low data rate with location and tracking (LDR-LT) applications. Various intended UWB system architectures and their key requirements and parameters are introduced. For such systems, potential MAC schemes and network solutions are illustrated and discussed. New ideas about wireless UWB access, synchronization, resource allocation, and topology management are also presented.**

***Index Terms*—Ultra wideband, wireless networks, low data rate, localization, tracking, medium access control**

I. INTRODUCTION

Ultra wide band (UWB) capabilities allow for precise real-time localization features that are unreachable with conventional narrowband systems, making UWB a best-fit alternative specifically for low data rate (LDR) indoor/outdoor positioning and location tracking (LT) applications. Such applications are considered as an excellent way to improve productivity and optimise resource usage when applied to industrial, healthcare, commercial and military environments. The narrow pulses used by UWB location systems enable them to make accurate signal measurements, allowing centimetre-level positioning even in the presence of severe multipath interference. In such a context, one of the main challenges that have still to be solved for the commercial success of UWB LDR-LT applications is the development of efficient and low-cost solutions for both the medium access control (MAC) and the networking.

Regarding MAC design for LDR-LT systems, different proposal have been presented in the recent past for IR-UWB networks, such as: *i)* the uncoordinated, wireless, and baseborn MAC for UWB networks [2], named $(\mathrm{UWB})^2$, which is based on the Aloha approach for medium sharing; *ii)* the fully distributed self-balanced receiver-oriented MAC protocol for ad-hoc UWB networks [3], named SEBROMA, *iii)* the resource control algorithm for distributed UWB networks which was first proposed in [4], and then extended in [5] and [6], *iv)* the sustained link networks (SLN) scheme proposed in [7], in which full-duplex connections are achieved thanks to the low duty cycle property of IR, *v)* the distributed MAC protocol for very low power UWB ad hoc networks described in [8], *vi)* the UWB MAC protocol for both best effort and real-time transmissions proposed in [9], and *vii)* the multiple access scheme adopted by the ZigBee technology [10], which is based on the same frame structure that is adopted in the IEEE 802.15.4 MAC protocol.

Regarding the design of the network layer for LDR-LT applications, a UWB-specific position-based and energy-efficient routing algorithm was proposed in [11]. In addition, routing issues for UWB ad hoc networks have been also addressed in [12].

This paper is organized as follows. Section II presents the application scenarios for LDR-LT systems that have been identified in the scope of the PULSERS project. For such scenarios, basic MAC and network solutions are proposed in Section III and IV, respectively. Concluding remarks are presented in Section V.

II. PULSERS LDR-LT SCENARIOS AND REQUIREMENTS

A. *Application scenarios*

A wide variety of UWB application scenarios have been identified and fully described in PULSERS project [13]. In particular, Intelligent Wireless Area Network (IWAN), Sensor Positioning and Identification Network (SPIN) and Wireless indoor/outdoor Tag Network have been identified as the main LDR-LT application environments in the scope of PULSERS, with UWB enabled devices such as PCs, PDAs, base stations, tags and sensors involved. From the initial set of scenarios proposed in [13], a strict selection has been carried out to identify the three most promising ones in terms of interest, demand and market volume estimates [14]:

- *Positioning in hospitals*. This scenario comprises a long-range asset and people real-time tracking system, designed to allow finding hospital equipment and personnel rapidly. The system is made of a UWB monitoring system (fixed base stations covering the full hospital area), of UWB tags attached to key staff and equipment and of appropriate software interfaces allowing the tracking of all people and items or certain selected items from a simple search window on a PDA or handheld device.

- *Industrial production chain enhancement.* UWB technology is considered a suitable candidate to enhance and improve the different stages in the industrial production chain, from warehouse tracking and smart shelf management to production line monitoring. In such a scenario, warehouse tracking and smart shelf management are enabled making use of UWB tags, electronic reconfigurable identifiers able to transmit information related to the tagged object (product code, production date, storage date) and communicate locally or remotely with a server, therefore allowing stock management and high-accuracy product tracking in a storage facility or a supermarket. For industrial monitoring purposes, UWB transmitters are attached to each machine in the production line thus enabling continuous status monitoring with localization features in case a fault is detected.
- *Environmental Protection Sensor Networks.* This scenario aims at monitoring, tracking and taking care of protected animal species by means of UWB tags carried by the animals themselves in close communication with a network of interconnected control nodes spread all over the area and linked to a central collector station. A similar multi-hop network architecture can be applied for early fire detection in forests.

