Deployment of Wireless Sensor Networks for Biomedical Applications

Quality of Service Improvement through Network Lifetime-Extending

Carlos Abreu
Escola Superior de Tecnologia e Gestão
Instituto Politécnico de Viana do Castelo
Viana do Castelo, Portugal
cabreu@estg.ipvc.pt

Paulo Mendes
Centro Algoritmi
University of Minho
Braga, Portugal
paulo.mendes@dei.uminho.pt

Abstract — **Biomedical wireless sensor networks are a key technology to enable the development of new healthcare services and/or applications, reducing costs and improving the citizens' quality of life. However, since they deal with health data, such networks should implement mechanisms to enforce high levels of quality of service. In most cases, the sensor nodes that form such networks are small and battery powered, and these extra quality of service mechanisms mean significant lifetime reduction due to the extra energy consumption. The network lifetime is thus a relevant feature to ensure the quality of service requirements. In order to maximise the network lifetime and its ability to offer the required quality of service new strategies are needed to increase the energy efficiency and balance in the network. The focus of this work is the use of the remaining energy in each node combined with information on the reliability of the wireless links, as a metric to form reliable and energy-aware routes throughout the network. This paper presents and discusses an implementation of a lifetime-extending methodology based on energy-aware routing and relay nodes simulated for three different logical topologies. Our conclusion is that such methodology may increase the network lifetime an average of 45%.**

Keywords—Quality of Service; Energy Effeciency and Balance; Network Lifetime; Biomedical Wireless Sensor Networks.

I. INTRODUCTION

A Wireless Sensor Network (WSN) is a distributed, self-organised network of small and highly constrained wireless nodes that interact to carry out a specific task [1]. WSNs differ from traditional wireless networks in several aspects. The WSN nodes have limited processing power, memory, and in several applications they use battery power or energy scavenging [2]. In addition to these limitations the communication channels have narrow bandwidths, and the wireless links may be exposed to high levels of interference.

A Biomedical Wireless Sensor Network (BWSN) is a small-size WSN designed for medical applications or healthcare services [3]. Typical applications of BWSNs include patient monitoring, catastrophe and emergency response, and ambient assisted living for disabled or elderly people [4]. Being a special set of the WSNs, the BWSNs share the same challenges and they add some others, depending on their purpose and application.

BWSNs have the potential to improve the healthcare quality through the development of new applications and services. In this context, due to the nature of the data carried by BWSNs, they have to guarantee high standards of Quality of Service (QoS). However, the QoS policy should not be focused only on typical QoS communication metrics such as delay, jitter, bandwidth, and packet reception rate. Moreover, due to the limited resources of WSN nodes, and in particular due to the limited capacity of the batteries, the QoS strategy must be planned accordingly. Therefore, to avoid the network nodes from becoming energy-depleted, it is necessary to provide energy efficiency and balance to the network in order to maximize its lifetime.

In what follows, the QoS requirements of BWSNs are outlined (section II), and then the need for energy efficiency and balance in BWSNs is discussed, and a deployment strategy based on Energy-Aware routing and Relay Nodes to increase the network lifetime is presented (section III). In Section IV, the proposed methodology is assessed and the results analysed, and finally some conclusions are drawn.

II. QOS REQUIREMENTS OF BIOMEDICAL WIRELESS SENSOR NETWORKS

Nowadays, healthcare professionals base most of their decisions on the information obtained from electronic or/and computer systems. Such information on the health condition of an individual must have medical quality. According to [5], medical quality can be defined as "*the degree to which health care systems, services and supplies for individuals and populations increase the likelihood for positive health outcomes and are consistent with current professional knowledge*". This definition makes clear that communication networks used to transport medical data must ensure a service with quality. In the context of communication networks this requirement is expressed in terms of QoS.

