OLIMPO, An Ad-Hoc Wireless Sensor Network Simulator for Public Utilities Applications

J. Barbancho, F.J. Molina, C. León, J. Ropero and A. Barbancho
Departamento de Tecnología Electrónica, University of Seville,
C/ Virgen de África, 7, Seville 41011, Spain
Phone.: (+034) 954 55 71 92, Fax: (+034) 954 55 28 33.
e-mail: jbarbancho@us.es

Abstract— **This paper introduces OLIMPO, an useful simulation tool for researchers who are developing wireless sensor communication protocols. OLIMPO is a discrete-event simulator design to be easily reconfigured by the user, providing a way to design, develop and test communication protocols.**

In particular, we have designed a self-organizing wireless sensor network for low data rate. Our premise is that, due to their inherent spread location over large areas, wireless sensor networks are well-suited for SCADA applications, which require relatively simple control and monitoring.

To show the facilities of our simulator, we have studied our network protocol with OLIMPO, developing several simulations. The purpose of these simulations is to demonstrate, quantitatively, the capability of our network to support this kind of applications.

I. Introduction

Wireless data networks have received research interest in recent years due to the desire for connectivity. New multimedia services, such as World Wide Web, e-mail, and data file transfers have been provided by different working groups. Two very well known examples are the 802.11 and the 802.15 Institute of Electrical and Electronic Engineers (IEEE) working groups. 802.11 has designed several protocols defining the Wireless Local Area Network (*WLAN*) standard [1]. 802.15 works in the design of several standards based on networks that employ no fixed infrastructure and have communication links less than 10 meters (known as Personal Operating Space, *POS*) in length (Wireless Personal Area Networks, *WPAN*) [2]. Both organizations are developing the definition of protocols with data throughputs greater than 100 Mb/s.

However there are other potential wireless network applications, with relaxed throughput requirements. These applications are industrial control and monitoring, home automation and consumer electronics, security and military sensing; asset and inventory tracking; supply chain management; intelligent agriculture; and health monitoring [3]. These low-data-rate applications involve sensing of one form or another. This is the reason why these networks are usually called wireless sensor networks, or Low-Rate *WPANs* (*LR-WPAN*s), because they require short-range links without a preexisting infrastructure [4]. Some of the characteristics of an *LR-WPAN* are described by the standard 802.15.4 [5] and are related below:

- Over-the-air data rates of 250 kb/s, 40kb/s, and 20 kb/s
- Star or peer-to-peer operation
- Allocated 16 bit short or 64 bit addresses
- Allocation of guaranteed time slots (*GT*s)
- Carrier sense multiple access with collision avoidance (*CSMA-CA*) channel access
- Fully acknowledge protocol for transfer reliability
- Low power consumption
- Energy detection (*ED*)
- Link quality indication (*LQI*)
- 16 channels in the 2450 MHz band, 10 channels in the 915 MHz band, and 1 channel in the 868 MHz band.

We have focused our research in networks that support this kind of applications. In particular, we are very interested in technologies for Automatic Meter Reading functions (*AMR*) and Distribution Automation (*DA*) for utilities applications (water, gas and electricity) [6][7]. These applications are often distributed throughout many computers. However, customer data polled from sensor networks, queries, remote control orders and network management messages must be processed by a unique computer named Utility Controller (*UC*). This entity works as a master in a Supervisory Control and Data Acquisition (*SCADA*) system. *UC* controls and collects data from many remote units (sensor nodes). There are many studies which show that solutions based on low power radio networks are viable and that they offer the best cost/permformance ratio [8][9][10]. Since the early 90's, radio and microcontroller technologies have allowed the development of smart sensor networks. Many research groups have focused their investigations in the network optimization. However neither of them have develop a network for optimizing this kind of applications.

The environment in which we are developing our study has the following features:

- Communication is usually between nodes and the *UC*.
- Nodes are densely deployed within the range area.
- Topological changes are possible (a node can be added or eliminated if radio range changes).
- Nodes must implement multi-hop mechanisms to let some kind of packets reach the destiny node.
- Nodes can be located without pre-planning.
- Nodes are prone to failure.
- Nodes have no mobility.