Cost will be a critical factor for UWB adoption in the above application scenarios. The key driver is the minimum additional materials cost for adding wireless communication functionality. Profit margins will require much higher volume production and unit (chip) costs should reach the €1 boundary to ensure real market penetration for UWB enabled devices. A wide variety of devices will be involved; PDAs, PCs and their peripherals could be again the first embedding UWB chips (€10-€20). The role of low-power and low cost UWB sensors and tags will be decisive and consequently, their cost evolution will be critical for LDR-LT solutions market adoption. It can be therefore inferred that UWB location and tracking capability allows the deployment of innovative services which might lead the way for mass UWB technology adoption. All the scenarios under analysis have positive sides, which might open up significant revenue streams for manufactures and service providers.

B. *Requirements*

One of the main priorities for the system design is to keep the target cost as low as possible. UWB devices operating in the above application scenarios, however, shall cope with high noise and multipath interference environments. In terms of mobility, walking speed (<2m/s) will be considered for mobile items to be monitored and tracked. Demanding location requirements have been envisaged in the order of 10s cm accuracy and around 1m for longer link distance.

Due to the fact that many applications are oriented to scenarios subject to strict regulations such as a hospital, the lowest possible electromagnetic exposure of human body and interference with other devices shall be guaranteed. Emitted power is intended to be low with regulatory constraints and so is power consumption, thus enabling battery life to last for several months. Achievable mean data rates of 10Kbps (1Kbps minimum, 100Kbps maximum) shall be provided by the UWB physical layer.

Regarding network requirements, ad-hoc and infrastructure (based on access points at known locations) topologies with up to 100 nodes and multi-point to point connectivity flow have been defined for the proposed scenarios. The access protocol could be centralized or distributed. Relaying capability is also to be implemented. Values for aggregated throughput around 1Mbps should be reached. In terms of QoS, a need for real time communications has been detected as well as for accurate synchronization of nodes for precise localization.

III. MAC SOLUTIONS FOR LDR-LT APPLICATIONS

In this section, we describe the main topics which were subject of investigation in the design of a MAC protocol for LDR-LT systems.

A. *Medium Sharing*

An UWB-specific solution for medium sharing in LDR networks was investigated in PULSERS. This solution is based on the peculiar property of pulse-based LDR UWB systems to verify very low duty cycle factors for each transmitter in the network. For such a scenario, a novel analytical method for modeling multi user interference (MUI) at the physical layer, named the pulse collision (PC) model, was developed [16]. As a general concept, it can be shown in fact that for LDR networks a model of interference based on probability of collision between pulses is in better agreement with simulation results with respect to the Standard Gaussian Approximation (SGA) typically assumed in MUI modeling. When evaluating the BER through [16], it can be easily verified that in the case of LDR-LT scenarios, the huge bandwidth adopted for transmissions translates in very short, rare pulses, and thus in a low probability of collisions between pulses emitted by different terminals. As consequence, reference scenarios for LDR-LT applications are characterized by low probabilities of collisions at the pulse level, and as such by low probabilities of collision at the packet level even in the presence of a few dozens of coexisting asynchronous transmissions. Under the hypothesis of low probability of packet error, the access to the medium can be heavily simplified. The most straightforward solution is an ALOHA-like medium sharing strategy combined with TH-CDMA, as investigated in [2]. In this approach, devices transmit in an uncoordinated fashion, relying on the resilience to MUI offered by UWB for achieving correct reception in presence of multiple simultaneous links. If Time Hopping – Impulse Radio (TH-IR) is the selected transmission technique, TH – Code Division Multiple Access (TH-CDMA) is a natural choice for multiple access. Under this hypothesis, two components cooperate in determining the robustness of to