In the industrial and scientific community, the QoS is understood in different ways. In its E.800 recommendation, the International Telecommunications Union defines QoS as the "*totality of characteristics of a telecommunication service that* *bear on its ability to satisfy stated and implied needs of the user of the service*". Regarding this definition, communication networks (in which BWSNs are included) used to transport medical data are a keystone to ensure high standards of quality in the services provided by healthcare professionals. RFC2386 defines QoS as: "*A set of service requirements to be met by the network while transporting a flow*". Given this definition, it is necessary to specify the requirements that must be ensured by the network, who imposes them and in what situations.

The QoS requirements of BWSNs depend on their application and purpose. In real deployments, BWSNs have to transport distinct data types. Figure 1 represents a patient monitoring network where each sensor node can generate several data flows (e.g. heart rate, body temperature, blood pressure and oximetry), with each one being assigned a specific QoS profile.

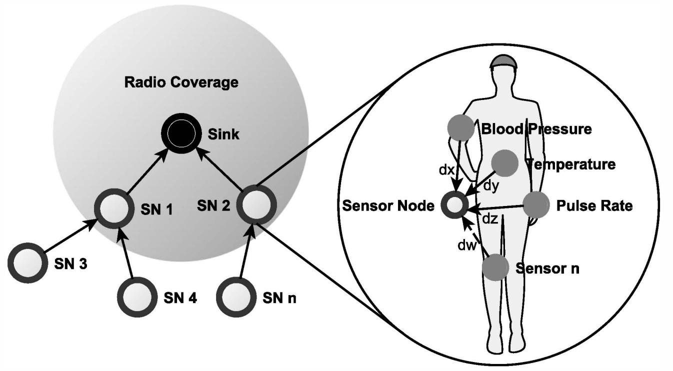

Figure 1: A BWSN were each sensor node can generate distinct data flows.

The QoS requirements of BWSNs are usually defined in the earliest stages of the project and they are guaranteed across the different layers of the communication protocol stack [6]. However, due to the dynamic nature of the surrounding environment, BWSNs can be exposed to very aggressive situations (e.g., interferences on the radio channel or nodes mobility). In such scenarios, the QoS provided by the network can change very often [7]. In fact, harsh environments, as hospital facilities, can compromise the communications and, consequently, the network's ability to provide the QoS required by medical applications and/or services. Furthermore, the impact of such environments on the network performance is unpredictable and hard to manage. The QoS degradation can be related with either random or deterministic factors. Random factors, such as the dynamic of the network or hospital environment, the radio interferences or the patient mobility, need to be detected and classified, thus using such information notify the healthcare professionals, patients or caregivers, to act properly in order to prevent the QoS degradation. Deterministic factors such as the network congestion, due to the over populated networks, can be avoided using QoS assessment and admission control mechanisms.

From the previous discussion, it is clear that developing healthcare applications and/or services based on BWSNs is a challenging task since they have to conform to very demanding functional and usability tests in order to be accepted by the healthcare professionals and by the patients. Furthermore, the BWSNs must provide a stable and reliable service during long time periods. Therefore, the network lifetime have to be maximised in order to ensure the network operation as long as possible, while maintaining all the specified QoS requirements.

III. Energy Efficiency and Network Lifetime

BWSNs are, typically, composed by dozens of battery powered sensor nodes and required to work as long as possible (depending on the target application, a lifetime from 24 hours to several days is mandatory). Thus, energy efficiency is one important requirement for BWSNs in order to maximise the network lifetime. Some of the most energy consuming tasks in BWSNs are related with radio-frequency communications [8] [9], consequently, the routing protocols play an important role to promote the energy efficiency in the network.

In recent years, several different approaches have been proposed to design energy-efficient routing protocols, most of them, focused on finding energy-efficient paths to increase the network lifetime [10] [11]. However, energy efficiency at each path may not be sufficient to guarantee, by itself, a network lifetime increase. It is necessary to consider the Remaining Energy (RE) on each sensor node in order to avoid the over use of the most energy-efficient paths, and balance the energy consumption on the network [11] [12]. As an example, consider a WSN with five sensor nodes (SN) and one sink, as pictured in Figure 2. When SN_1 send its messages to the sink, it may attempt to send it always through SN_4, which is its best parent and belongs to the most energy-efficient path to the sink, what may lead SN_4 to inactivation due to the energy exhaustion [13]. This can have a significant impact in the network ability to satisfy the required QoS. Nevertheless, an energy-balanced network, where alternative paths are used to route the data throughout the network, will remain active, and fully functional, for a longer time period, since all sensor nodes persist active.

