2011 IEEE 22nd International Symposium on Personal, Indoor and Mobile Radio Communications

Performance Evaluation of Wireless Multihop Communications for an Indoor Environment

Petros Spachos, Francis M. Bui, Liang Song, Yves Lostanlen and Dimitrios Hatzinakos
Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S 3G4, Canada
Department of Electrical and Computer Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A9, Canada
E-mail: {petros,songl,yves.lostanlen,dimitris}@comm.utoronto.ca, francis.bui@usask.ca

***Abstract*—The effect of an arbitrary indoor infrastructure environment on the performance of a wireless multihop network is investigated. To this end, an accurate channel modeling tool based on 3D ray tracing is used first to evaluate the signal strength in different areas of the environment. Then, a discrete event simulator is applied to examine the performance of the network with two classes of routing protocols: traditional vs. opportunistic. It is shown that for an indoor environment, opportunistic routing performs better based on the obtained results, with respect to throughput, delay and delivery ratio.**

I. INTRODUCTION

Wireless multihop networks have attracted much attention due to their flexibility and connectivity possibilities. In an indoor environment, such as buildings, the deployment of such a network is relatively straightforward, and with low cost. A wireless multihop network consists of spatially distributed autonomous nodes for data acquisition. Typical applications include monitoring of physical or environmental conditions.

One of the main challenges of these networks in indoor environments, such as building, is the non-light-of-sight (NLOS) problem. In indoor environments, the light-of-sight (LOS) path can be blocked and the communications are conducted through reflections and diffractions.

This work investigates the effect of the infrastructure of an arbitrary indoor environment on the performance of a wireless network. First, a deterministic channel modeling tool is used to evaluate the signal strength in different areas of the environment. Then, based on these results, a discrete event simulator is applied to examine the performance of the network with two different routing protocols: traditional vs. opportunistic routing.

This approach, consisting of a judicious combination of the two modeling and analytical tools, permits an accurate and practical evaluation of the performance benefits due to improved routing mechanisms. In particular, the channel model utilized is not only based on mathematical abstraction, but also endowed with experimental characteristics as measured from a corresponding physical environment. This means that the obtained simulation results should have excellent correspondence to actual behaviors in the physical application scenario. Furthermore, the discrete event simulator allows for a comprehensive evaluation of the benefits of intelligent routing in a network. Indeed, the value of opportunistic routing, which can adapt rapidly to changes of the network conditions, is manifested in a number of perspectives: throughput, delay and delivery ratio. These enhanced characteristics are achievable due to the strategy of selecting the optimal path between the source and the destination for each packet transmission, based on the network conditions at that particular time.

The rest of this paper is organized as follows. In Section II, the related works are reviewed. The design and the routing protocols are presented in Section III while channel model is described in Section IV. In Section V, performance analysis and simulation results are presented, followed by conclusions in Section VI.

II. RELATED WORKS

During the last decade, a number of opportunistic protocols have been developed. The first opportunistic routing method is introduced in [1]. *Extremely Opportunistic Routing* (ExOR) selects the next relay node by a slotted ACK (acknowledge) mechanism. Having successfully received a data packet, the node calculates a priority level, which is inversely proportional to the *expected transmission count metric* (ETX) [2], defined based on the distance between the node and the destination. The shorter the distance, the higher the priority. The node with the highest priority will then be selected as the next relay node. The main drawback of ExOR is that it prevents spatial reuse because it needs global coordination among the candidate nodes. Candidate nodes transmit in order, only one node is allowed to transmit at any given time while all the other candidate nodes attempt to overhear the transmission in order to learn which node will be the next relay node. Moreover, the simple priority criteria that it uses, ETX distance, may lead packets toward the destination through low-quality routes. To overcome this problem, *Opportunistic Any-Path Forwarding* (OAPF) [3] introduces an *expected any-path count* (EAX) metric. This approach can calculate the near-optimal candidate set at each potential relay node to reach the destination. However, it needs more state information about the network and it has high computational complexity.

ExOR ties the MAC with routing, imposing a strict schedule on routers access to the medium. The scheduler goes in rounds. *MAC-Independent Opportunistic Routing and Encoding Protocol* (MORE) [4] tries to enhance ExOR. MORE uses the concept of innovative packets in order to avoid duplicate packets which might occur in ExOR.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC), and by the MRI-Ontario under an ORF-RE grant.