Ad-hoc networks are best suited to support these features. We propose (in this paper) a simulation tool to study a multi-hop self-organizing wireless sensor network. We have called this simulator *OLIMPO*.

This paper is organized as follows. In section II, a brief summary of sensor network performances objectives is given. In section III, our network protocol is presented. In section IV, we describe the OLIMPO design. In section V, the results of our network simulation over OLIMPO are discussed. Concluding remarks are given in section VI and future works are listed in section VII.

The goal of this paper is to outline the design of our self-organizing multi-hop network protocol, showing results of several experiments made with our network simulator, *OLIMPO*.

II. Sensor Network Performance Objectives

Wireless sensors design must be developed assuming the following devices' characteristics:

- Low power consumption and low supply voltage.
- Low cost.
- Flexibility.
- Short transmission range.
- Embedded processor implementing a distributed intelligence process [11].
- Microelectromechanical systems (*MEMS*), actuators and radio technology integrated in a reduced space [12].

In that sense, there is a trend to develop and commercialize this kind of embedded systems. This is the case

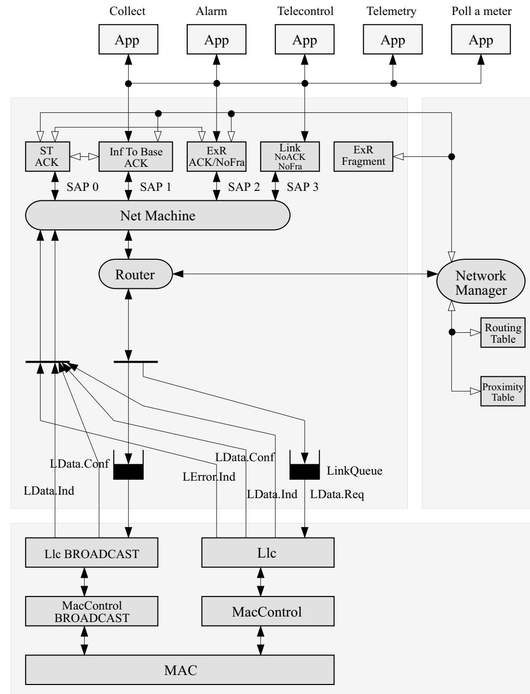

Fig. 1. *OLIMPO* protocol stack

of $Zigbee^{TM} Alliance$ an international association of semiconductor companies, software providers, system integrators, and original equipment manufacturers (*OEMs*) such as ZMD®, ATMEL® CompXs®, Microchip®, betronic® and chipcon® [13]. Another example of this trend is neuRFon^{TM} sensor, from Motorola® Labs, a relative simple device that has been inspired in sensory receptors of the nervous system, which are capable of detecting changes in the environment due to stimuli [14].

Given the nature of these nodes, our network must assume some limitations in the network performance. Due to the low radio power (less than 100 mW), the low battery life and the noisy RF band (Industrial Scientific Band, ISM) the data throughtput will be quite low. Simulations made by Morotola® with his neuRFon^{TM} network show an average data throughput of 40 kbps with a raw bit rate of 250 kps [15][16]. Furthermore, the packets' multi-hop necessity for reaching the end, increase the messages latency. Experiments made by Morotola® with a neuRFon^{TM} network, formed by 64 nodes with ten meters of radio range and a maximal number of four hops in order to reach the end, show a messages latency of 2.6 seconds [15][16].

Another very important issue we have to consider is the duty channel time. This time is closely related with the channel contention [17]. That's why we must consider the influence of the design of the Medium Access Control (MAC) layer on the collision effect. Slotted and unslotted channel access are provided in several MAC designs. We have measure this item in our simulation.

III. Self-Organizing Sensor Network Protocol and *SCADA* Application

Many network protocols have been proposed recently [18][19][20][21][22]. However, we have designed a network protocol to optimize SCADA applications [23] [24] [25].

We have focused our research on a modified unslotted CSMA-CA channel access mechanism. Each time a node wishes to transmit data frames, it will wait for a random period. If the channel is idle, the device will transmit the data. If the channel is found to be busy, the node waits for another random period before trying to access the channel again.

