Remote Patient Monitoring Based on ZigBee: Lessons from a Real-World Deployment

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Abstract

Aim: This work presents detailed experimental performance results from tests executed in the hospital environment for Health Monitoring for All (HM4All), a remote vital signs monitoring system based on a ZigBee® (ZigBee Alliance, San Ramon, CA) body sensor network (BSN). **Materials and Methods:** *Tests involved the use of six electrocardiogram (ECG) sensors operating in two different modes: the ECG mode involved the transmission of ECG waveform data and heart rate (HR) values to the ZigBee coordinator, whereas the HR mode included only the transmission of HR values. In the absence of hidden nodes, a non–beacon-enabled star network composed of sensing devices working on ECG mode kept the delivery ratio (DR) at 100%.* **Results:** *When the network topology was changed to a 2-hop tree, the performance degraded slightly, resulting in an average DR of 98.56%. Although these performance outcomes may seem satisfactory, further investigation demonstrated that individual sensing devices went through transitory periods with low DR. Other tests have shown that ZigBee BSNs are highly susceptible to collisions owing to hidden nodes. Nevertheless, these tests have also shown that these networks can achieve high reliability if the amount of traffic is kept low. Contrary to what is typically shown in scientific articles and in manufacturers' documentation, the test outcomes presented in this article include temporal graphs of the DR achieved by each wireless sensor device.* **Conclusions:** *The test procedure and the approach used to represent its outcomes, which allow the identification of undesirable transitory periods of low reliability due to contention between devices, constitute the main contribution of this work.*

Key words: *e-health, remote patient monitoring, body sensor network, ZigBee, telemedicine*

Introduction

A body sensor network (BSN) is a network technology that enables wireless data communication with sensing devices located in, on, or around a human body.[1] BSNs can be used to monitor multiple vital signs in real time, delivering the collected data, through a base station, to a remote server, where it can be recorded and accessed by the medical staff. This technology has the potential to provide substantial benefits to diagnosis and treatment of patients, with minimum constrains to daily life activities, allowing the patient to move freely, inside or outside the hospital, while providing continuous monitoring, which can be particularly useful when long periods of monitoring are required. However, the wireless nature of the network links poses several challenges to the communication reliability of these networks.

Most BSN systems proposed in the literature[2–6] are based on a two-stage architecture where the sensing devices send the data wirelessly to a personal unit, carried by the patient, which forwards the data to a base station. On the other hand, in the BSN system presented in this article, named Health Monitoring for All (HM4All), the sensing devices communicate directly with the base station (a ZigBee® [ZigBee Alliance, San Ramon, CA] coordinator) or with ZigBee routers. (A ZigBee router is capable of routing messages between devices and supporting associations. It is mainly used to extend a ZigBee network's range.) This approach has the advantage of avoiding the need of the patient to carry a personal unit. It also decreases the number of wireless links between the sensing devices and the base station.

ZigBee, a standard-based protocol developed by the ZigBee Alliance, a nonprofit association of companies, governmental regulatory groups, and universities,[7] was designed to support multi-application environments and interoperability between devices from various manufacturers. The lower layers of the ZigBee protocol are defined by the IEEE 802.15.4 standard,[8] which was widely adopted by the wireless sensor network community.[9] ZigBee has been successfully used on several wireless sensor network applications, which typically generate event-based and low data rate traffic. Currently, it is also the most widely used protocol in BSN applications,[1] although BSNs normally generate periodic and, frequently, data-intensive traffic.

ZigBee is based on carrier sense multiple access (CSMA)–collision avoidance (CA), which is susceptible to collisions[10] that decrease the communication reliability. (CSMA is a common category of medium access control protocols where the stations listen to the channel before transmitting. Some Ethernet versions use CSMA–collision detection variations, whereas wireless networks such as ZigBee and Wi-Fi use CSMA-CA variations. In the first case, the stations stop their transmissions when a collision is detected, allowing the channel
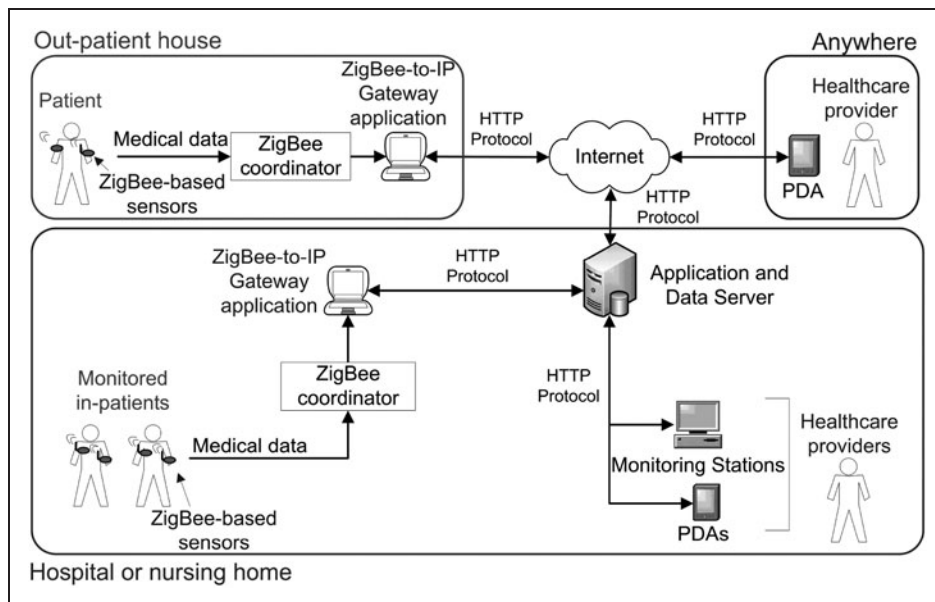
Fig. 1. HM4All architecture. HTTP, hypertext transfer protocol; IP, Internet protocol; PDA, personal data assistant.