978-1-4577-1348-4/11/$26.00 ©2011 IEEE

In [5], [6] a *Geographic Random Forwarding* (GeRaF) technique was proposed. In GeRaF each packet carries the location of the sender and the destination, so that the prioritization of the candidates nodes is based on location information. This technique is simple to be implemented, but requires location information for all the nodes in the network. *Hybrid ARQ-Based Intercluster Geographic Relaying* (HARBINGER) [7] is a combination of GeRaF with hybrid automatic repeat request(ARQ). In GeRaF, when there is no forwarder within the range of the sender node, everything must start over again, while in HARBINGER hybrid ARQ is used for a receiver to combine the information accumulated over multiple transmissions from the same sender.

A number of other opportunistic routing protocols have been proposed [8]–[12]. *Coding-Aware Opportunistic Routing Mechanism* (CORE) [8] is an integration of localized interflow network coding and opportunistic routing. By integrating localized network coding and opportunistic forwarding, CORE enables a packet holder to forward a packet to the next hop that leads to the most coding changes among its forwarder set. *Opportunistic Routing in Dynamic Ad Hoc Networks* (OPRAH) [9] builds a braid multipath set between source and destination via on-demand routing to support opportunistic forwarding. For this purpose, OPRAH allows intermediate nodes to record more subpaths back to the source and also those subpaths downstream to the destination via received Route Request and Route Replies.

III. DESIGN AND ROUTING PROTOCOLS

In this section, the network address and transmission process are described, followed by a description of two routing protocols.

A. Network address

Network address is related to the context and is subjected to a "cost of delivery" criterion. Given a node address n and the destination address d of a data packet, this "cost of delivery" $c_{n,d}$ should be locally obtained. This could indicate the average or the approximate cost of delivering a packet from the node n toward the destination d, independent of any dynamic change in the network. Usually, in large-scale wireless sensor networks $c_{n,d}$ is correlated with the distance between the two nodes.

Initially, the destination node broadcasts a number of identity advertisement packets and every nodes thereon flood the packet to the network. On the reception of a packet, a node can count the smallest number of hops from the destination and use it as "cost of delivery" criteria, $c_{n,d}$. Whenever a new node joins the network, it can estimate its logic address by acquiring the logic address of its neighbor nodes. If the destination node changes, the procedure should start from the beginning. When the source node changes there is no need to repeat the procedure. If a node leaves the network, it will not take part in the selection process.

B. Transmission Process

A node in the network can transmit packets to all the neighbor nodes that are in its transmission range. Every packet transmission process is subjected to a Packet Error Rate (PER). We assume that a number of packets can be transmitted in one time slot. Every damaged or lost packet will be retransmitted in the next assigned slot. If we use BPSK without channel coding, the Packet Error Rate, $PER(i)$, can be written as [13],

$$PER(i) = 1 - \Big(1 - Q\Big(\sqrt{\frac{2P_t(i) \cdot \hat{G}(i)}{\sigma_n^2}}\Big)\Big)^{F_d}, \qquad (1)$$

where P_t is the transmission power, F_d is the length of the data, σ_n^2 is the noise power, $Q(x) = \frac{1}{\sqrt{\pi}} \cdot \int_{\frac{x}{\sqrt{2}}}^{\infty} e^{-t^2} dt$ and

$$\hat{G}(i) = A \cdot \hat{D}_s(i)^{-n}, \qquad (2)$$

where A is a constant and $\hat{D}_s(i)$ is the distance between the sender node s and the next node i, and n is wireless channel path loss component.

C. Traditional Routing

Traditional routing has an initialization phase. During this phase, each node in the network calculates the PER for all the links with its neighbor nodes. Next, it picks the most reliable link for packet transmission, i.e., the link with the smallest PER. After this initialization phase, every node keeps transmitting all the packets through the most reliable link. If a packet is lost or damaged, the node will continue trying to retransmit the packet through that link.

This approach of traditional routing enhances the reliability of the network. The PER between the transmitting nodes is small and in each time slot, packets are transmitted between neighbor nodes. In an indoor environment, such as buildings, this approach will avoid retransmissions caused from lost or damaged packets, and deliver all the packets to the destination.

