2010 5th International Symposium on Wireless Pervasive Computing (ISWPC)

Control Information Exchange through UWB in Cognitive Radio Networks

Ahmed Masri
Politecnico di Torino, Torino, Italy
Email: ahmed.masri@polito.it

Carla-Fabiana Chiasserini
Politecnico di Torino, Torino, Italy
Email: chiasserini@polito.it

Alberto Perotti
Politecnico di Torino, Torino, Italy
Email: alberto.perotti@polito.it

***Abstract*—The implementation of a common control channel is one of the most challenging issues in cognitive radio networks, since a fully reliable control channel cannot be created without reserving bandwidth specifically for this purpose. In this paper, we investigate a promising solution that exploits the Ultra Wide Band (UWB) technology to let cognitive radio nodes discover each other and exchange control information for establishing a communication link. The contribution of this paper is threefold: (i) we define the communication protocol needed to let cognitive radio nodes discover each other and exchange control information for link set up, (ii) we overcome the gap in coverage, which typically exists between UWB and long-medium range technologies, by using multihop communications, (iii) we evaluate the performance of our approach and show its feasibility through extensive simulations.**

I. Introduction

Recently, it has been considered the possibility to open licensed frequency bands to unlicensed operations, with the aim to improve their utilization. This new regulatory model requires the development of cognitive radio (CR) devices that are able to detect spectrum opportunities in licensed bands and map them into logical channels, which can be used for communication till the selected spectrum portions remain available. CR nodes are typically called secondary users, to differentiate them from licensed owners of spectrum bands, i.e., primary users.

In this work, we consider a distributed system architecture where no central controller is required. In such scenario, one of the major issues is the implementation of a common control channel (CCC), over which CR nodes can (i) discover each other and establish a first contact, (ii) coordinate their access to the spectrum, and (iii) identify common spectrum opportunities to set up data communication on those frequencies. Note that, as observed in [1], independently of the medium access control (MAC) scheme used to access the data channel, the operation in (i) is at the basis of any communication: given two CR nodes, which may sense a different set of channels as available, they need to *meet* on a channel that is available for both of them, in order to set up a communication link.

To address the CCC problem in CR networks, various solutions have been proposed. In particular, several works consider that a spectrum portion is reserved for exchanging control information. This approach has two main drawbacks: if a dedicated channel is selected [2], the bandwidth available for traffic communications reduces; if, instead, a spectrum hole in licensed bands is exploited [3], the CCC has to be "moved" to a different spectrum portion whenever the previous one is occupied by a primary user. Other works, e.g., [1], explore the possibility to set up a network without an a-priori selected CCC, by implementing an in-band signaling on the available channels: some CR nodes send (either sequentially or at random) beacon messages on the available channels, while other nodes scan the spectrum. In this case, two nodes can establish a direct contact only when one of them receives the beacon transmitted by the other, hence, meeting a specific device to communicate with may take a long time.

In this paper, we adopt a different perspective with respect to previous work and consider that the CCC is implemented by using the Ultra Wide Band (UWB) technology: each CR node is equipped with an UWB interface, for transmitting/receiving control information, and with one or more radio interfaces (such as IEEE 802.11) for data communication. This solution, which was first proposed in [4], is appealing for the following reasons: (1) UWB communications cause negligible interference to narrowband transmissions; (2) by using at first a common spreading code, all nodes are able to discover each other over the UWB channel; (3) UWB radio interfaces feature very low complexity and power consumption (namely, 1.2 mW, see [5] and references therein); (4) although being generally considered a short-range technology, experimental results [4], [6] show that UWB can provide a radio range of 100 m and beyond.

In this work, we first describe our system model in Section II, and highlight how, by exploiting the paradigm of multihop communications, UWB can be used for implementing a CCC among CR nodes that want to exchange data traffic through a medium-range technology like 802.11. We detail the protocol that allows CR nodes to establish a communication link in Section III and investigate the performance of our solution in Section IV. Finally, in Section V we draw some conclusions and discuss future work.