to be used again. In order to detect collisions, the stations listen to interfering signals during their own transmissions. This approach is normally not practical for wireless networks because the interfering signal is much weaker than the station's own signal; therefore, these networks rely on CA mechanisms. In both cases, despite the use of the CSMA mechanism, the frequency of collisions tends to increase when the traffic load increases.) Additionally, CSMA-CA-based protocols are vulnerable to the hidden-node problem.[11–13] In a CSMA-based network, a node can only transmit if it senses the channel idle. The hidden-node problem occurs when the carrier sensing fails and a node starts transmitting when the other node has already occupied the channel. If both transmissions are within the reach of a receiver, a collision occurs.

No specific mechanism to avoid the hidden-node problem is provided by the IEEE 802.15.4 protocol, which motivated some authors to consider specific scenarios and propose strategies to mitigate it. Three of the most prominent ones involve grouping nodes that have bidirectional connectivity between each other.[12,14,15] However, these strategies require the modification of the original protocol and consider beacon-enabled networks consisting of static nodes, which is not the scenario considered in this work. Given the particular BSN traffic characteristics, the suitability of ZigBee for BSN applications needs to be assessed.

The main contribution of this article is the communication performance evaluation of the HM4All vital signs monitoring system, based on field tests performed at an inpatient floor of Hospital Privado de Guimarães, a Portuguese hospital. Contrary to which is typically included in related scientific works or in the documentation of commercial systems, the results presented in this work include graphs of the delivery ratio (DR) achieved by each wireless sensing device over time, allowing the identification of undesirable transitory

periods of contention between devices. The contributions made by this work have substantial relevance to groups that aim to develop and evaluate remote patient monitoring systems, due to the detailed and rigorous approach used.

Related Work

Although simulation and laboratory tests are steps toward obtaining insight into systems performance, an important further step is real-world experiments.[16–18] The execution of field tests in hospitals requires a great deal of preparation and effort, which contributes to limit the number of studies conducted on this environment.

One of the first wireless sensor network–based systems for patient monitoring in the hospital environment was presented by researchers from the University of Texas, in 2006, and was based on a ZigBee multi-hop network.[19] A wearable patient unit consisting of a MicaZ mote was interfaced with a commercial blood pressure (BP) and a heart rate (HR) monitor. Routers were also based on MicaZ motes. The system was tested solely in the laboratory environment using three patient units, resulting in no data loss.

MEDiSN, a remote vital sign monitoring system, was deployed, and its performance was assessed in the waiting areas of the emergency room of The John Hopkins Hospital.[20] MEDiSN is composed of a gateway, a variable number of patient monitoring units, and a wireless backbone of eight relay points. All wireless devices are based on Telos motes. Over the IEEE 802.15.4 protocol stack, the devices run the Collection Tree Protocol provided by TinyOS.[21] The system was tested while being used to monitor the HR and oxygen saturation on an average of 3 patients, having achieved an end-to-end DR higher than 99.90%. Contrary to our study, where several causes for packet losses were analyzed, the authors have restricted their analysis to the quality of the wireless links and to the performance of the routing protocol.

The performance study presented by Chipara et al.[22] is based on the same hardware and software components used by MEDiSN. However, the authors have developed a Collection Tree Protocol companion routing mechanism called Dynamic Relay Association Protocol, which is deployed on patient sensors to discover and select relay nodes as the patient moves. The analysis of the data collected from 32 patients over a total of 31 days of monitoring has shown that the median network reliability per patient was equal to 99.92%. Despite good overall results, the authors did not include the number of patients being concurrently monitored, which prevents readers from making any judgment about the system's reliability.

All studies referenced previously in this section use sensors that generate very low traffic. On the other hand, the system evaluated in this work uses electrocardiogram (ECG) sensors, which generate substantially more traffic, posing additional challenges to the

Table 1. Amount of Data Generated by Wireless Sensing Devices

SENSING DEVICE	PERIOD BETWEEN GENERATED DATA MESSAGES	PAYLOAD LENGTH
ECG		
ECG mode	$T = 500$ ms	79 bytes
HR mode	$T = 3$ s	4 bytes
Axillary thermometer	$T = 1$ min	3 bytes

ECG, electrocardiogram; HR, heart rate; T, time.

provisioning of quality of service. Moreover, our study considers not only the average DR, but also the DR achieved over time.