D. Opportunistic Routing

Opportunistic routing follows a similar approach to [14]. It uses four types of packets: Request To Send (RTS), Clear To Send (CTS), DATA and ACK. RTS/CTS are used during the handshake process between neighbor nodes while ACKs are used for verification of DATA delivery. All the packets transmissions are subjected to PER.

When a node s has to transmit a packet, it first broadcasts a RTS packet, which includes its own address and the destination address, d. Then node s keeps listening. If a neighbor node, n, receives the RTS packet, it calculates the *cost of delivery* between the sender node and the destination, $c_{s,d}$ and compare it with the *cost of delivery* between the current node n and the destination, $c_{n,d}$.

If the neighbor node is closer to the destination than the sender node, ($c_{n,d} < c_{s,d}$), it will initialize a timer, with

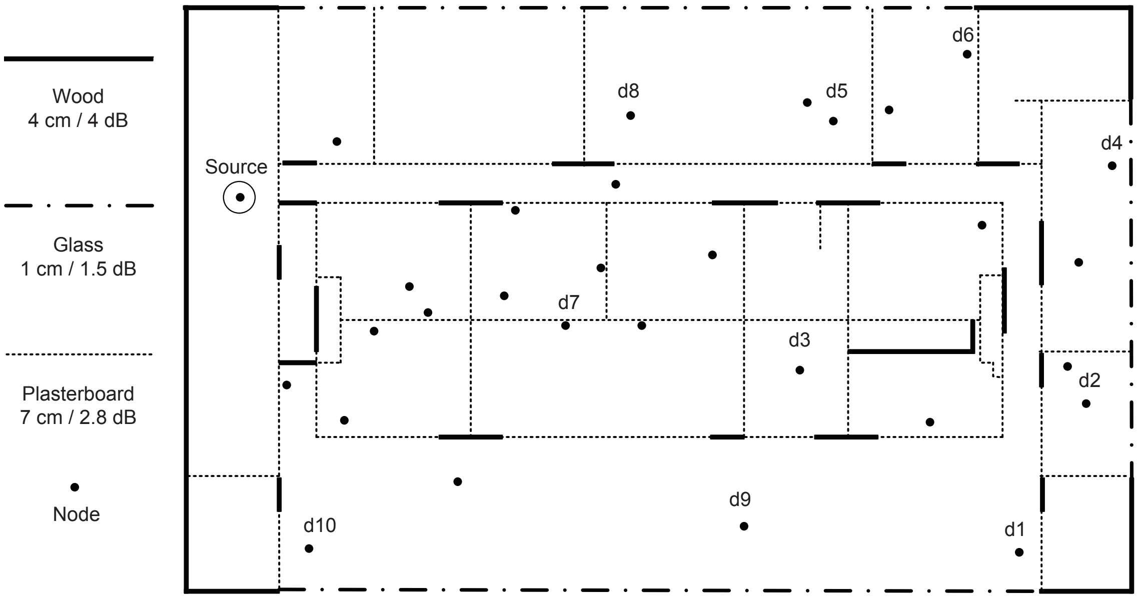

Fig. 1: Building model and network topology.

timeout period as T_i, which is inversely proportional to the difference $c_{s,d} - c_{i,d}$ and can be determined as:

$$T_i = \frac{C_0}{c_{s,d} - c_{i,d}} + SIFS, i \neq d \tag{3}$$

where C_0 is a constant and SIFS is the smallest time interval between the RTS and CTS.

After the timeout period, it will reply with an CTS packet. The sender node will transmit the DATA to the neighbor node that replies first with A CTS packet.

In this way, the node that is closer to the destination will try to reply first. However, because of the PER, which is increased as the distance between the sender and the receiver increased, the RTS and/or the CTS packet might get lost or damaged. In every packet transmission the sender node selects the next node dynamically according to the channel condition in that time slot. As a result, the routing path between the source and the destination is not predefined as in traditional routing but change dynamically.

IV. CHANNEL MODEL

In this section, the channel model is presented. For channel modeling Volcano Lab has been used. A wireless network is analyzed in a realistic environment. Radio nodes are distributed over an area, for example a building.

Our approach consists of modeling the indoor wireless channels based on an accurate ray-based simulator [15]. This propagation prediction tool computes the radio links between each node. Thus the full space-time channel behavior is available for each link: radio signal strength, delay spread, and angular spread.