II. System Model and CCC Implementation

We consider a communication network composed of N CR nodes. Each node is equipped with an UWB and an IEEE 802.11 radio interface, and use them for control and data transmissions, respectively. UWB transmissions are performed by using a spreading code common to all nodes; only after two nodes have got in contact with each other, they can agree on

978-1-4244-6857-7/10/$26.00

a spreading code to be used for the remaining part of their message exchange on the UWB CCC.

For the UWB channel, we adopt the propagation model described in [7, Sec. III-D] for UWB transmissions in outdoor environments. Given a generic pair of nodes (i, j), the power received at node j is:

$$P_{R,ij} = P_T - PL_0 - 10\eta \log_{10} \frac{d_{ij}}{d_0} - S \quad \text{dBm}$$

where P_T is node i's transmitted power, $PL_0 = 48.96$ dB is the path loss at distance $d_0 = 1$ m, d_{ij} is the Euclidean distance between i and j, $\eta = 1.58$ is the path loss exponent, and the shadowing loss S is a Gaussian-distributed random variable with zero mean and standard deviation $\sigma = 3.96$ dB.

Under the above UWB channel model, in the following we will refer to two CR devices (i, j) as one-hop UWB neighbors if their signal-to-noise ratio $\text{SNR}_{ij} = P_{R,ij} - N_0 B$ dB is above 10 dB. Here, $B = 500$ MHz is the signal bandwidth and $N_0 = kTFL_M$ is the one-sided power spectral density of the additive white Gaussian noise, where $k = 1.38 \times 10^{-23} J/K$ is the Boltzmann's constant, $T = 300$ K is the equivalent temperature, $F = 6$ dB is the receiver's noise figure, and $L_M = 5$ dB is the link margin (see [8, eq. 19 and 20]).

As for the outcome of UWB packet transmissions, we consider that a failure occurs when two or more CR nodes access the channel at the same time instant, using the common spreading code. In all other cases, we compute the signal-to-noise plus interference ratio (SINR) on the UWB radio link between transmitter and receiver, (i, j), as:

$$\text{SINR}_{ij} = \frac{P_{R,ij}}{\sum_{q \in \mathcal{T} \setminus i} P_{R,qj} + N_0 B} \qquad (1)$$

with $\mathcal{T}$ being the set of nodes simultaneously transmitting. Then, we rewrite (1) as

$$\text{SINR}_{ij} = \frac{E_{b,ij}/T_b}{\sum_{q \in \mathcal{T} \setminus i} P_{R,qj} + N_0 B} = \frac{1}{BT_b} \frac{E_{b,ij}}{N_I + N_0} \qquad (2)$$

where $E_{b,ij}$ is the bit energy on the link from node i to node j, T_b is the bit duration, and $N_I = \sum_{q \in \mathcal{T} \setminus i} P_{R,qj}/B$. By assuming a binary Pulse Amplitude Modulation (2PAM), we use (2) to estimate the bit error rate of the UWB system as follows:

$$P_{b,ij}(e) \simeq \frac{1}{2} \text{erfc} \sqrt{\frac{E_{b,ij}}{N_I + N_0}}. \qquad (3)$$

The error rate of the radio channel is then enhanced by employing a Bose-Chaudhuri-Hocquenghem (BCH) error-correcting code [9, Ch.10]. Moreover, in order to enable the receiver to detect message integrity after channel decoding, an 8-bit cyclic-redundancy-check (CRC) code is employed. Assuming that the decoder operates with a bounded t-distance decoding algorithm, it is easy to derive an approximate evaluation of the packet error probability, as [9, Eq. (10.67)]

$$P_w(e) \simeq \binom{n}{t+1} p^{t+1} (1-p)^{n-t-1} \qquad (4)$$

where, for brevity, p denotes the bit error probability computed as in (3).

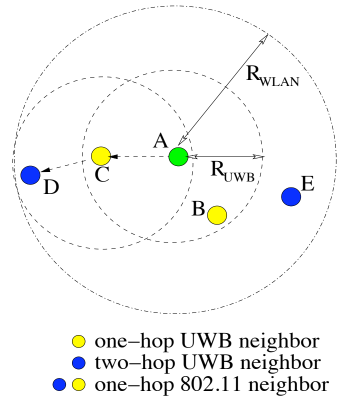

Fig. 1. UWB and 802.11 neighbors: an example. A has B and C as one-hop UWB neighbors, D and E as two-hop UWB neighbors, and B, C, D, and E as one-hop 802.11 neighbors.