Curtis et al.[23] have developed SMART. This system can monitor oxygen saturation, ECG, and the location of multiple patients. A commercial oxygen saturation sensor was used, whereas the ECG sensor was developed as a Cricket mote daughter board. Curtis et al.[24] subsequently presented the results of the qualitative evaluation of a temporary deployment of SMART in the waiting areas of an emergency department of Brigham and Women's Hospital in Boston, MA, which involved simultaneously monitoring a maximum number of 4 patients. The authors concluded that the system was well accepted by patients and caregivers. Similarly to our approach, raw ECG data were transmitted by sensing devices. However, their system used wired connections from the sensing devices to a personal unit, whereas our system uses fully wireless sensing devices.

Evaluation Scenario

HM4ALL ARCHITECTURE AND COMPONENTS

HM4All was developed to monitor both inpatients and outpatients. Its high-level system architecture is shown in *Figure 1*. Data generated by wearable sensing devices are transported by ZigBee routers and coordinators to a ZigBee-to-Internet protocol (IP) Gateway application, which validates and processes data frames received from a ZigBee coordinator and sends the processed data to the application and data server through a hypertext transfer protocol (HTTP) connection. Additionally, it contains a user interface where data generated by sensing devices are exhibited and recorded and connections are established and monitored. Data sent to the application and data server are stored and made available to monitoring applications running on monitoring stations and wireless portable devices, such as personal digital assistants, carried by nurses and doctors.

Two sensing devices were developed: a single-channel ECG and an axillary thermom-

eter. Both sensing devices are based on the JN5139-M00 module, from Jennic.[25] ECG sensors can operate in one of two different modes: the ECG mode involves the transmission of ECG waveform data and HR values, whereas the HR mode includes only the transmission of HR values. The amount of data generated by each sensing device is shown in *Table 1*. ZigBee coordinators and routers are based on the JN5139-M02 high-power module[25] and use the same electronic printed circuit board and case.

The developed system adopts a simple communication model where data are transferred using a proprietary application profile. An option to this approach would be the adoption of the IEEE 11073 device specializations,[26,27] which are used as the basis of the personal area network and local area network interfaces defined by the Continua guidelines.[28] The adopted option does not compromise the performance analysis of the ZigBee protocol at the medium access control level.

EVALUATION SETUP

The ZigBee-to-IP Gateway application and the embedded software of all network devices were substituted for specific test routines developed to register all messages received by all transmitting devices. However, the size of the exchanged packets and the frequency between packets were kept. The exchanged packets were also recorded using the SNA network analyzer and the 2400E network adapter.[29,30] The hospital floor where tests were performed has a Wi-Fi network based on the IEEE 802.11g protocol whose operating frequency band overlaps with IEEE 802.15.4 channel 22, but not with channel 26.

The test settings used are shown in *Figures 2* and *3*. Test settings included six sensing devices operating in ECG mode. This is because previously executed laboratory tests indicated that for the 2-hop tree topology it would be necessary to limit the maximum number of sensing devices to six to achieve a DR of 99.9% or above. The end-to-end delay values are not reported because they do not exceed 167.7 ms per hop, which is within the acceptable limits for real-time waveform transmission according to the IEEE 11073-00101-2008 standard if the maximum number of hops is limited.[31]
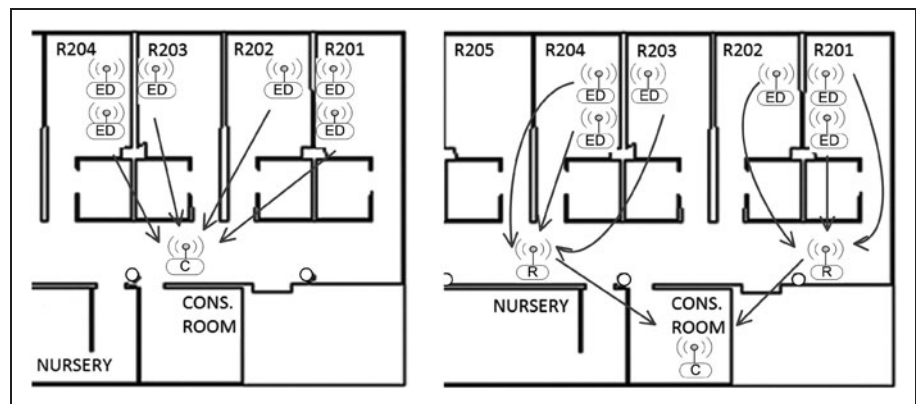