The most sophisticated deterministic solutions, such as the predictor used in this paper, to model multi-floor indoor propagation are generally based on 3D ray-tracing [16]. The trajectory of the reflected, transmitted and diffracted rays is constructed by 3D ray-tracing from the image theory. The ray-tracing technique allows a fine accuracy in the calculation of the multi-path trajectories. Multiple contributions between radio nodes are thus constructed by reflections, transmissions and diffractions on the building structures. Each interaction will create attenuated rays. The simulator outputs are, for each radio node, a set of time-delayed attenuated rays. The combination of these attenuated rays yields to the radio signal strength prediction. The field strength, which is usually expressed in terms of received power in dBm, is given by the UTD theory. A post-processing of these multiple ray set of predictions gives estimated angular and delay spreads.

The simulations are based on a 3D Digital Building Model (DBM) where the floors, the walls, the windows, the doors and any other kinds of partition are precisely represented. The location of these partitions, their width and the material characteristics are obtained from architect plans which may be corrected using recent pictures taken in the field. Figure 1 gives the layout of the building under consideration in the paper, and the topology of the radio nodes. The 3D DBM are available either on paper or in CAD files. The location and width of all partitions are generally given with high accuracy, on the order of a few centimeters.

Figure 1 also depicts the building layout with the exterior and internal walls represented here by segments. A nature of material and a width are assigned to any segment.

V. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

In this section, we will compare traditional routing and opportunistic routing with respect to throughput, delay and delivery ratio.

We utilized simulation tools to study the performance of the proposed schemes. The network simulation was performed via the discrete event simulation system OMNeT++ with 30 nodes, with radio transmission range 10 meters, uniformly randomly distributed over an indoor environment. The communication parameters were chosen based on IEEE 802.15.4, as listed in Table I.

The channel modeling simulation was performed via the network planning tool Volcano Lab [17]. We used the indoor model, which is a building with a number of rooms. There are wooden walls and doors, class and plasterboard. The infrastructure of the network area, with the nodes and the topology of the building can be seen in Figure 1.

The simulation were conducted in two steps: In the first step, we used Volcano Lab to calculate the power of the received signal between all the nodes in the network. In the second step, the simulation results from Volcano Lab were used in OMNeT++ to calculate the PER of the different links and apply the routing strategy of the two protocols.

Throughput: Throughput is the number of bits divided by the time needed to transport the bits. From the source node 1000 packets were transmitted toward each of the 10 different destinations ,$d1-d10$, in Figure 1. The packet size is $200bytes$ and the bit rate is $250kbps$, hence, the packet transmission time is $6.4ms$. The results can be seen in Figure 2.

Traditional routing follows the path that was discovered during the initialization phase for all the packet transmission. For the indoor environment of the simulation, traditional routing is following paths around the different rooms, avoiding the plasterboard.

Opportunistic routing tends to find the best available and shorter path in each time slot toward the destination, leading to better throughput compared with the traditional approach. The path changes dynamically in each packet transmission and it uses nodes that are not used from traditional routing. As a result, the path for each packet might be different and shorter than that of the traditional routing. In this manner, it can achieve better performance in terms of throughput.

Delay: Delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. The source node sends 1000 packets toward each destination, $d1-d10$, with transmission time is $6.4ms$. The results can be seen in Figure 3.

In traditional routing every packet transmission needs exactly the DATA transmission time to be transmitted between any two nodes.

Opportunistic routing needs also the RTS/CTS handshake hence, the time needed for one transmission between two nodes is:

$$Time = RTStime + BackoffTime + CTStime$$

$$+DATATransmission$$

Parameter	Unit	Value
n		2.5
A	dB	-31
σ_n^2	dBm	-92

TABLE I: Communication Parameters Setup

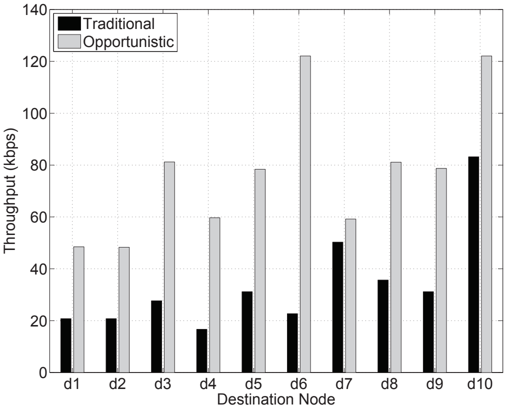

Fig. 2: Throughput in different destination from the source.