In our scenario, we assume that a CR node i "feels" the need to start a traffic flow toward another CR node j according to a Poisson distribution, with rate equal to $\lambda_{ij} = \lambda$, $\forall\, i, j$. The traffic flow destination is randomly selected among the one-hop 802.11 neighbors of i, i.e, among all j's such that, using the 802.11 interface, $\text{SNR}_{ij} \geq 8$ dB [10].

We point out that the transmission power spectral density used for UWB communications is limited by the FCC/ETSI regulations [7], [11] to a very low value, thus hindering long-range communications. However, it has been shown that outdoor UWB transmissions in the 3-6 GHz frequencies can reach medium ranges, when moderately low data rates are employed [4], [6]. In particular, when power-efficient modulations (e.g., 2PAM) are employed, the achievable transmission range reaches more than one hundred meters for required data rate of few tens of kilobits per second. Since we target a data rate of several hundreds of kilobits per second, the following relationship holds:

$$R_{WLAN} \approx n \cdot R_{UWB} \qquad (5)$$

where $n = 1, 2, 3$, and R_{UWB} and R_{WLAN} are the largest distance at which, respectively, an UWB and an IEEE 802.11[1] one-hop neighbor can be located. In other words, as shown in Fig. 1 for $n = 2$, CR nodes that can directly communicate using their 802.11 interface, may not be in each other radio proximity when they use their UWB interface.

We therefore define a *direct logical common control channel (D-CCC)*, which is implemented through one-hop UWB transmissions, and an *indirect logical common control channel (I-CCC)*, which is instead implemented through multihop UWB communications.

A D-CCC allows a CR node to set up a link with a node that is its one-hop neighbor when either the 802.11 or the UWB interface is used, while the I-CCC is employed to contact a node that is an one-hop 802.11 neighbor but not an one-hop UWB neighbor. An example is shown in Fig. 1, where node A can use a D-CCC to set up an 802.11 link with node B,

[1] In outdoor environments, IEEE 802.11 transmissions can reach a coverage of few hundreds of meters.

while it must use an I-CCC to establish an 802.11 link with D.

Finally, to access the common control channel, we assume that CR nodes employ an Aloha scheme, which is often adopted as access technique in UWB systems [12].

In the next section, we focus on the usage of UWB for exchanging control information and detail how CR nodes can employ either the D-CCC or the I-CCC to set up a IEEE 802.11 link for data traffic transfer. Clearly, other information, like reporting of sensing operations, can be exchanged on the CCC channel as well; however, in this work we do not address sensing in cognitive radio environments.

III. The UWB Common Control Channel

Given the network system described above, we assume that, on a regular basis, all CR nodes transmit and receive through their UWB interface by using a common spreading code. Only after two nodes have got in contact with each other, they can continue their message exchange on the UWB CCC by using a distinct spreading code, which is randomly selected by the exchange initiator out of a set of available codes.

Below, we detail the message exchange on the UWB channel that allows CR nodes to build their knowledge on the network topology, as well as to meet and establish a communication link on a data channel.

A. Discovering the network topology

All network nodes periodically transmit a Hello message over the UWB D-CCC, using the common spreading code. A Hello includes the sender's identifier (ID), as well as the ID of its k-hop UWB neighbors, with $k = 1, \dots, n-1$. In this way, even in a dynamic scenario where nodes may join or move out of the network, a CR device knows the nodes with which it can directly communicate over the UWB channel, or that can be reached in up to n hops.

Now, let us consider a newly arrived CR device wishing to communicate with other nodes. By using its UWB interface, the newly arrived device listens to the common code channel and waits for Hello messages from nearby nodes. If it does not hear any Hello message within a given time interval, it broadcasts on the UWB D-CCC a Join Request Message (JRM), which is transmitted using the common spreading code. The JRM includes the IDs of the sender and of the selected spreading code. Upon receiving the JRM message, a nearby node replies using the selected code, with a unicast packet called Join Answer Message (JAM). The JAM is transmitted after a random time since the JRM reception, so as to avoid collisions among different replies; it carries the list of nodes that are the k-hop UWB neighbors of the sender, with $k = 1, \dots, n-1$.