Fig. 2. Test settings in the absence of hidden nodes: **(left)** star topology and **(right)** 2-hop tree topology. C, coordinator; ED, sensing device; R, router.
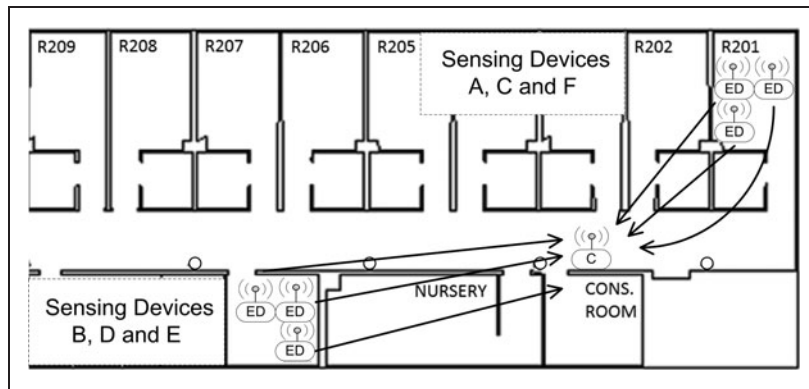
Fig. 3. Test setting for a star topology with 50% hidden nodes. C, coordinator; ED, sensing device.

The setting presented in the left side of *Figure 2* was used to perform tests using a star network. The coordinator was positioned on the hallway, whereas ECG devices were distributed into four patient rooms. The right side of *Figure 2* presents the settings used to test a 2-hop tree network. Two routers were added, and the coordinator was brought into one of the staff rooms. According to previous measurements, all sensing devices could communicate and hear each other's transmissions. The distance between associated devices did not exceed an approximate value of 10 m. Moreover, to assure a good link quality, the coordinator and routers were programmed to transmit at +10 dBm, whereas ECG devices were programmed to transmit at +2 dBm (the maximum transmit power that can be achieved by the JN5139-M00 module). The receiver sensitivity of high-power modules and regular modules are −100 dBm and −96.5 dBm, respectively.

The setting shown in *Figure 3* was used to evaluate the performance of a star network in the presence of hidden nodes. The coordinator was placed in the hall, whereas the sensing devices were positioned on rooms relatively far from each other. Previous measurements confirmed that sensing devices placed at one room could not communicate or hear the transmissions done by sensing devices placed at the other room.

Three configurations were used during field tests: beacon-enabled IEEE 802.15.4 star networks with guaranteed time slots allocated to ECG sensors, non–beacon-enabled ZigBee star networks, and non–beacon-enabled ZigBee 2-hop tree networks. These tests were executed using IEEE 802.15.4 channels 26 and 22. By choosing these channels, it was possible to investigate the impact of the wireless local area network interference on the IEEE 802.15.4 and ZigBee networks.

ECG sensors used a sample resolution of 12 bits and a sampling rate of 200 Hz. Sampled data were further compressed at a rate of 2:1. Data rate varied with the operation mode adopted. In ECG mode, one data message was generated every 500 ms. Each message included a payload of 79 data bytes corresponding to 50 ECG samples plus 2 bytes for HR data and 2 bytes for control data required by the application. In HR mode, one data message was generated every 3 s. Four bytes were included in the payload: 2 bytes for HR data and 2

bytes for control data required by the application. In both modes, each data message included a fixed protocol overhead of 39 bytes.

All successfully received messages were acknowledged at each hop. Devices could make up to four attempts to access the channel, and up to three retries were allowed. The APS acknowledgement mechanism was not used. The network coordinator and routers have their radios switched on permanently, whereas the ECG devices have their radios switched off between transmissions.

Evaluation Results
ECG TRAFFIC IN THE ABSENCE OF HIDDEN NODES

The tests described in this section were performed using sensing devices operating in ECG mode. *Table 2* enumerates, for each test, the configuration used, the duration in hours, and the average DR achieved, which was computed as the ratio of the number of messages successfully delivered to the network coordinator to the number of messages generated by all sensing devices. As shown, star networks that operated on channel 26 were able to deliver all generated messages, irrespective of the use of the guaranteed time slot or the CSMA-CA mechanism. The performance achieved by 2-hop networks is worse than the performance achieved by star networks. Contrary to our expectations, the 2-hop tree network operating on channel 22 achieved a slightly higher average DR than the one operating on channel 26. Therefore, the effect of contention between devices on the DR, which is aggravated in multihop networks because of the relative increase in the traffic load, was more significant than the impact of Wi-Fi interference for this configuration.

Table 2. Average Delivery Ratio for Sensing Devices Operating in Electrocardiogram Mode in the Absence of Hidden Nodes

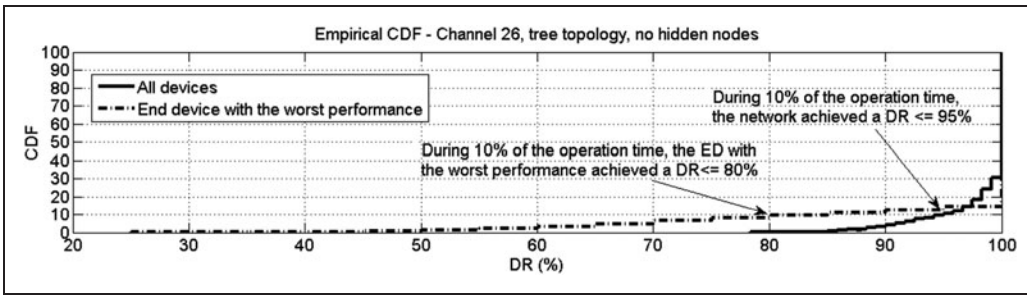| TEST CONFIGURATION	DURATION (H)	AVERAGE DR (%)
IEEE 802.15.4, beacon-enabled star network, GTSs attributed to sensing devices		
Channel 26	4.1	100
Channel 22	4.1	99.9
ZigBee, non–beacon-enabled		
Star network		
Channel 26	5.1	100
Channel 22	2.3	99.8
2-hop, tree network		
Channel 26	16.7	98.6
Channel 22	4.5	99.0
DR, delivery ratio; GTS, guaranteed time slot.		