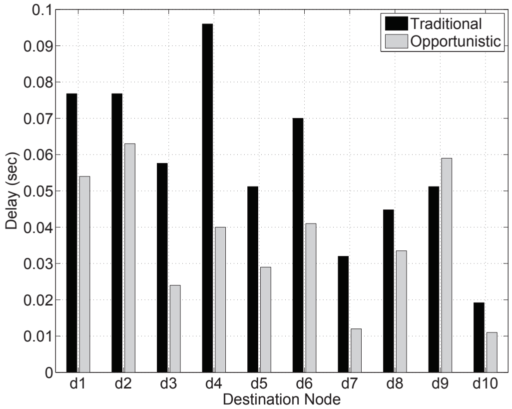

Fig. 3: Delay in different destination from the source.

where $RTStime$ and $CTStime$ are $0.1ms$ while $BackoffTime$ can be derived from Equation 3 and is inversely proportional to the distance between the sender and the receiver node.

Traditional routing utilizes the same nodes for each packet transmission. Every packet follows the same path toward the destination and the delay for all the packets, to the same destination, is the same.

Opportunistic routing tends to transmit toward nodes that are closer to the destination in each time slot. Following this routing strategy, opportunistic routing can find shorter paths toward the destination and reduce the packet delay.

Delivery Ratio: Delivery ratio is the percentage of the packets that successfully reaches the destination. The source node sends 100 packets to each of the 10 destination nodes. The results are the average delivery ratio toward all the destinations. The source traffic rate was 3,5 and 7 packets per slot, meaning that, during one simulation slot time 3,5, or 7 packets were transmitted from the source node toward the available neighbor nodes. Each node has a buffer to store the packets. When the buffer of a node is full, the packet is discarded. Figure 4 shows the results for traditional routing and Figure 5 shows the results for opportunistic routing, under different buffer sizes and packet frequencies.

Traditional routing has a predefined routing path. When the

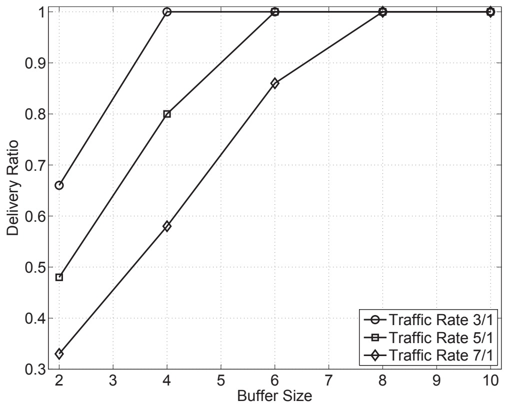

Fig. 4: Delivery ratio for Traditional routing.

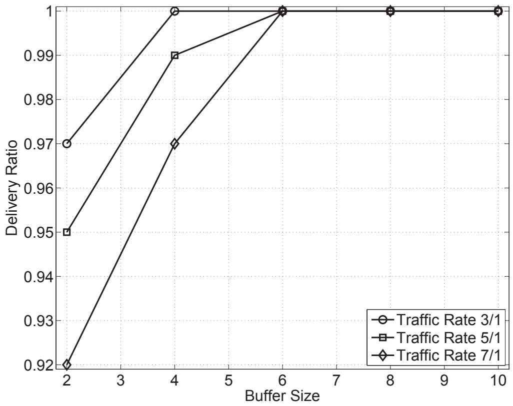

Fig. 5: Delivery ratio for Opportunistic routing.

source traffic rate is greater than the buffer size of a node, the node starts discarding packets. When the traffic rate is same or less than the size of the buffer, the delivery ratio is perfect.

Opportunistic routing performs better in terms of delivery ratio. When the buffer of a node is full, this node does not participate in the RTS/CTS handshake. The transmitter will try to find an available node for data transmission. If all the nodes have full buffer, or there are no more neighbor nodes, the packet is discarded. As it can be inferred from Figure 5 even in high source traffic rates, opportunistic routing can deliver almost all the packets.

VI. CONCLUSION

In this work, we have studied the performance differences of opportunistic and traditional routing in an indoor environment. An accurate indoor channel model is adopted by considering the walls and other structural impacts on RF propagation. In the specific topology, it is shown that the opportunistic routing can perform up to five times better than the upper bound of a traditional scheme, in terms of throughput and end-to-end delay. The opportunistic approach also shows much higher delivery ratio when the buffer size per node is limited.