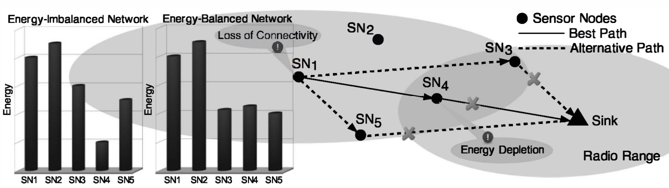

Figure 2: Residual energy distribution in imbalanced and balanced networks.

In order to achieve energy efficiency and balance in the network, it was developed an Energy-Aware Objective Function (EAOF) for the Routing Protocol for Low-Power and Lossy Networks (RPL) standard, proposed by the Routing Over Low-Power and Lossy Networks working group and recently approved by the Internet Engineering Task Force [14]. The RPL is a flexible distance vector routing protocol that uses an Objective Function (OF) to specify how the network nodes form paths to route the data packets though the network. The flexibility of the RPL permits the use of distinct OFs according to the particular requirements of each network.

The proposed EAOF, designed to be used by the RPL, uses two metrics to compute the best path to route the data packets to the sink, the link Expected Transmission Count (ETX) and the RE of each node. The working principle is the following each node selects, from its neighbours, the nodes with more reliable (lowest ETX) links to the sink and, from that subset, the node having the maximum RE is selected to be the node's best parent. Figure 3 shows the proposed EAOF algorithm.

```
BestParent(P1, P2)

MAX_ETX (configurable)
MIN_ENER (configurable)

if ((P1.ETX <= MAX_ETX)&(P2.ETX <= MAX_ETX))
then {
    if ((P1.RANK <= RANK)&(P2.RANK <= RANK))
    then {
        if ((P1 == PREF_PARENT)||(P2 == PREF_PARENT))
        then {
            if ((P1.ENER <= P2.ENER + MIN ENER)&
                (P1.ENER >= P2.ENER − MIN_ENER))
            then {returnPREF_PARENT;
        else {return(P1.ENERGY > P2.ENERGY)?P1 : P2;
    else {
        if ((P1.RANK <= RANK)||(P2.RANK <= RANK))
        then {return(P1.RANK < P2.RANK)?P1 : P2;
        else {returnNULL;
else {
    if ((P1.ETX <= MAX_ETX)||(P2.ETX <= MAX_ETX))
    then {return(P1.ETX < P2.ETX)?P1 : P2;
    else {returnNULL;
```

Figure 3: The EAOF algorithm selects, to be the best parent, the neighbour with the lowest ETX and higher RE.

From the energy point of view, each sensor node selects, from its neighbours, the node with more RE and uses it to route the data packets to the sink. Using this capability combined with strategic placed Relay Nodes (RN) it is possible to extend the network lifetime. Since the RNs do not have energy constraints they are preferentially used to relay the data packets generated by the sensor nodes to the sink, resulting in substantial energy savings in the sensor nodes. The RNs are also used to form a backbone necessary to provide network coverage across the deployment area.

IV. Experiment and Evaluation

As an alternative to real deployments, network simulators are commonly used to evaluate and compare the performance of WSNs [15]. In this work, a hybrid approach was used based on the cross level emulator and simulator entitled as COOJA [16]. COOJA is a flexible node emulator and network simulator designed to simulate WSNs running the Contiki OS [17]. The network used on this work was implemented on the Contiki OS with the ContikiRPL [18] and evaluated using the QoS assessment framework presented in [19].