Fig. 4. Cumulative distribution functions (CDFs) of the delivery ratio (DR) of the ZigBee non–beacon-enabled 2-hop tree network operating on channel 26 and the integrating device that achieved the worst performance. No hidden nodes are present. ED, sensing device.

To allow the evaluation of the DR over time, during the tests, the instantaneous DR for each sensing device was calculated continuously at intervals of four messages (which corresponds to 2 s for the ECG traffic and 12 s for the HR traffic, given the periods between messages provided in *Table 1*), using a 20-message window length (10 s for the ECG traffic and 60 s for the HR traffic).

The cumulative distribution function (CDF) of the instantaneous DR reflects more accurately the reliability of the networks over the time than the average DR because it shows the percentage of time during which the DR was below a given value. *Figure 4* presents the CDF of the DR, using the 20-message window length, for the non–beacon-enabled ZigBee 2-hop tree network operating on channel 26. *Figure 4* also includes the CDF of the device that achieved the worst performance. As shown, this device achieved a DR ≤80% during 10% of the time, which is well below the average DR presented in *Table 2* (98.6%), whereas the network achieved a DR ≤95% during the same percentage of time. This example shows that the aggregate performance results alone are not sufficient to describe accurately the performance of individual devices.

The graphs of the instantaneous DR over time for each individual sensing device (A–F) presented in *Figure 5* explain the results presented on the CDFs shown in *Figure 4*. As shown, for about half an hour after the beginning of the test, no packet is lost. However, after that, the instantaneous DR values for the devices C and D decrease together for approximately half an hour, before they start to increase again. The same behavior pattern, with some occurrences highlighted in the graphs, is observed for other pairs of sensing devices.

This transitory degradation of the DR observed for pairs of sensing devices occurs during corresponding transitory periods of contention. Although all sensing devices are programmed to generate a message at fixed 500-ms intervals, these time intervals

vary owing to the device's clock drifts and the lack of network synchronization[32] support on non–beacon-enabled ZigBee networks. Occasionally, the time differences between messages generated by sensing devices decrease significantly, which generates contention.

It was observed experimentally that, during contention periods, most message losses occurred because of an implementation option adopted by the protocol stack manufacturer,[33] whereas few losses occurred because of successive collisions between contending devices. This implementation option refers to the CSMA-CA algorithm implementation and affects the router performance when it competes for the access to the wireless channel with a child device. Considering two child devices, D1 and D2, associated with the same router, if D2 transmits a data message just after D1 receives an acknowledgement frame for its data message from the router, the router affected by this issue can neither receive the D2 message, because it has already initiated the CSMA-CA algorithm, nor forward the D1 message, because it senses the channel busy and has to back off. After D2 reaches the maximum transmission retries, its message is lost. This issue can be avoided if the ZigBee router implementation allows the reception of incoming messages during the execution the CSMA-CA algorithm. However, such behavior is not required by the standard and, consequently, is not implemented by all manufacturers, including Jennic.

ECG AND HR TRAFFIC IN THE PRESENCE OF HIDDEN NODES

Two tests were performed using the configuration shown in *Figure 3*, which involves the presence of 50% hidden nodes (as shown, sensing devices A, C, and F are hidden from sensing devices B, D, and
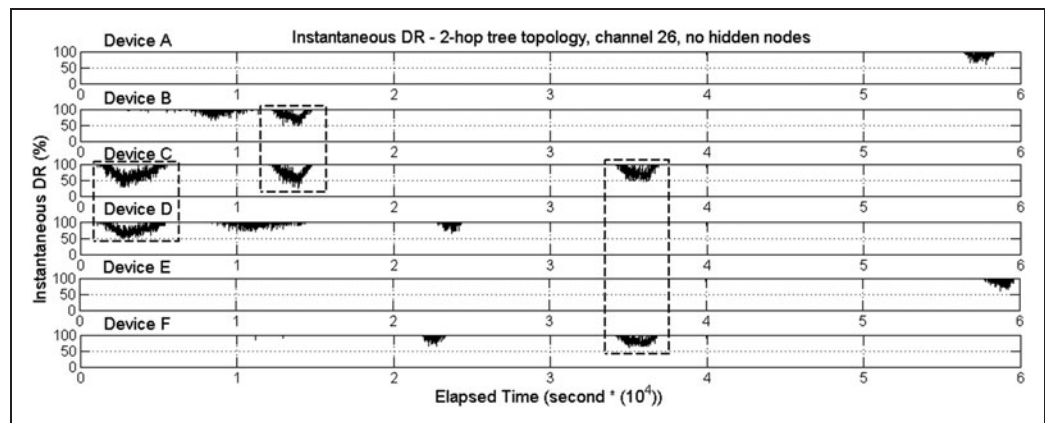

