Performance Analysis of ZigBee Technology for Wireless Body Area Sensor Networks

Huasong Cao[1], Xuedong Liang[2], Ilangko Balasingham[3], and Victor C.M. Leung[1]

[1] Department of Electrical and Computer Engineering
The University of British Columbia
2332 Main Mall, Vancouver, BC, Canada V6T 1Z4
{huasongc,vleung}@ece.ubc.ca
[2] Rikshospitalet University Hospital
University of Oslo, Oslo, Norway N-0027
xuedongl@medisin.uio.no
[3] Norwegian University of Science and Technology
Trondheim, Norway N-7491
ilangkob@medisin.uio.no

Abstract. A Wireless Body Area Sensor Network (WBASN) is a radio-frequency (RF) based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on or around a human body. Complementing the coverage of Wireless Personal Area Networks (WPANs), WBASNs target diverse applications. This paper extensively evaluates the performance of ZigBee technology for WBASN-WPAN system by analysis and computer simulations. Specifically, we configure the system deployment, network structure, applicable data rates for WBASN sensor nodes, and underlying radio parameters. Average reception ratio, throughput and latency have been evaluated for the overall system performance; fairness across sensor nodes has been examined; preliminary results regarding mobility support of ZigBee for WBASN are also shown. After examining the performance of ZigBee network with our WBASN-WPAN configurations, we come to the conclusion that serveral optimizations should be done before applying ZigBee to such a system.

Keywords: WBASN, WPAN, ZigBee, performance analysis, OPNET Simulation.

1 Introduction

With the growing needs in ubiquitous communications and recent advances in very-low-power wireless technologies, there has been considerable interest in the development and application of wireless networks around humans. A Wireless Body Area Sensor Network (WBASN) is a radio-frequency (RF) based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on or around a human body. Typically, it covers a short range, of about 2 meters. Complementing the coverage of Wireless Personal Area Networks (WPANs)*, which is

* There is no strict difference in definition between WBASN and WPAN. In this paper, we use WBASN specifically for the wireless network of sensor nodes in or on a human body, while use WPAN to refer to the wireless network of peripherals in proximity to a person.

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usually about 10 meters, WBASNs target diverse applications, including healthcare, athletic training, workplace safety, consumer electronics, secure authentication, and safe-guarding of uniformed personnel. In this paper, we focus on a WBASN-WPAN system, which combines WBASNs and WPAN together, with the intent to facilitate medical care in a hospital environment.

Both existing and emerging open technologies can be leveraged to enable these short-range communications, such as ZigBee [1], Bluetooth [2] and the appearing IEEE 802.15.6 standard — Body Area Networks (BANs) [3]. ZigBee is a standard targeting low-data-rate, low-power-consumption and low-cost wireless applications. Its lower physical data rate is traded for lower power consumption, and together with a simpler protocol stack, ZigBee devices enjoy relatively longer lifetime. It is complementary to Bluetooth technology in terms of infrastructure-oriented mesh networking support.

However, compared to a general wireless sensor network (WSN) [4], which ZigBee is designed for, a WBASN-WPAN system has its own characteristics, listed as follows. These distinguish WBASN-WPAN from WSN, and also indicate that optimizations should be done before applying ZigBee for such a system.

1) Architecture. A WBASN-WPAN system consists of two parts. One involves multiple WBASNs, each of which has certain sensor nodes in or on a human body; the other one is a WPAN, which includes router nodes around human body as an infrastructure, for relaying data from WBASNs. WSNs, however, have no distinguishment in node's role. Every node is a sensor node, as well as a router node.

2) Density. The number of sensor nodes deployed on body depends on the application; as for the router nodes, deployment varies in environments. As a whole, we see a WBASN-WPAN system with sensor nodes aggregated into different groups, while routers are widely distributed. Typically, body sensor nodes are not densely deployed for the tolerance of node failures as in traditional WSNs, and thus not require high node density.

3) Data rate. Most WSNs are applied for remote monitoring, where events can happen irregularly. In comparison, human's physiological activities are mostly periodic, and as a result, the generated packet streams have stable data rates.

4) Latency. For certain medical applications, latency caused by underlying communications network of a WBASN-WPAN system is crucial. In WSNs, nodes normally trade latency for longer life time, as they are not supposed to be easily reachable by humans. Power saving is definitely beneficial in WBASN-WPAN, but certain nodes could be always on rather than go to sleep often, and have battery changed whenever necessary.

5) Mobility. Humans move. Even those people with special medical treatment are likely to move sometimes. As a consequence, sensor nodes in a WBASN move in group. Compared to wired bedside equipments which limit patients' mobility, WBASN takes advantage of wireless links. However, this also contributes to the complexity of the network.