MUI: *i)* the low duty cycle of emitted signals, and *ii)* the association of different TH-Codes to different links. With regard to the duty cycle of emitted signals, the range of data rates foreseen for the LDR-LT scenarios leads to a time between two consecutive pulses emitted by a device which is in the order of $10^{-4}/10^{-5}$ s, with an average duration of emitted pulses typically on the order of 10^{-10} s. Theoretical duty cycle of the signals can be thus as low as 10^{-6}. The adoption of TH-CDMA can introduce an additional degree of freedom, since the effect of pulse collisions is further reduced by the adoption of different codes on different links. CDMA is a well-known solution for wireless networks, and its application to ad hoc networking has been widely investigated, as already described in Section II. In [2] a hybrid solution based on the combination of a common TH code for transmitting signaling information, and transmitter-unique TH codes for transferring data has been investigated. This solution increases system robustness against MUI and allows terminals to listen on a single TH code in the idle mode. In addition, the exchange of packets between transmitter and receiver in order to set-up the data transmission can enable a simple ranging procedure, based on the three way exchange that which is presented in Fig. 1. According to Fig. 1, transmitter Tx and receiver Rx set up a data transmission by exchanging a *Link Establishment* (LE) packet. The LE packet is transmitted on the common TH code. After the reception of the LE packet, the intended receiver Rx waits for a fixed time Δ and then replies with a *Link Confirm* (LC) packet. The LC packet is generated by applying the unique TH-code associated to Tx. Finally, a *DATA* packet is generated by Tx with the proper TH-code. Such a handshake allows the determination of the distance *d* between Tx and Rx to both the devices involved in the communication. The *d* value that is estimated by Tx is given by:

$$d = c\frac{t_2 - t_0 - \Delta}{2} \tag{1}$$

where *c* is the speed of light. The same distance is estimated by Rx as follows:

$$d = c\frac{t_3 - t_1 - \Delta}{2} \tag{2}$$

It should be noted that, even in the case TH-CDMA is not adopted, the low duty cycle of emitted signals could by itself guarantee the requested robustness to MUI. This is a possibility which should be taken into account especially for very low-cost devices, such as RF Tags. Under the hypothesis of not having TH-CDMA, the LE/LC/DATA handshake for the exchange of information on the adopted TH code is no longer mandatory. Nevertheless, the handshake is still required in order to support the ranging procedure described in [2]. The availability of such a procedure at the MAC level may allow the set up of a database of distances that can be used by upper layers, for example for positioning purposes. It also allows taking into account the effect of the LE/LC handshake on network performance, in terms of generated interference.

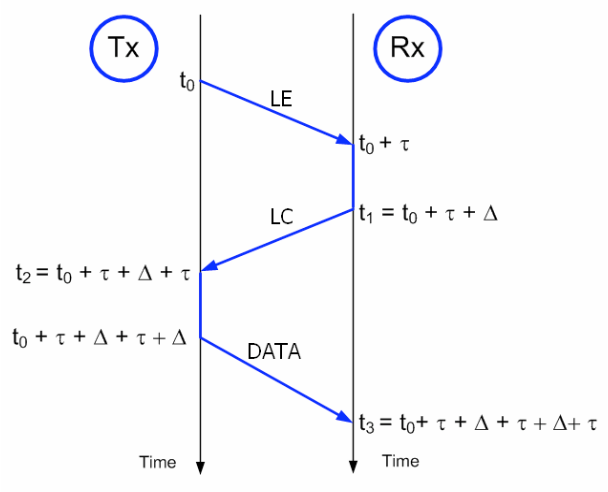

Figure 1 – Example of ranging procedure

Performance of the LDR MAC described above was evaluated by simulation of different propagation scenarios. For each scenario, we compared a pure Aloha strategy with a slotted Aloha strategy, in order to check if the higher performance which is guaranteed by slotted Aloha in narrowband networks is also present in UWB networks, where the negative impact of packet collisions is reduced by the high processing gain.

Figures 2 and 3 show the results of simulation for both line of sight (LOS) and non line of sight (NLOS) propagation scenarios. Performance of the proposed solution is expressed in terms of throughput (Fig.3) and transmission delay (Fig.4) vs. the number of active terminals in the network. These results were obtained considering UWB devices randomly deployed within an area of 50m×50m, and a transmission range for each device equal to 70m (full network connectivity). Devices transmit data packets of 2100 bits (each one including 100 bits of synchronization trailer) at the rate of 10kb/s. Packets are generated through a Poisson process, and for each packet a uniform distribution is applied for selecting the destination node.