Through the above message exchange, a CR node can acquire or update the structure of the network topology, up to a distance of n UWB hops. It can therefore build/maintain a *CCC routing table* where it records the list of nodes it can reach through the D-CCC or the I-CCC. More specifically, each entry in the CCC routing table of a CR device will include the ID of the destination node, the ID of the next-hop node that allows the device to reach that destination with the minimum number of hops, and the distance in number of hops from the destination. An example, which refers to the topology in Fig. 1, is reported in Tab. I.

TABLE I
CCC routing table at node A

Destination ID	Next-hop ID	Distance (#hop)
B	B	1
C	C	1
D	C	2
E	B	2

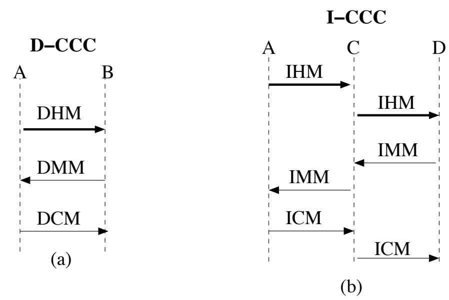

Fig. 2. Message exchange (a) on the D-CCC and (b) on the I-CCC. Messages transmitted using the common and the selected spreading codes are denoted by the thick and the thin line, respectively. In (a), A and B are, respectively, initiator and destination node; in (b), A, C and D act as initiator, relay and destination node, respectively.

B. Establishing a data link

CR devices can use CCC routing tables to set up 802.11 links with other nodes.

As an example, let us first consider that node A in Fig. 1 wishes to establish a data communication with node B which, according to A's CCC routing table, is one of its one-hop UWB neighbors. In this case, A will use the D-CCC and the common spreading code to contact B. In particular, A will send a Direct Handshake Message (DHM) including the set of channels that A senses as available, ordered according to their quality level, and the preferred channel to be selected for communication through the 802.11 interface. Also, A will include in the DHM its own ID, the destination ID, and the ID of the spreading code that A has randomly selected among the available ones. This code will be used for exchanging the following control messages so as to reduce the channel interference level.

By using the selected code, B replies with a Direct Matching Message (DMM) that carries several important information. Firstly, it indicates whether A's selection has been accepted, or if another channel (among the ones listed by A) is proposed; secondly, it includes a backup channel that B identifies based on the channel list provided by A and its own list; thirdly, it makes the information exchange about the available channels list symmetric, by including the list of channels that B senses as available, ordered according to their quality level. Finally, A sends a Direct Confirmation Message (DCM) to B (again using the chosen spreading code);

afterwards the 802.11 communication on the selected channel can start. Fig. 2(a) reports the message exchange described above.

We point out that, during the above message exchange, if a node does not receive the reply message associated to its transmission, it waits for a random time (backoff time) and then it sends the message again. As a maximum number of attempts is reached, the message is discarded. When instead the message exchange is successful and the data communication starts but, at a certain point in time, a primary user shows up on the selected data channel, A and B can both switch onto the (previously agreed) backup channel and continue their data communication there.

Now, let us consider that A wants to communicate with node D, which is a two-hop UWB neighbor. Then, the I-CCC has to be employed. According to its CCC routing table, A sends an Indirect Handshake Message (IHM) to the next-hop node C, by using the common spreading code. The IHM includes the IDs of the sender, of the next-hop node and of the final destination, as well as the list of channels sensed as idle by A with their associated quality level. As before, the IHM also carries the ID of the randomly selected spreading code to be used for transmitting the following messages. Once the relay node, C, receives the IHM, it forwards the message toward the final destination (still using the common code). By using the selected code, the destination D will reply with an Indirect Matching Message (IMM) that contains the same information as a DMM, but it is relayed back toward the handshake initiator. A then transmits an Indirect Confirmation Message (ICM) to the destination. Afterwards the data communication between A and D can start on the selected 802.11 channel.