Fig. 5. Instantaneous delivery ratio (DR) results for the individual sensing devices that integrated the 2-hop tree network operating on channel 26 with no hidden nodes.
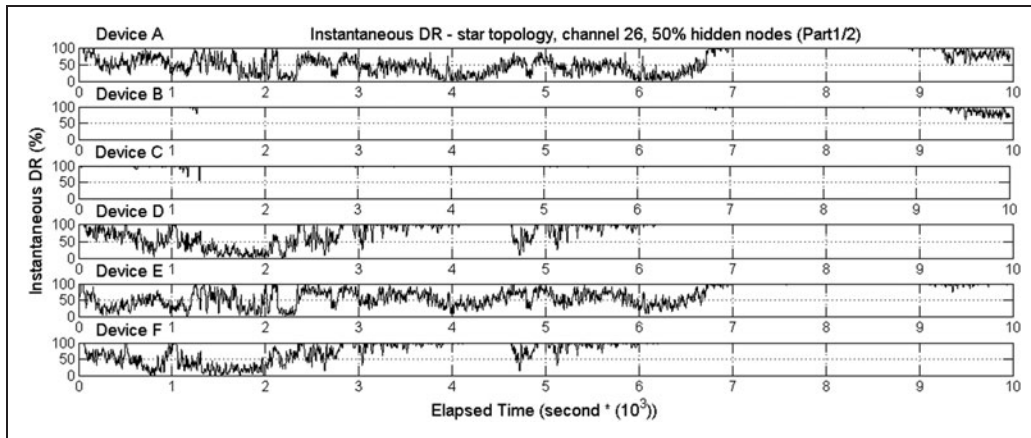
Fig. 6. Instantaneous delivery ratio (DR) results for the individual sensing devices that integrated the star network operating on channel 26 with 50% hidden nodes (Part 1/2).

E), using a non–beacon-enabled CSMA-CA star network operating on channel 26. The sensing devices were programmed to operate on ECG mode during the first test and on HR mode on the second one.

During the first test, data were recorded in two parts of around 2.8 h and 4.2 h, respectively, with an interruption of 50 min between the parts. During the first part, the average DR was equal to 84.0%, considerably worse than the average DR observed in the test without hidden nodes, where only a negligible number of messages was lost. During the second part of the test, the transmission times of the sensing devices did not overlap, allowing the network to achieve an average DR near to 100%.

The DR over time for each sensing device during the first part of the test is presented in *Figure 6*, which shows that the DRs for sensing devices A and E start to drop together and recover at the same time. Similar behavior is observed for devices D and F and for devices A and B at the end. As shown in *Figure 3*, all these are hidden-node pairs.

The second test (HR mode) lasted 10.2 h, a period long enough to capture contention periods caused by clock drifts. An average DR of 99.9% was achieved. *Figure 7* presents the CDF of the instantaneous DR achieved by the network and the device with the worst performance. In this case, the DR values are computed over a sliding time window of 1 min in length, which corresponds to 20 messages. As shown, the network maintains a DR > 99.0% during 99.96% of the time, whereas the device with the worst performance achieves a DR > 95.0% during 99.8% of the time.

The instantaneous DR results achieved by the devices with the worst performance are presented in *Figure 8*. A common contention period with message losses is

highlighted. Comparing the results for HR and ECG traffic (see *Fig. 6*), we can conclude that sensing devices that generate HR traffic contend for less time and lose fewer messages than the ones that generate ECG traffic. Specifically, the worst performance was observed for sensing device A, which achieved an average DR equal to 99.7%.

Discussion

Sensing devices operating on non–beacon-enabled networks are unable to maintain fixed time relations between their transmissions because of the clock drift of their oscillators. Therefore, a reliable estimation of the expected performance of a non–beacon-enabled network can only be obtained if sufficiently long tests are performed.

The implementation of a network synchronization procedure to avoid clock drift may be considered to enhance the performance of the ZigBee BSNs. However, such a procedure is not enough and may be even prejudicial in some cases, given the periodic nature of the traffic generated by BSN sensing devices, if it is not accompanied by a mechanism to distribute the traffic generated by the sensing devices along the time, in order to avoid repeated contention.

The measurement of the DR values achieved by individual sensing devices using a running window, as presented in this work, has decisively contributed to the correct evaluation of the performance of the networks under test and demonstrated that the use of the global average value of the DR is not sufficient. Instead, the performance of individual sensing devices over time shall be considered.