The design has been inspired following the *ISO* model of architecture for Open Systems Interconnection (*OSI*) [26]. The protocol stack defined uses two link layers protocol as depicted in figure 1. With this structure every node is capable to process -transmit and receive- broadcast packets while maintaining a data link dedicated to other node. It is possible to select the type of data link -with or without fragmentation- and the simultaneous number of them. Acknowledgement service is available.

Our multi-hop network protocol creates a spanning tree logical structure over the physical topology. All nodes develop an algorithm to maintain this logical backbone where the root of the tree -we refer it as base station- will have access to all network nodes. In addition, every node will be able to route its packets to the base station.

Nodes always know the path to root through the parent node, but any selected algorithm must allow the root node (*UC*) to have an approximate image of current tree topology. This way, packets from nodes to the root do not contain information about routing. Conversely, messages from root to nodes generally use an explicit routing scheme, so packets must contain information about the path. Packet header size must be optimized because radio frames should be as short as possible to reduce the transmission error ratio, effective bandwidth, etc.

The collecting algorithm is shown in figure 2. An application layer in all the nodes receives the order. This node passes the token to one of its children (figure 2(2)), and waits for a response. When it is received, (figure

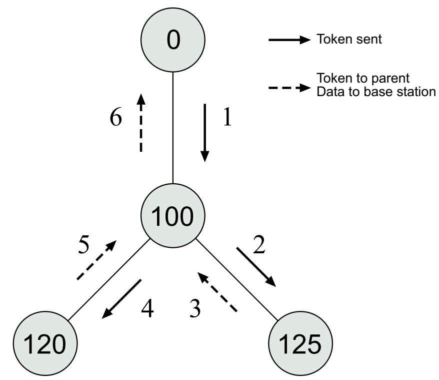

Fig. 2. Collecting scheme

2(3)) the node sends data to the root, and it passes the collect order to the next child (figure 2(4)). Only when there are no more children to be polled, will the node answer with its own data (figure 2(6)). Only one token is being passed between parent and children, so no path header information is necessary, and the answer token is simultaneously flowing to the root. To prevent a lost token, a timeout period guarantees the token passes to the next child.

IV. *OLIMPO*, simulator design

The motivation to develop a new network simulation tool is the need for capability to track specific traffic -*SCADA* packets- from one node to base station through multi-hops. There are other network simulators such as OPNET [27], ns-2 [28], WinneuRFon [19], SensorSimII [29]. However we have designed a new simulator based on the Event Discrete Scheduler (*EDS*), to support our networks applications over a high number of sensor nodes. OLIMPO has been create with C++ Borland® Builder 6, creating a friendly Graphical User Interface (*GUI*).

OLIMPO is open source, providing an useful tool to simulate new communication or application protocols for other researchers.

The current version of *OLIMPO* provide a graphical experiment configuration. User can create several experiments changing easily the simulation parameters, e.g.: timers, random process, radio range, nodes deployment. . . *OLIMPO* also provide several simulation modes -*MAC* step, Logical Link Control (*LLC*) step, network step and application step- providing a way to debug protocols. While executing the simulation many reports are generated in real time filling a text file, that is closed and saved when the simulation ends.

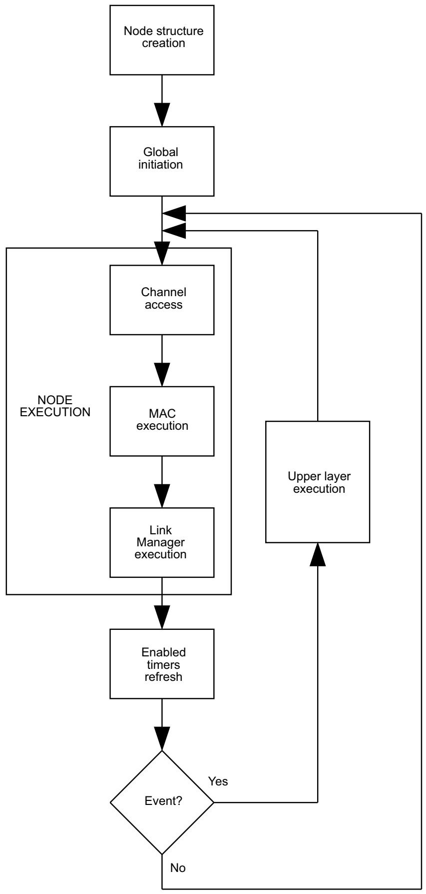

Fig. 3. Execution model for a node in an *OLIMPO* simulation

Figure 3 shows the execution model for a node, and figure 4 shows the *GUI* created.