Fig. 2(b) summarizes the message exchange on the I-CCC.

Note that, in case of unsuccessful transmission, the same procedure as described for the D-CCC case is adopted, so as to recover the message failure.

IV. Performance Evaluation

Here, we first detail the simulation scenario, then we show the performance of our solution when CR nodes wish to establish an 802.11 communication link for data traffic.

A. Reference scenario

We consider N static nodes, which are randomly deployed according to a uniform distribution in a square region of side equal to 250 m. We assume that the power transmitted through the UWB interface equals the FCC limit for the 0.5 GHz bandwidth, i.e., $P_T = 36.5$ μW, corresponding to -14.38 dBm.

As a node wishes to start a traffic flow, it accesses the UWB channel using the Aloha scheme. We consider both the pure and the slotted technique; in the latter case the slot duration is equal to 0.241 ms. The length of the spreading codes is equal to 176 chips, while the UWB data rate is 966 kb/s [12]. In case of failure, a message can be retransmitted up to four times. When pure Aloha is adopted, the backoff time is randomly selected in the range [0,2.41 ms]; in the slotted case, instead, it is computed by multiplying the slot duration (i.e., 0.241 ms) by an integer number, which is extracted according to a uniform distribution in the range $[0, 10]$.

The physical layer synchronization trailer of the packets exchanged on the UWB channel is set to 8 bytes [12]; their length, however, depends on the type of control information they carry. More specifically, we set the size of the ID field equal to 6 bytes, the size of the channel list field to 6 bytes (being the number of data channels equal to 12 and the channel ID encoded onto 4 bits), and the CRC to 1 byte, while the ID of the selected spreading code is encoded onto 4 bits. As for 802.11 communications, we assume that 12 channels are available for data traffic and they are sensed with the same quality level by all CR nodes. Thus, the size of the largest message (i.e., the DHM) at the input of the BCH encoder is equal to 20 bytes. We consider a (255,239,2) BCH code, shortened to match the message length; such code adds 16 redundancy bits to each message and its error correction capability is $t = 2$ bits. It follows that in our scenario the packet error probability resulting from (4) is $P_w(e) \leq 4 \times 10^{-4}$.

B. Results

We focus on the communication link establishment between CR nodes, derive the system performance under the network scenario described above.

Fig. 3 presents the success probability of single messages transmitted on the UWB channel (top plot), and of the complete message handshake needed to set up a communication link (bottom plot). Results are shown in both the cases of pure and slotted Aloha, as the per-node flow rate varies and for two different values of the number of CR users (namely, $N = 40, 80$). Firstly, we note that the pure Aloha scheme always provides the best performance, for both message and complete handshake transmissions. Indeed, in the case of pure Aloha the probability that two users access the channel at the same time instant using a common code is lower than in the case of slotted Aloha. Secondly, we observe that the success probability for complete handshakes is always higher than for single message transmissions. Indeed, the latter is computed as the ratio of the number of successful messages to the total number of messages sent over the channel (transmissions and retransmissions). Thus, the probability to complete a handshake is higher than the message success probability, since failed messages can be retransmitted and, if eventually successful, they lead to a successful handshake. Thirdly, as expected, the per-node flow rate λ does have an impact on the system performance since the higher the traffic load, the higher the interference level experienced by a receiving node. A similar observation holds as the number of CR nodes increases. However, we stress that excellent results are achieved, even for $\lambda = 0.5$ and $N = 80$, especially for the handshake success probability.

Such good performance is confirmed by the plot in Fig. 4, where we focus on the handshake success probability and present the results for $\lambda = 0.1, 0.2$ and varying values of N.