Figure 2 shows that slotted Aloha leads to a slightly higher value of throughput with respect to a pure Aloha medium sharing strategy. This confirms that for LDR UWB networks the MUI resilience guaranteed by UWB is good enough to potentially allow for reliable transmissions. As one could expect, the gap between the two strategies increases as the number of terminals (and as a consequence the offered traffic) increases. Also note in Fig.2 that LOS and NLOS scenarios are characterized by comparable results: this is justified by the fact that in both scenarios MUI is the main cause of packet errors.

If the advantage of slotted Aloha over pure Aloha is not significant in terms of throughput, we can derive from Fig. 3 that the slotted Aloha approach leads in average to a higher transmission delay. This is due to the fact that in pure Aloha a packet is sent immediately, as soon as it is inserted in the queue, and thus in absence of high packet error rates, the delay is limited to the packet transmission time over the channel.

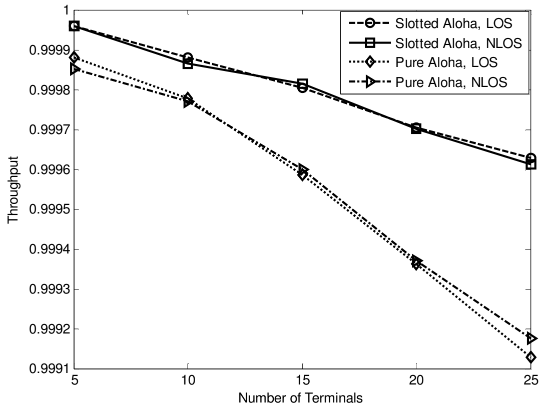

Figure 2 – Throughput as a function of number of terminals

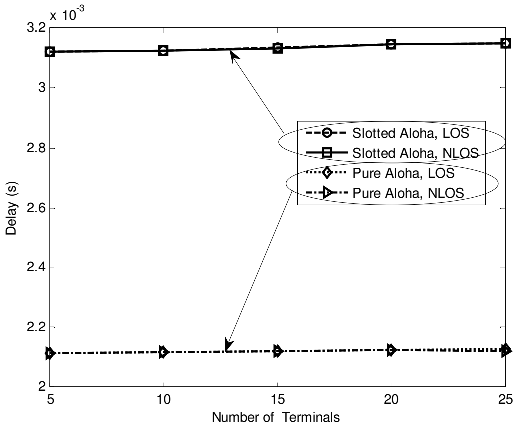

Figure 3 – Delay as a function of number of terminals

B. *MAC organization*

Two main approaches are possible regarding network organization at the MAC level: *i)* a *flat* MAC structure where all devices perform the same actions, without any neither local nor global coordinating device, or *ii)* a *clustered* MAC structure, where a subgroup of devices controls the management of the remaining devices, which are organized in clusters around the coordinators. As an example, the solution proposed by the IEEE in the 802.15.4 standard and adopted in [10] relies on a clustered MAC structure, in which devices organize themselves in WPANs managed by a coordinator. The coordinator defines a superframe divided into time slots, which allow devices in the WPAN to access the medium adopting a slotted CSMA-CA protocol within the superframe boundaries. The decision of adopting a clustered architecture requires the definition of dedicated procedures for election of cluster coordinators and for cluster maintenance: this constitutes an overhead compared to the case of a flat network. Furthermore, the definition of clusters poses a problem of scalability in the network, since communication within devices in different clusters is normally made more difficult. This aspect should be taken into account when defining both MAC and network aspects, since it could limit the feasibility of range extension techniques based on relaying.

On the other hand, the adoption of a clustered MAC structure could simplify the execution of several tasks demanded to the MAC, such as: *i)* association and de-association of network nodes, *ii)* scheduling, and *iii)* power-saving. More in general, a clustered MAC structure improves the execution of all those tasks which benefit for the knowledge of the status of more than one device.

Medium sharing techniques based on a random access approach are compatible with a clustered MAC structure, as shown by the choice of IEEE of proposing a combination of clustered structure and random access based on CSMA-CA for the 802.15.4 standard. The selection of a clustered MAC structure is straightforward in the presence of a scheduling algorithm for the medium sharing. Although distributed scheduling protocols can be defined, the coordinator of a cluster is generally favored for scheduling data transmissions of all devices in its cluster, thus simplifying the scheduling task. The ALOHA-like solution for the medium sharing that has been presented in Section III.A perfectly fits both the flat and clustered MAC structure, and provides thus the highest flexibility in network organization.