V. *OLIMPO* Simulation and Results

The simulated network model includes a maximal number of 127 sensor nodes populated over 600 meters x 600 meters area. The deployment of nodes has been chosen in an hexagonal distribution, forming a dense network, where every node has a radio range of 60 meters and consequently there is a maximal number of neighbors of 6. Figure 4 shows the spanning tree generated. Each node establish a logical parent-child relationship with its neighbors, looking for the best path to the root. The number above every node represents the MAC address. Node 0 -shown in yellow color in figure 4- is assumed to be the root and its radio range is depicted with a circle. It's placed in the center of the network topology.

The simulation was generated with a unslotted *CSMA-CA* channel access configuration, and packets with and without acknowledgement. Our objectives were to measure the performance issues related in section II and to obtain efficiently *SCADA* application data from all the nodes.

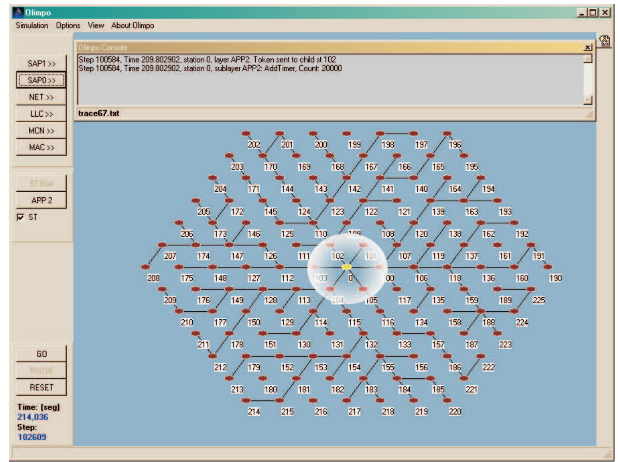

Fig. 4. 127 nodes network simulation, with *OLIMPO*

We have created several experiments, incrementing the number of networked nodes until 127, although *OLIMPO* hasn't restrictions on the maximal number of networked nodes.

After the simulation we have obtain some relevant results. The time for spanning tree creation is related in table I. These times depend on the configuration

TABLE I
TIME FOR SPANNING TREE CREATION

Number of nodes	Time for Creation (sec)
7	7
14	11
21	23
28	25
37	31
64	68
127	130

times (e.g.: time to beacon). Anyway, we consider it to be reasonable good result because this formation time is a very short time compared with the typical *SCADA* application time. After the spanning tree was created, we executed the *SCADA* application proposed. Data application were collecting by the *UC* successfully, obtaining the following network performance results:

- The average data packet delivery end-to-end delay performance for 20 hours of simulation run time is shown in figure 5. We can see that this time depend directly on the number of hops. Once we

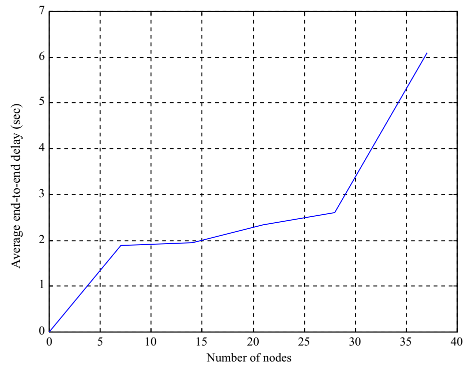

Fig. 5. Average End to End Delay

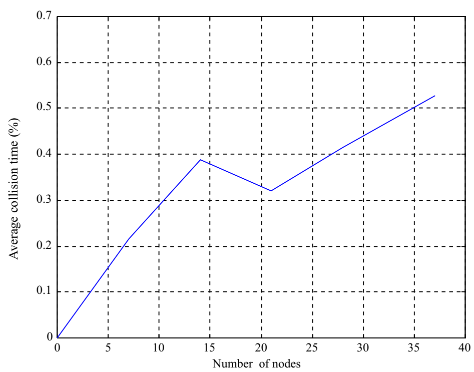

Fig. 6. Average Collision Time

increase the number of nodes, the number of hops also increases, and, consequently, the average data packet delivery end-to-end delay increases too.