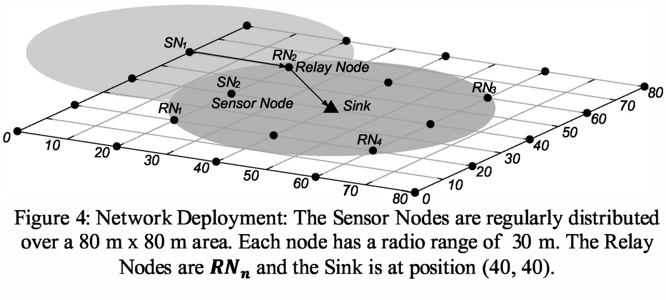

Figure 4: Network Deployment: The Sensor Nodes are regularly distributed over a 80 m x 80 m area. Each node has a radio range of 30 m. The Relay Nodes are RN_n and the Sink is at position (40, 40).

To evaluate the proposed EAOF, it was implemented and simulated a BWSN used to perform a monitor and reporting task. As inpatients on a hospital unit are at pre-established locations having low mobility, the network deployed attempts to recreate such conditions and, at the same time, maximise the covered area by strategic placing the RNs. The network was regularly deployed in a square area of about 80 m x 80 m, as shown in Figure 4. The 26 nodes (1 sink, 4 relay nodes and 21 sensor nodes) have a radio range of 30 m. After the network setup time of about 60 s, each sensor node starts sending data packets at a predetermined rate. The network was simulated for 10 different reporting intervals (2 s, 4 s, 6 s, 8 s, 10 s, 20 s, 30 s, 40 s, 50 s, 60 s). For each reporting interval the network was tested in 3 different logical topologies, i.e. routing trees. The following performance analysis is based on the comparison with the Minimum Rank Objective Function with Hysteresis (MRHOF) [20] using the ETX metric.

Table 1: Simulation results and statistics

	MRHOF	EAOF RELAY	Gain
Average Packet Reception Ratio	93.3%	91.8%	-1.5%
Network Lifetime (s)	3850	5590	45%

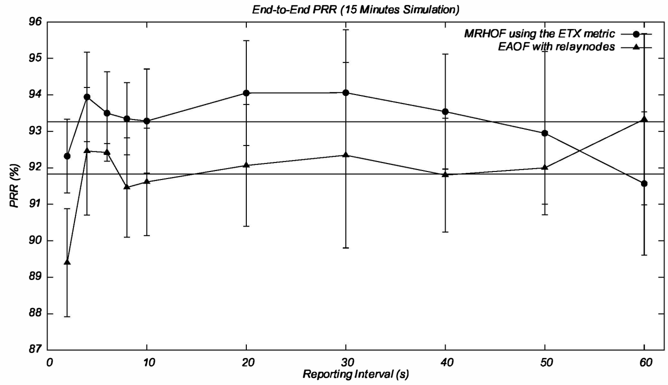

Figure 5: Average and Standard Deviation of the Packet Reception Ratio for different reporting intervals (traffic loads).

The results presented in the Table 1 show a significant improvement in the network lifetime, at the cost of a little degradation of about 1.5% (in average) in the Packet Reception Rate (PRR) (see Figure 5 for more details about the PRR for each reporting interval). This small degradation on the PRR is a consequence of the criterion used by the EAOF to select the best parent of each node. The EAOF uses a trade-off between the link ETX value and the RE of each node. The node's best parent is the neighbour with more RE and acceptable ETX value, using the pre-established limits. Consequently, this approach might result on the use of less reliable or longer paths to route the data packets to the sink and, consequently, in a little degradation of the PRR.