VII. ACKNOWLEDGEMENT

The authors would like to thank SIRADEL [17] for providing the Volcano Lab platform to host part of this research, and Gregory Gougeon for his valuable comments and making available part of the simulation data.

REFERENCES

[1] Sanjit Biswas and Robert Morris, "Opportunistic routing in multi-hop wireless networks," *SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 1, pp. 69–74, 2004.

[2] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris, "A high-throughput path metric for multi-hop wireless routing," *Wirel. Netw.*, vol. 11, no. 4, pp. 419–434, 2005.

[3] Zifei Zhong, Junling Wang, Srihari Nelakuditi, and Guor-Huar Lu, "On selection of candidates for opportunistic anypath forwarding," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 10, no. 4, pp. 1–2, 2006.

[4] Szymon Chachulski, Michael Jennings, Sachin Katti, and Dina Katabi, "Trading structure for randomness in wireless opportunistic routing," in *SIGCOMM '07: Proceedings of the 2007 conference on Applications, technologies, architectures, and protocols for computer communications*, New York, NY, USA, 2007, pp. 169–180, ACM.

[5] Michele Zorzi and Ramesh R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: Energy and latency performance," *IEEE Transactions on Mobile Computing*, vol. 2, no. 4, pp. 349–365, 2003.

[6] Michele Zorzi and Ramesh R. Rao, "Geographic random forwarding (geraf) for ad hoc and sensor networks: Multihop performance," *IEEE Transactions on Mobile Computing*, vol. 2, no. 4, pp. 337–348, 2003.

[7] Bin Zhao, R.I. Seshadri, and M.C. Valenti, "Geographic random forwarding with hybrid-arq for ad hoc networks with rapid sleep cycles," in *Global Telecommunications Conference, 2004. GLOBECOM '04. IEEE*, nov.-3 dec. 2004, vol. 5, pp. 3047 – 3052 Vol.5.

[8] Yan Yan, Baoxian Zhang, H.T. Mouftah, and Jian Ma, "Practical coding-aware mechanism for opportunistic routing in wireless mesh networks," in *Communications, 2008. ICC '08. IEEE International Conference on*, may 2008, pp. 2871 –2876.

[9] Cedric Westphal, "Opportunistic routing in dynamic ad hoc networks: the oprah protocol," in *Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on*, oct. 2006, pp. 570 –573.

[10] Yuan Yuan, Hao Yang, Starsky H. Y. Wong, Songwu Lu, and William Arbaugh, "Romer: Resilient opportunistic mesh routing for wireless mesh networks," in *in The 1st IEEE Workshop on Wireless Mesh Networks (WiMesh*, 2005.

[11] M.S. Nassr, Jangeun Jun, S.J. Eidenbenz, A.A. Hansson, and A.M. Mielke, "Scalable and reliable sensor network routing: Performance study from field deployment," in *INFOCOM 2007.*, may 2007, pp. 670 –678.

[12] S. Jain and S.R. Das, "Exploiting path diversity in the link layer in wireless ad hoc networks," in *World of Wireless Mobile and Multimedia Networks, 2005. WoWMoM 2005. Sixth IEEE International Symposium on a*, june 2005, pp. 22 – 30.

[13] J.G. Proakis, *Digital Communication*, McGraw-Hill Inc., 1995.

[14] Petros Spachos, Liang Song, and Dimitrios Hatzinakos, "Performance comparison of opportunistic routing schemes in wireless sensor networks," in *Communication Networks and Services Research Conference, 2011. CNSR '11. Ninth Annual*, may 2011.

[15] Y. Corre Y. Lostanlen, "Studies on indoor propagation at various frequencies for radio local networks," in *First COST 273 Workshop, "Opportunities of the Multidimensional Propagation Channel"*, june 2002.

[16] Y. Corre Y. Lostanlen, G. Gougeon, "UWB communication chapter: A deterministic indoor uwb space-variant multipath radio channel modeling," in *Ultrawideband Short Pulse Electromagnetics, vol.7 ed. F. Sabath, E. Mokole, U Schenk, D. Nitsch, 2007, Springer Science+Business Media, pp796-816*, june 2002.

[17] "http://www.siradel.com/," .