The performance of tree networks could have been improved if routers would have been able to interrupt the execution of the CSMA-CA algorithm to receive incoming messages. However, such a
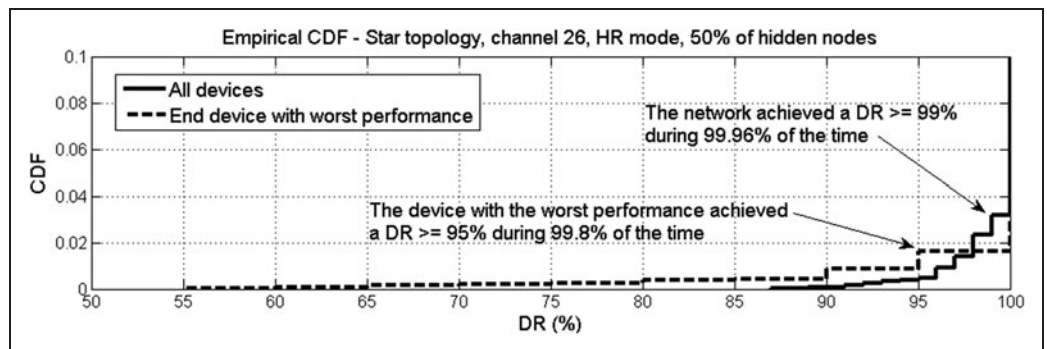

Fig. 7. Cumulative distribution function (CDF) of the delivery ratio (DR) measured for the ZigBee non–beacon-enabled star network operating on channel 26, in heart rate (HR) mode, with 50% of hidden nodes.
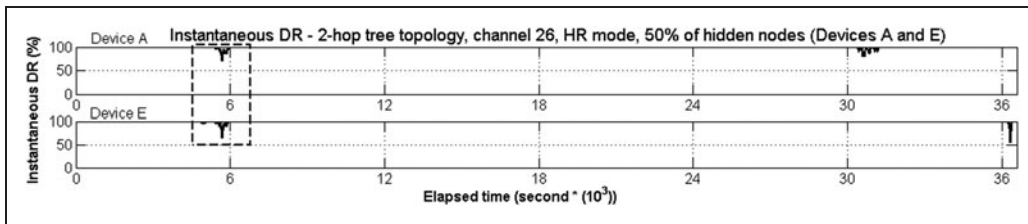
Fig. 8. Instantaneous delivery ratio (DR) results for devices A and E operating in heart rate (HR) mode.

procedure is not mandatory by the standard. Therefore, some ZigBee protocol implementations (particularly, the one used in this work) may not follow it.

The test results shown in *Figure 6* demonstrate that the performance of CSMA-CA-based ZigBee BSNs can be severely affected by the presence of hidden nodes under high traffic. On the other hand, the same network can present an acceptable performance under low traffic conditions, as shown by the good results obtained using sensing devices that generated only HR traffic.

Conclusions

This work presented a detailed experimental performance evaluation of HM4All, a ZigBee-based remote vital signs monitoring system, based on field tests performed in the hospital environment. In the absence of hidden nodes, both star and 2-hop tree networks composed of six ECG sensors achieved DR values >98.5%. However, by analyzing the performance of individual sensing devices that operated in the 2-hop tree network, it is possible to observe periods of contention where the DR decreases severely. These results demonstrate that the indication of the global average value of the DR is not enough and that the evaluation of the performance of individual sensing devices with time provides much more meaningful results.

Further tests in the presence of hidden nodes for a non–beacon-enabled star network consisting of six devices generating ECG traffic achieved a performance considered unsatisfactory for patient monitoring purposes. However, the same ZigBee network presented an acceptable performance for the transport of HR traffic, which makes the network suitable for the transport of medical data generated by multiple sensing devices if the traffic is kept low.

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Disclosure Statement

No competing financial interests exist.

REFERENCES

1. Chen M, Gonzalez S, Vasilakos A, Cao H, Leung VC. Body area networks: A survey. *Mobile Network Applic* **2011;**16:171–193.

2. Harris M, Habetha J. The MyHeart Project: A framework for personal health care applications. In: *Computers in cardiology.* New York: IEEE, **2007;**34:137–140.

3. Lymberis A, Paradiso R. Smart fabrics and interactive textile enabling wearable personal applications: R&D state of the art and future challenges. *Conf Proc IEEE Eng Med Biol Soc* **2008;**5270–5273.

4. Paradiso R, Gemignani A, Scilingo EP, De Rossi D. Knitted bioclothes for cardiopulmonary monitoring. *Conf Proc IEEE Eng Med Biol Soc* **2003;**3720–3723.

5. Rienzo MD, Rizzo F, Parati G, Brambilla G, Ferratini M, Castiglioni P. MagIC System: A new textile-based wearable device for biological signal monitoring. Applicability in daily life and clinical setting. *Conf Proc Eng Med Biol Soc* **2006;**7167–7169.

6. Konstantas D, Herzog R. Continuous monitoring of vital constants for mobile users: the MobiHealth approach. *Conf Proc IEEE Eng Med Biol Soc* **2003;**3728–3731.

7. ZigBee Alliance. Wireless control that simply works. **2011.** Available at www.zigbee.org (last accessed April 2, 2011).