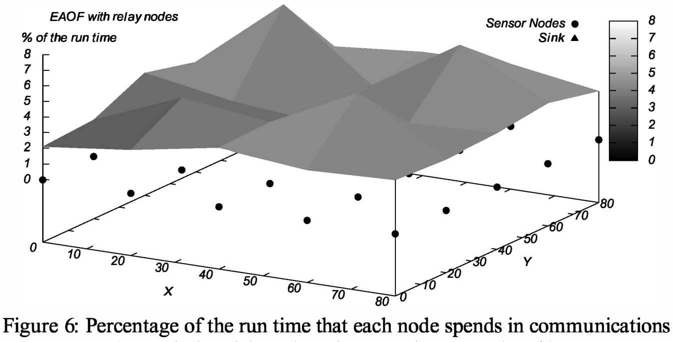

Figure 6: Percentage of the run time that each node spends in communications (scenario in wich each node transmits 0.5 packets/s).

Figure 6 shows the percentage of the time that each node spends transmitting or receiving data (the energy consumption of a node strongly depends on its radio activity, thus, the time spent in communications can be used as an indirect measure of the energy consumption). It is clear that the RNs have a significant increase on its radio activity when compared with sensor nodes. The overuse of the RNs results in considerable energy savings in the sensor nodes and, consequently, in the extending of the network lifetime.

Regarding the network lifetime, it can be defined in many ways as discussed in [21]. On this analysis, since BWSNs are made up of few nodes (with low levels of redundancy), the network lifetime was defined as the time when the First Dead Node (FDN) appears. On the network lifetime evaluation, several simulations were performed, with the results showing a significant improvement of about 45%. Table 2 shows the network lifetime results for each simulated reporting-time.

TABLE 2: THE USE OF THE EAOF WITH RELAY NODES INCREASES THE NETWORK LIFETIME, IN AVERAGE, BY 45%. S_n STANDS FOR THE SIMULATION SCENARIO IN WHICH EACH NODE TRANSMITS 1 PACKET EVERY n SECONDS.

First Dead Node Time (s)	MRHOF	EAOF RELAY	Gain
S_2	2190	3481	59%
S_4	2490	4190	68%
S_6	2340	3780	62%
S_8	2700	4580	70%
S_{10}	2790	4950	77%
S_{20}	3710	5260	42%
S_{30}	4760	6460	36%
S_{40}	5030	7430	48%
S_{50}	5490	7530	37%
S_{60}	7002	8235	18%
Average	**3850**	**5590**	**45%**

Based on the previously presented results, it is clear that the BWSNs deployment using the EAOF with RNs provides a substantial improvement on the network lifetime, with a minor impact on the PRR. Regarding the use of BWSNs in hospital units, the improvement of the network lifetime allows the continuous monitoring of inpatients for longer periods, without batteries replacement, and a more efficient use of human resources and equipment.

V. CONCLUSIONS

Biomedical wireless sensor networks have to fulfil high levels of reliability and confidence in order to be accepted and used to improve inpatient monitoring in hospital units. To achieve such requirements it is necessary, not only, to guarantee high standards of QoS regarding the traditional communication metrics, but also to consider new metrics such as the network lifetime. To maximise the network lifetime, the energy efficiency is a key factor in biomedical wireless sensor networks. In this way, this work presents the implementation and evaluation of an energy-aware deployment strategy based on an energy-aware objective function designed to the used by the RPL protocol. The proposed method, combined with the use of strategic placed relay nodes improves the network lifetime an average of 45% at the cost of a minor degradation of about 1.5% on the packets reception ratio.

ACKNOWLEDGMENT

Work supported by the Portuguese Foundation for Science and Technology, FCT, PhD Grant SFRH/BD/61278/2009.

REFERENCES

[1] I.F. Akyildiz, T. Melodia, and K.R. Chowdury, "Wireless multimedia sensor networks A survey," *Wireless Communications, IEEE*, vol. 14, no. 6, pp. 32-39, December 2007.

[2] T. Watteyne et al, "From MANET To IETF ROLL Standardization: A Paradigm Shift in WSN Routing Protocols," *IEEE Communications Surveys \& Tutorials*, vol. 13, no. 4, pp. 688-707, 2011.