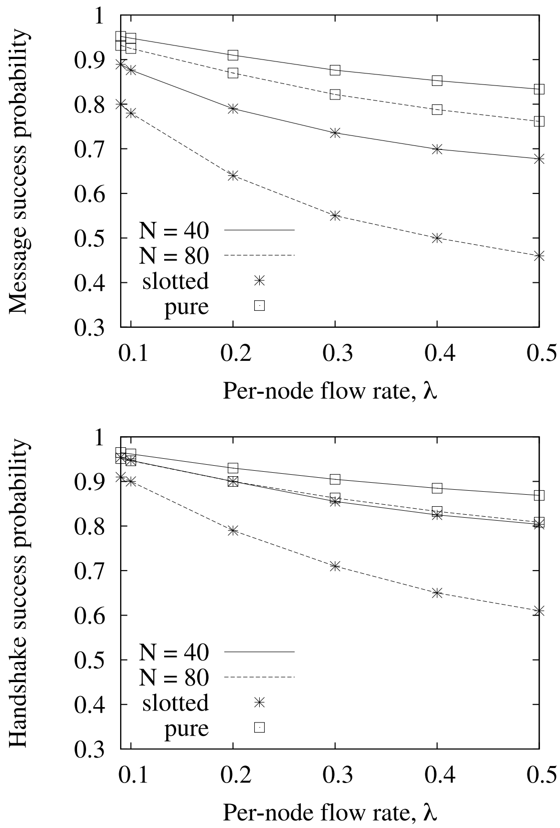

Fig. 3. Success probability for single messages (top) and complete message handshakes (bottom) over the UWB CCC, as λ and N vary. Pure and slotted Aloha are compared.

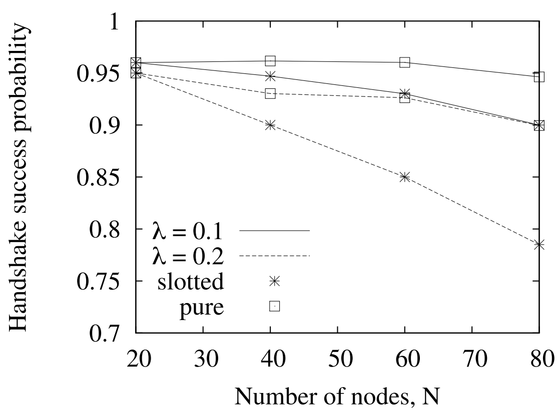

Fig. 4. Handshake successful probability as the number of CR nodes varies, in the case of pure and slotted Aloha, and for $\lambda = 0.1, 0.2$.

Next, one may wonder what distance can be covered by transmissions on the UWB D-CCC (i.e., direct transmissions). Fig. 5 shows the success probability of a message handshake when the source and destination nodes are at a given distance, for $N = 20, 40, 80$. In this case, only the most performing access scheme (i.e., pure Aloha) is shown. Interestingly, we note that, for $N = 20$, the UWB D-CCC allows nodes that are even farther than 130 m away to successfully get in contact with each other. As the number of network nodes grows, the distance at which successful message exchanges occur decreases, but it is still equal to about 80 m for a value of N as large as 80.

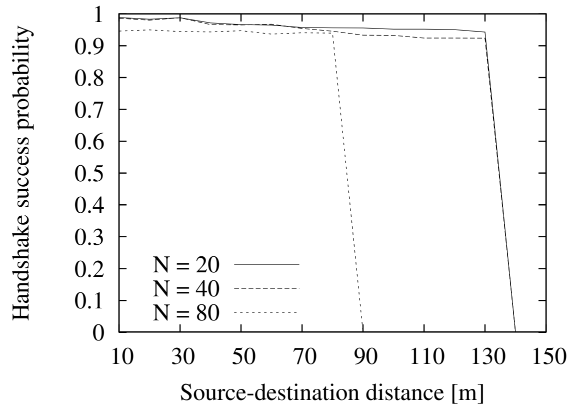

Fig. 5. Handshake success probability on the UWB D-CCC as a function of the distance between source and destination, when pure Aloha is used, $\lambda = 0.1$, and for different values of the number of CR nodes.