8. IEEE. IEEE standard 802.15.4-2003: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks. New York: IEEE, **2003.**

9. Buratti C, Conti A, Dardari D, Verdone R. An overview on wireless sensor networks technology and evolution. *Sensors (Basel)* **2009;**9:6869–6896.

10. Fernandez-Lopez H, Macedo P, Afonso JA, Correia JH, Simões R. Evaluation of the impact of the topology and hidden nodes in the performance of a ZigBee network. In: Hailes S, Sicari S, Roussos G, eds. *S-Cube 2009.* Berlin: Springer, **2009;**256–271.

11. Ray S, Starobinski D, Carruthers JB. Performance of wireless networks with hidden nodes: A queuing-theoretic analysis. *Comput Commun* **2005;**4:19.

12. Ruzzelli AG, Jurdak R, O'Hare GMP, Stok PVD. Energy-efficient multi-hop medical sensor networking. *HealthNet'07.* New York: ACM, **2007;**37–42.

13. Tsertou A, Laurenson DI. Revisiting the hidden terminal problem in a CSMA/CA wireless network. *IEEE Trans Mobile Comput* **2008;**7:817–831.

14. Koubaa A, Severino R, Alves M, Tovar E. Improving quality-of-service in wireless sensor networks by mitigating "hidden-node collisions." *IEEE Trans Ind Inform* **2009;**5:299–313.

15. Hwang L-J, Sheu S-T, Shih Y-Y, Cheng Y-C. Grouping strategy for solving hidden node problem in IEEE 802.15.4 LR-WPAN. *2005 First International Conference on Wireless Internet.* Piscataway, NJ: IEEE, **2005;**26–32.

16. Ali M, Saif U, Dunkels A, et al. Medium access control issues in sensor networks. *ACM SIGCOMM Comput Commun Rev* **2006;**36:33–36.

17. Tschudin C, Gunningberg P, Lundgren H, Nordstrom E. Lessons from experimental MANET research. *Ad Hoc Networks* **2005;**3:221–233.

18. Kiess W, Mauve M. A survey on real-world implementations of mobile ad-hoc networks. *Ad Hoc Networks* **2007;**5:324–339.

19. Hande A, Polk T, Walker W, Bhatia D. Self-powered wireless sensor networks for remote patient monitoring in hospitals. *Sensors (Basel)* **2006;**6:1102–1117.

20. Ko J, Gao T, Terzis A. Empirical study of a medical sensor application in an urban emergency department. *BodyNets '09.* Brussels: ICST, **2009:**8.

21. Gnawali O, Fonseca R, Jamieson K, Levis P. *CTP: Robust and efficient collection through control and data plane integration.* Stanford Information Networks Group Technical Report SING-08-02. Stanford, CA: Stanford Information Networks Group, **2008.**

22. Chipara O, Lu C, Bailey TC, Roman G-C. *Reliable patient monitoring: A clinical study in a step-down medical unit.* St. Louis: Washington University in St. Louis, **2009.**

23. Curtis D, Pino EJ, Bailey JM, et al. SMART—An integrated, wireless system for monitoring unattended patients. *J Am Med Inform Assoc* **2008;**15:44–53.

24. Curtis D, Shih E, Waterman J, et al. Physiological signal monitoring in the waiting areas of an emergency room. *BodyNets '08.* Brussels: ICST, **2008:**5.

25. Jennic. JN5139 data sheet. IEEE802.15.4 support page. **2010.** Available at www.jennic.com/support/datasheets/jn5139_module_datasheet (last accessed November 14, 2011).

26. IEEE. *IEEE standard 11073-10406-2011. Part 10406: Device specialization—Basic electrocardiograph (ECG) (1- to 3-lead ECG).* Piscataway, NJ: IEEE Standards Association, **2011.**

27. IEEE. *IEEE standard 11073-10408-2011. Part 10408 Device specialization—Thermometer.* Piscataway, NJ: IEEE Standards Association, **2011.**

28. Continua Alliance. *Continua design guidelines version 2012+ errata.* Beaverton, OR: Continua Alliance, **2012.**

29. Sensor network analyzer. **2010.** Available at www.daintree.net/sna/sna.php (last accessed November 30, 2010).

30. 2400E sensor network adapter. **2010.** Available at www.daintree.net/sna/adapter.php (last accessed November 22, 2010).

31. Fernández-López H, Afonso JA, Correia JH, Simoes R. The need for standardized tests to evaluate the reliability of data transport in wireless medical systems. In: Martins F, Lopes L, Paulino H, eds. *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Volume 102: Sensor systems and software: 3rd International ICST Conference, S-Cube 2012, Lisbon, Portugal, June 4–5, 2012, revised selected papers.* New York: Springer, **2012:**137–145.

32. Sundararaman B, Buy U, Kshemkalyani AD. Clock synchronization for wireless sensor networks: A survey. *Ad Hoc Networks* **2005;**3:281–323.

33. Fernández-López H, Afonso JA, Correia JH, Simoes R. Towards the design of efficient nonbeacon-enabled ZigBee networks. *Comput Networks* **2012;**56:2714–2725.

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