- Figure 6 shows the average collision time for all nodes. Collision time never is above 0.6 % for all nodes and 1.5 % for base station.
- Data throughput is obtained applying the equation 1

$$\frac{SuccesfulAttempts}{TotalAttempts} \cdot RawBitRate \quad (1)$$

With a raw bit rate of 4800 bps, we have obtain a throughput of approximately 4655 bps.

- The simulation shows an average duty time of 2.4-3.6% as depicted in figure 7.

VI. Conclusion

We have presented *OLIMPO*, a network simulator, as an useful tool to develop *SCADA* applications over wireless sensor networks. We have developed a network protocol that constructs and maintains the spanning tree.

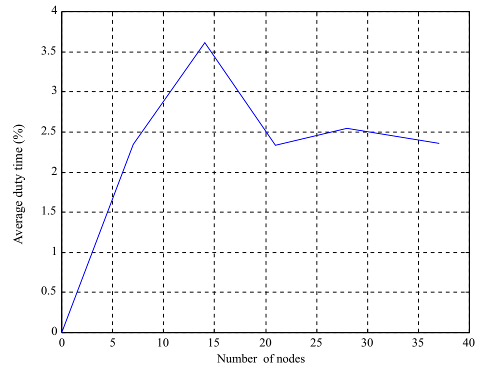

Fig. 7. Average Duty Time

To illustrate the capabilities of *OLIMPO*, we have generated several experiments, presenting simulation results showing network formation time, data packet delivery response time, collision time, throughput and average duty time. We have obtained relevant results for *SCADA* applications.

VII. Future works

For the proposed simulator, we are developing new protocols, such as Low Duty cycle *MAC (LD-MAC)*, slotted *CSMA-CA* channel access, Mediation Device (*MD*) protocol and Distributed *MD* protocol.

Due to the good results, obtained with *OLIMPO*, we have begun to work on the implementation of some *SCADA* applications over real sensor nodes.

References

[1] I. of Electrical and E. Engineers, *IEEE 802.11-1999(ISO/IEC 8802-11:1999) IEEE Standard for Information Technology - Telecomunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. New York, USA: IEEE Press, 1999.

[2] J. A. Gutiérrez, "IEEE 802.15.4: A developing standard for low-power, low-cost wireless personal area networks," in *IEEE Network*, ser. v. 15, no. 5, IEEE. New York, USA: IEEE Press, October 2001, pp. 12–19.

[3] D. E. et al., "Instrumenting the world with wireless sensor networks," in *Acoustics, Speech, and Signal Proccesing*, ser. v. 4, IEEE. New York, USA: IEEE Press, 2001, pp. 2033–2036.

[4] E. Elnahrawy and B. Nath, "Context-aware sensors," in *Wireless Sensor Networks*, ser. Lectures Notes in Computer Science, H. Karl, A. Willig, and A. Wolisz, Eds., no. 2920, EWSN. Berlin, Germany: Springer-Verlag, January 2004, pp. 77–93.

[5] I. of Electrical and E. Engineers, *IEEE 802.15.4-2003 IEEE Standard for Information Technology - Telecomunications and Information Exchange between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY)*

Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). New York, USA: IEEE Press, 2003.
[6] A. Bond, "The water industry (automatic meter reading)," *IEE Colloquium on 'Low Power Radio and Metering'. IEE, London, UK*, no. Digest No.1994/060, 1994.
[7] B. Adams and M. Philips, "Trends towards standard communications for metering," *Ninth International Conference on Metering and Tariffs for Energy Supply. IEE, London, UK*, no. Conf. Publ No.462, 1999.
[8] A. Fox, "The business case for radio based AMR," *IEE Colloquium on 'Low Power Radio and Metering'. IEE, London, UK*, no. Digest No.1994/060, 1999.
[9] S. Mak and D. Radford, "Design considerations for implementation of large scale automatic meter reading systems," *IEEE Transactions on Power Delivery*, vol. 10, no. Digest No.1994/060, Jan 1995.
[10] F. J. Molina, M. G. Gordillo, J. Luque, and J. Barros, "Radio network architecture for automatic meter reading," *Conférence Internationale des Grandes Réseaux Électiques, Krakow POLAND*, 1999.
[11] R. Estrin, J. Heideman, and S. Kumar, "Next century challenges: Scalable coodination in sensor networks," in *ACM/IEEE International Conference on Mobile Computing and Networking*, ser. v. 5, 1999, pp. 263–270.
[12] S. Tilak, N. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless microsensor network models," in *ACM Mobile Computing and Communications Review, MC2R*, 2002.
[13] P. Kinney, "Zigbee technology: Wireless control that supply works," in *Communication Design Conference*. IEEE, 2003.
[14] L. Hester, Y. Hung, O. Andric, A. Allen, and P. Chen, "neuRFon^{TM} NetForm. A self-organizing wireless sensor network," 2003.
[15] J. Huang, Y. Huang, E. Callaway, Q. Shi, and B. 0'Dea, "Simulation of a low duty cycle protocol," in *OPNETWORK 2001*, Washington, D.C., August 2001.
[16] Y. Huang, J. Huang, L. Hester, A. Allen, O. Andric, P. Chen, and B. 0'Dea, "Opnet simulation of a multi-hop self-organizing wireless sensor network," in *OPNETWORK 2002*, Washington, D.C., August 2002.
[17] P. Santi and J. Simon, "Silence is golden with high probability: Maintaining a connected backbone in wireless sensor networks," in *Wireless Sensor Networks*, ser. Lectures Notes in Computer Science, H. Karl, A. Willig, and A. Wolisz, Eds., no. 2920, EWSN. Berlin, Germany: Springer-Verlag, January 2004, pp. 106–121.
[18] J. Broch, D. Maltz, D. B.Johnson, Y. Hu, and J. Jetcheva, "A performance comparison of multi-hop wireless ad hoc network routing protocols," *MOBICOM, Dallas, TX*, Aug 1998.
[19] E. H. C. Jr., *Wireless Sensor Network*. Boca Raton, USA: AUERBACH PUBLICATIONS, 2003.
[20] J. J. Garcia-Luna-Aceves and M. Spohn, "Source-tree routing in wireless networks," *Proc. IEEE ICNP 99, 7th ntl. Conference on Network Protocols, Toronto, Canada*, Oct 1999.
[21] Couto and B. Aguayo, "Performance of multihop wireless networks: Shortest path is not enough," *Proceedings of the HotNets, Princeton, New Jersey*, Oct 2000.
[22] R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-eficient routingprotocols for wireless microsensor networks," *In Hawaii International Conference on System Sciences (HICSS '00)*, Jan 2000.
[23] F. J. Molina, J. Barbancho, and J. Luque, "Application protocol for SCADA on a wireless metropolitan area network," in *Communication Systems and Networks*, C. P. Salvador, Ed., IASTED. Benalmádena, Spain: ACTA Press, September 2003, pp. 227–232.
[24] ——, "Automated meter reading and SCADA application for wireless sensor networks," in *Ad-Hoc, Mobile and Wireless Networks*, ser. Lectures Notes in Computer Science, S. Pierre, M. Barbeau, and E. Kranakis, Eds., no. 2865, ADHOC-NOW 2003. Montréal, Canada: Springer-Verlag, October 2003, pp. 223–234.
[25] A. Bakshi and V. K. Prasanna, "Structured communication in single hop sensor networks," in *Wireless Sensor Networks*, ser. Lectures Notes in Computer Science, H. Karl, A. Willig, and A. Wolisz, Eds., no. 2920, EWSN. Berlin, Germany: Springer-Verlag, January 2004, pp. 138–153.
[26] H. Zimmermann, "OSI reference model - the ISO model of architecture for open systems interconnection," in *IEEE Trans.Commun.*, ser. v. COM-28, no. 4. IEEE, 1980.
[27] "http://www.opnet.com/nsnam/ns/."
[28] "http://www.isi.edu."
[29] C. Ulmer, "http://users.ece.gatech.edu/ grimace/research/sensorsimii/," 2000.