[3] Carlos Abreu, Manuel Ricardo, and Paulo Mendes, "Monitoring QoS over Wireless Sensor Networks for Medical Applications," in *Biodevices 2011*, Rome Italy, January 2011.

[4] J.M.L.P. Caldeira, J. J P C Rodrigues, P. Lorenz, and Lei Shu, "Intra-mobility handover enhancement in healthcare wireless sensor networks," in *e-Health Networking, Applications and Services (Healthcom), 2012 IEEE 14th International Conference on*, 2012, pp. 261-266.

[5] American College of Medical Quality. (2010) Index of Policies.

[6] R. Asokan, "A review of Quality of Service (QoS) routing protocols for mobile Ad hoc networks," in *Wireless Communication and Sensor Computing, 2010. ICWCSC 2010. International Conference on*, 2010.

[7] JeongGil Ko et al., "Wireless Sensor Networks for Healthcare," *Proceedings of the IEEE*, vol. 98, no. 11, pp. 1947-1960, nov. 2010.

[8] Giuseppe Anastasi et al, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 7, no. 3, pp. 537-568, 2009.

[9] L. Oberg and Youzhi Xu, "A Complete Energy Dissipation Model forWireless Sensor Networks," in *Proc. Int. Conf. Sensor Technologies and Applications SensorComm 2007*, 2007, pp. 531-540.

[10] Kemal Bicakci and Bulent Tavli, "Prolonging network lifetime with multi-domain cooperation strategies in wireless sensor networks," *Ad Hoc Networks*, vol. 8, no. 6, pp. 582-596, 2010.

[11] Changsoo Ok, Seokcheon Lee, Prasenjit Mitra, and Soundar Kumara, "Distributed routing in wireless sensor networks using energy welfare metric," *Information Sciences*, vol. 180, no. 9, pp. 1656-1670, 2010.

[12] Chang-Soo Ok et al,"Distributed energy balanced routing for wireless sensor networks"*Computers & Industrial Engineering*, vol.57, no. 1, 2009, Collaborative e-Work Networks in Industrial Engineering.

[13] Ahmed E.A.A. Abdulla, Hiroki Nishiyama, and Nei Kato, "Extending the lifetime of wireless sensor networks: A hybrid routing algorithm," *Computer Communications*, vol. 35, no. 9, 2012, Special Issue: Wireless Sensor and Robot Networks: Algorithms and Experiments.

[14] T. Winter et al., RPL: IPv6 Routing Protocol for Low power and Lossy Networks, March 2012.

[15] Xuedong Liang, "QoS Provisioning for Wireless Sensor Networks: Algorithms, Protocols and Modeling,", University of Oslo, 2009.

[16] F. Osterlind, A. Dunkels, J. Eriksson, N. Finne, and T. Voigt, "Cross-Level Sensor Network Simulation with COOJA," in *Local Computer Networks, Proceedings 2006 31st IEEE Conference on.* Nov. 2006.

[17] A. Dunkels, B. Gronvall, and T. Voigt, "Contiki - a lightweight and flexible operating system for tiny networked sensors," in *Local Computer Networks, 2004. 29th Annual IEEE International Conference on*, nov. 2004, pp. 455-462.

[18] Jeonggil Ko et al., "ContikiRPL and TinyRPL: Happy Together," in *Proceedings of the workshop on Extending the Internet to Low power and Lossy Networks (IPSN 2011)*, Chicago, IL, USA, April 2011.

[19] Carlos Abreu, Manuel Ricardo, and Paulo Mendes, "Framework for QoS Performance Assessment on Biomedical Wireless Sensor Networks," in *Biodevices 2012*, Vilamoura Portugal, February 2012.

[20] O. Gnawali and P. Levis, The Minimum Rank Objective Function with Hysteresis, draft-ietf-roll-minrank-hysteresis-of-10, May 2011.

[21] Isabel Dietrich and Falko Dressler, "On the lifetime of wireless sensor networks," *ACM Trans. Sen. Netw.*, vol. 5, no. 1, Fev. 2009.