C. *Power Saving*

The tight requirements on device autonomy presented in Section II demand for effective power-saving schemes at the MAC layer, in order to assure an efficient use of available power. The problem of power management has been already faced for existing WLAN standards and for sensor networks [17]-[19]. As an example, the Power-Aware Multiple Access protocol with Signaling for ad-hoc networks (PAMAS) [18] is based on the assumption that a CSMA-CA approach is adopted at the MAC level, and it achieves power saving by minimizing the time a terminal spends in idle state without neither transmitting nor receiving. The main idea behind PAMAS is that when a node detects the channel as busy thanks to Carrier Sensing, it goes in sleep mode rather than waste power in idle mode without being able of exchanging data packets. Differently from PAMAS, the LEACH protocol [19] assumes a cluster-oriented network and a TDMA-based medium access strategy within each cluster. The adoption of pre-determined Time Slot allocations within the frame, and of a rigid star topology for data exchange, heavily simplifies the problem of power management and allows obtaining significant power savings without performance losses.

Both the above solutions are based on specific assumptions regarding network topology or application scenarios, and do not provide a general solution to the problem of power management. Requirements imposed for the single LDR-LT device, on the contrary, suggest a MAC solution which should be capable of dealing with different scenarios and network topologies. Such an issue can be addressed by allowing the MAC to trade dynamically system performance with power consumption for the devices. As an example, we can consider a scenario characterized by very low traffic but stringent requirements on latency, as is the case of a sensor network for early fire detection in forests. In this case, the requirement for long device autonomy would call for a very low duty cycle of the devices and for the selection of random access without the burden of setting up a frame by means of periodic beacons, given the very low traffic. On the other hand, this would translate in a potentially high latency due to the difficulty of synchronizing the devices without any common time reference: if such latency was incompatible with traffic requirements, this would necessarily lead to the choice of adopting an scheduled medium sharing approach based either on a regular time structure or on devices with higher duty cycles, thus at the price of a reduced power saving.

D. Synchronization

The synchronization task can be divided into three distinct operations: *i) common timing reference synchronization*, *ii) frame synchronization,* and *iii) clock synchronization*.

The *common timing reference synchronization* is implemented in synchronous networks in order to align different devices to a common timing reference. Such an operation is necessary in the presence of a time-based medium access scheme, such as TDMA or slotted ALOHA, and is generally achieved by introducing a superframe structure at the MAC level. In a centralized synchronous network, the coordinator sends out a periodic beacon that enables the other nodes to synchronize to the coordinator. In a distributed synchronous network, each node uses a dedicated timeslot of the superframe for periodically sending its own beacon, which is used for informing its neighbors about the own knowledge of the superframe structure. In an asynchronous network there is no common timing reference and there is no superframe structure. In that case, if a communication is to be initialized, the synchronization operation reduces to frame synchronization, and is performed on-the-fly. Hybrid modes may also exist in the case of distributed networks. In this case, devices maintain a rough synchronization with respect to the superframe structure. They occasionally readjust their synchronization to the distributed superframe, e.g., after power down mode. This is interesting for low power applications, such as the ones mentioned in Section II.

Frame synchronization is required at each receiver for detecting incoming packets and separating protocol overhead from user data. Such an operation is always required, regardless of the adopted network topology configuration. Even in the presence of a common timing reference among devices, the synchronization accuracy is usually not precise enough for the demodulation operation. Frame synchronization can be achieved by sending a trailer especially dedicated to synchronization, prior to sending the actual data packet [2].

Clock synchronization is required at each receiver in order to avoid a decrease in performance for the demodulation process at the end of the packet. Clock synchronization could be omitted in the case where data packets are short and the clock specifications are tight enough so that clock drift does not impact the demodulation performance. To avoid clock synchronization is very interesting for LDR systems, where power saving and low complexity are key design parameters. In fact, even if the very low cost target reflects into the availability of imprecise and drifty oscillators, with LDR applications one can transmit longer synchronization trailers and shorter data packets because of the reduced amount of data to be transmitted.