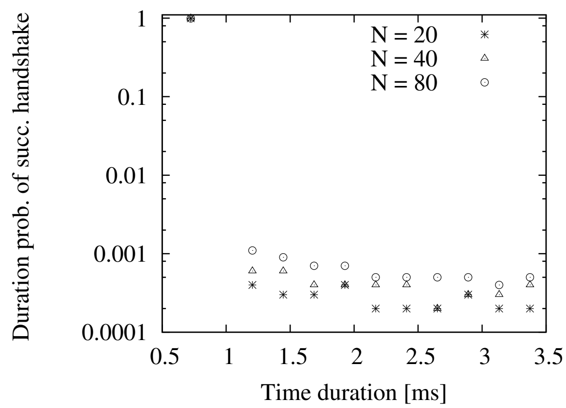

Fig. 6. Duration probability of successful handshakes on the UWB D-CCC, when pure Aloha is used, $\lambda = 0.1$, and for different values of the number of CR nodes.

Finally, in Fig. 6 we present the duration probability for successful message handshakes, when the pure Aloha is used on the UWB D-CCC, for $\lambda = 0.1$ and $N = 20, 40, 80$. We note that the duration of a successful message handshake is about equal to 0.75 ms, with very high probability, for any value of N we considered. Also, the time needed to complete the whole handshake never exceeds 3.5 ms.

V. Conclusion and Future Work

We addressed the problem of establishing a common control channel in cognitive radio networks, by exploiting the UWB technology. We identified multihop communications as a means to overcome the gap in coverage that typically exists between UWB and long-medium range technologies, and we defined the communication protocol needed to let cognitive radio nodes discover each other and exchange control information for link set up.

Our simulation results show that an UWB common control channel allows CR nodes, which are even 100 m far away from each other, to successfully get in contact with each other and "meet" on a data link, with very high probability.

Future work will further evaluate the performance of the proposed solution in the case of multihop UWB transmissions, in presence of mobile nodes and of different channel access schemes. It will also focus on comparing the performance of the proposed solution against other techniques based on in-band signalling, in terms of success probability and latency in establishing a communication link, as well as in terms of energy consumption.

REFERENCES

[1] Y. R. Kondareddy, P. Agrawal, K. Sivalingam, "Cognitive radio network setup without a common control channel," *IEEE MILCOM,* Nov. 2008.

[2] I. Akyildiz, W.-Y. Lee, M. C. Vuran, M. Shantidev, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks,* vol. 50, no. 13, Sep. 2006, pp. 2127–2159.

[3] J. Zhao, H. Zheng, G.-H. Yang, "Distributed coordination in dynamic spectrum allocation networks," *IEEE DySPAN*, Nov. 2005.

[4] M. E. Sahin, H. Arslan, "System design for cognitive radio communications," *Int. Conf. on Cognitive Radio Oriented Wireless Networks and Commun. (CrownCom 2006)*, Mykonos Island, Greece, June 2006.

[5] A. Gerosa, M. Dalla Costa, A. Bevilacqua, D. Vogrig, A. Neviani, "An energy-detector for non-coherent impulse-radio UWB receivers," *IEEE Trans. Circuits and Systems - I*, vol. 56. no. 5, May 2009.

[6] J. Nascimento, H. Nikookar, "On the range-data rate performance of outdoor UWB communication," *2nd Intl. Conf. on Wireless Broadband and UWB Communications,* 2004.

[7] A. F. Molisch, *et al.*, "IEEE 802.15.4a channel model-final report," *Document IEEE 802.15.04-0662-02-004a,* 2005.

[8] H. Sheng, P. Orlik, A. M. Haimovich, L. J. Cimini, Jr, J. Zhang, "On the spectral and power requirements for ultra-wideband transmission," *IEEE ICC*, 2003.

[9] S. Benedetto, E. Biglieri, *Principles of digital transmission with wireless applications,* New York: Plenum/Kluwer Publishers, 1999.

[10] http://www.oberonwireless.com/WebDocs/Dot11Monitor/DOT11MonitorSLATechNote.pdf [Accessed on Jan. 2010].

[11] Federal Communications Commission, "Revision of part 15 of the commission's rules regarding Ultra-Wideband transmission systems," ET-Docket 98-153, Washington, D.C., Apr. 2002.

[12] M. G. Di Benedetto, L. Nardis, G. Giancola, "The Aloha access $(UWB)^2$ protocol revisited for IEEE 802.15.4a," University of Rome La Sapienza, Italy, *ST Journal of Research,* vol. 4, no. 1,pp. 131, May 2007.