IV. NETWORK SOLUTIONS FOR LDR-LT APPLICATIONS

Based on preliminary studies [21] and a literature review work on standardization activities, the development of a new complete proprietary software solution over UWB MAC and physical layers has been not considered an advantageous approach. In particular, a proprietary solution for the network layer would not contribute much to UWB becoming widespread, since interoperability issues could arise among UWB manufacturers and companies. Consequently, preliminary attempts were made in order to select a set of features for defining a higher layer architecture model suitable for the scope of PULSERS LDR-LT applications. In the field of LDR-LT user applications (see Section II), highly demanding constraints are given by the processing and memory resources of the devices. For such a scenario, three potential candidates have been recognized to be adapted and applied to the scope of PULSERS LDR-LT applications:

- **Bluetooth** [22]**.** Bluetooth has been developed as a complete connectivity solution, with a set of profiles supported by a full open standard protocol stack. There is a general feeling in the Bluetooth community about UWB being the next transport layer for current Bluetooth profiles, since some of the usage scenarios overlap for both technologies. Bluetooth based profiling over UWB PHY and MAC harnesses the strength and availability of the Bluetooth software stack and would avoid proprietary developments as much as possible. Since most of Bluetooth profiles were designed to target low data rate applications, it could be reasonable to apply them to PULSERS LDR-LT applications. In particular, Bluetooth *Local Positioning Profile* was thought to be applied to LDR-LT platforms, given the amount of potential applications making use of this capability. Although the feasibility of Bluetooth for sensors networks has been put into question due to the complexity of its protocol stack, the release of several flexible open source implementations has encouraged some members of the research community to develop Bluetooth based sensor networks, with interesting results. On the other hand, it has been recently announced that the Bluetooth SIG and some UWB developers will work together to combine the strengths of both technologies in order to enable high-speed applications, reduce fragmentation and bring organizations together for the greater good of short range wireless technologies [23],[24]. The ultimate goal of such a trendy approach is to work towards an architecture that allows devices to take advantage of UWB data rates for scenarios requiring that speed while maintaining backward compatibility with both existing *Bluetooth* devices on the market and future products not requiring the higher data rate.

- **Zigbee** [25]. The Zigbee Alliance has recently ratified its first specification for a complete software stack over IEEE 802.15.4 PHY and MAC for low rate and low power connections, which are mainly targeted to remote monitoring, remote control as well as sensory network applications. At this moment, Zigbee architecture has not reached enough maturity yet, but the great interest shown by manufacturers is likely to speed up its development in the short term. The main advantage of Zigbee lies in the lightness of its protocol stack, around 32 kb for a full implementation, and its profile application oriented structure. The main difficulty in developing a higher layer architecture based on Zigbee profiles lies in the fact that this is an industry standard not released to the public at the moment. Network, transport and application layers should be therefore replaced by proprietary implementation. This would entail almost a full implementation of new stack, which is not considered the best approach, as it has been previously stated in this section.
- **UPnP** [26]. The strength of UPnP lies mainly in its effectiveness for service discovery purposes. UPnP architecture leverages TCP/IP, and convergence with Web Services is also foreseen in the near future. One of the main advantages of UPnP is that it is open to the public and can be easily implemented. However, in order to successfully place UPnP architecture model onto PULSERS PHY and MAC layers, an additional adaptation layer should be included in the protocol stack in order to sticks the MAC layer upper interface to the IP layer lower interface, with significant efforts on the development of proprietary software.

V. CONCLUSIONS

This paper presented MAC and networking concepts and solutions for UWB LDR-LT applications. Several UWB system architectures and their key requirements and parameters were summarized. Also, potential MAC schemes for LDR–LT applications were presented and analyzed by simulation.

Results indicated that UWB location and tracking capability can enable the introduction of power efficient and low-cost solutions, allowing for the development of innovative services and applications, opening new scenarios for both manufactures and service providers.

ACKNOWLEDGMENT

This work was partially supported by the European Union under the 6th Framework Integrated Project P.U.L.S.E.R.S. (project no. 506897).

REFERENCES

[1] www.pulsers.net

[2] Di Benedetto M-G, De Nardis L, Junk M & Giancola G (2003), "(UWB)^2: uncoordinated, wireless, baseborn medium access for UWB communication networks," to appear in MONET: WLAN optimization at the MAC and network levels, 2005.

[3] Anouar H, Souilmi Y & Bonnet C, "Self-balanced receiver-oriented MAC for ultra-wideband mobile ad hoc networks," in Proceedings of the 2003 International Workshop on Ultra Wideband Systems (IWUWBS), 2003, Oulu, Finland.

[4] Cuomo F, Martello C, Baiocchi A & Capriotti F, "Radio resource sharing for ad hoc networking with UWB," in IEEE Journal on Selected Areas in Communications, 2002, 20(9): 1722–1732.

[5] Cuomo F, Martello C, "Ultra Wide Band WLANs: a self-configuring resource control scheme for accessing UWB hot-spots with QoS guarantees," to appear in Mobile Networks and Applications special issue on WLAN Optimization at the MAC and Network Levels, 2005.

[6] Giancola G, Martello C, Cuomo C, and Di Benedetto M-G, "Radio Resource Management in Infrastructure-based and Ad-hoc UWB Networks," to appear in Wireless Communications and Mobile Computing Journal (2005).

[7] Kolenchery SS, Townsend JK & Freebersyser JA, "A novel impulse radio network for tactical military wireless communications," Proc. IEEE Military Communications Conference (MILCOM), 1998.

[8] Le Boudec J-Y, Merz R, Radunovic B, and Widmer J, "A MAC protocol for UWB very low power mobile ad-hoc networks based on dynamic channel coding with interference mitigation," EPFL Technical Report ID: IC/2004/02.

[9] Xu H & Ganz A, "A radio resource control method in UWB MAC protocol design," in Proc. IEEE Military Communications Conference (MILCOM), 2003.

[10] Kinney P, "ZigBee technology: wireless control that simply works," Communications Design Conference, 2003, [Online]: http://www.zigbee.org/resources/documents/ZigBee_Technology_Sept2003.doc

[11] De Nardis L, Giancola G & Di Benedetto M-G, "A position based routing strategy for UWB networks," in Proc. IEEE Conference on Ultra Wideband Systems and Technologies (UWBST), 2003.

[12] Horie W & Sanada Y, "Novel packet routing scheme based on location information for UWB ad-hoc network," in Proc. IEEE Conference on Ultra Wideband Systems and Technologies (UWBST), 2003.

[13] PULSERS, "Definition of UWB scenarios for commercial, domestic and industrial environments – intermediate version", PULSERS deliverable D2a2, December 2004.

[14] PULSERS, "Definition of UWB business feasibility – initial version", PULSERS deliverable D2a1, April 2005.

[15] PULSERS, "Definition of advanced UWB integration platforms – System requirements – Intermediate", PULSERS deliverable D2a3, June 2005.

[16] Giancola G & Di Benedetto M-G, "Evaluating BER in Sparse IR-UWB networks under the Pulse Collision Model," in Proceedings of the IEEE WirelessCom Conference, 2005.

[17] IEEE Std 802.11, "Local and metropolitan area networks–part 11: wireless," available Online at: http://standards.ieee.org/getieee802/download/802.11-1999.pdf

[18] Singh S & Raghavendra CS, "PAMAS: Power aware multi-access protocol with signalling for ad hoc networks," Computer Communication Review 28(3), 1998, pp. 5–26.

[19] Heinzelman WB, Chandrakasan AP & Balakrishnan H, "An application-specific protocol architecture for wireless microsensor networks," IEEE Transactions on Wireless Communications 1(4), 2002. pp. 660–670

[20] PULSERS, "Interface specifications and performance requirements of MAC and networking layer – first internal draft [HDR and LDR-LT]," PULSERS deliverable D52.1/2, December 2004.

[21] PULSERS, "Candidate architectures for HDR and LDR-LT operational modes," PULSERS deliverable D3a2, December 2004.

[22] www.bluetooth.org

[23] "Bluetooth looks to UWB for bandwidth", Techworld, May 2005 [Online] http://www.techworld.com/mobility/news/index.cfm?NewsID=3595

[24] "Why UWB needs Bluetooth", Techworld, May 2005 [Online] http://www.techworld.com/mobility/features/index.cfm?FeatureID=1419

[25] www.zigbee.org

[26] www.upnp.org