Considering all these characteristics, thorough evaluation of WBASN-WPAN's performance is crucial before its deployment. There have been performance evaluations of ZigBee protocols through both computer simulations [5]-[8], and experimental study [9]. But to our best knowledge, no work has been done to specifically configure WBASN-WPAN's characteristics for evaluation in a ZigBee network. In

[5], it compares the two routing paradigms of ZigBee network, by measuring end-to-end delay, packet loss and routing overhead. [6] studies the suitability of ZigBee for medical applications and evaluates the effect of packet segmentation and backoff parameters, as well as interference caused by devices working in the 2.4 GHz ISM band. However, only star network topology has been studied. [7] adds mobility to sink node, and compares the performance of random and predictable mobility strategies of the sink. [8] evaluates mobility support of end-device and routers in ZigBee network for both routing schemes, by varying speeds and percentage of mobile devices. Besides all the computer simulations, [9] implements ZigBee protocol stack on hardware development board and evaluates the throughput and packet loss in a very small-scale network, due to the feasibility issue. These works again have been based on general WSN setup, without considering configurations for a WBASN-WPAN.

Complimenting the above researches, this paper extensively evaluates the performance of ZigBee technology for WBASN-WPAN system by analysis and computer simulations. Specifically, we configure the WBASN-WPAN system deployment, network structure, applicable data rates for WBASN sensor nodes, and underlying radio parameters. Average reception ratio, throughput and latency have been evaluated for the overall system performance; fairness across sensor nodes has been examined; preliminary results regarding mobility support of ZigBee for WBASN are also shown. After examining the performance of ZigBee network with our WBASN-WPAN configurations, we come to the conclusion that several optimizations should be done before applying ZigBee to such a system.

The following of this paper is organized as this. Section 2 discusses WBASN-WPAN's architecture. Section 3 analyzes ZigBee's support for such a system. Section 4 describes simulation setup and results. We then conclude the paper in Section 5.

2 Architecture

WBASNs are seldom working alone. Connection to WPAN or other wider area networks, e.g. cellular network, not only helps extend its communications range, but also facilitates data exchanges, leading to an ubiquitous computing environment. Following we discuss about the architecture of a WBASN-WPAN system, which fosters the simulation setup in Section 4. The first subsection describes how WBASNs and WPAN are interconnected; the second subsection describes topology alternatives within one WBASN area.

2.1 System Architecture

For the deployment of a WBASN-WPAN system, we consider an area with limited range, e.g. home, playground or building, where one short-range radio is able to cover the whole span. Router nodes utilizing the same radio are deployed across the area as infrastructure to facilitate multi-hop routing. Data exchanges happen within or between WBASNs, and between WBASNs and these router nodes. Ideally, nodes on body are relatively smaller in size, more comfortable in material, while router nodes have larger memory and computing capability. However, in current practice, two kinds of nodes are mostly implemented on the same hardware flashed with different firmware, for proof-of-concept.

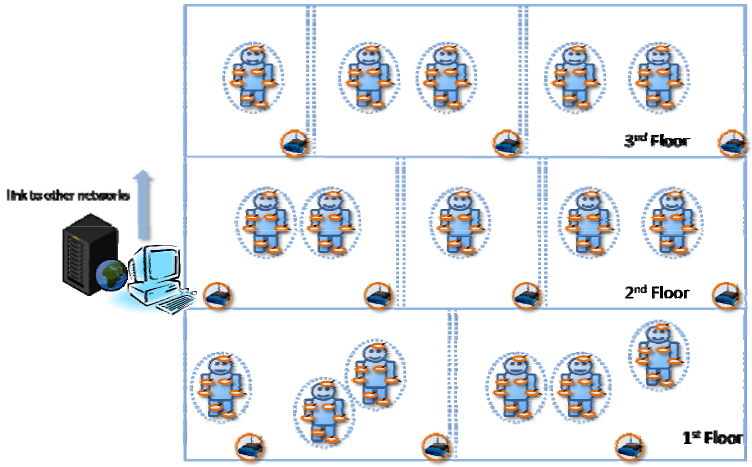


Fig. 1. A WBASN-WPAN system deployment in a building with three floors

Fig. 1 illustrates an example of WBASN-WPAN system deployment in a building with three floors. Double dot lines in the figure indicate separations between rooms. All sensor nodes in WBASNs and router nodes across the building are wirelessly connected through one radio, e.g., ZigBee. A gateway server sitting on the left side of this figure is in charge of network management, data storage and remote access etc (there can be more than one gateway in the system). It also helps extend the communications range to wider area networks, e.g. the Internet. All WBASN-WPAN communications in the building share the same bandwidth and as a result, collisions occur relatively more easily as number of WBASNs increasing. In such a distributed network, asynchronous media access control (MAC) mechanism, e.g., carrier sense multiple access (CSMA), is likely to be used for collision avoidance.

While devices with dual radios, e.g., ZigBee radio and Wi-Fi radio, can be available, it adds complexity in terms of intelligent use of the second radio. In addition, current Bluetooth and Wi-Fi radios have no natural support for multi-hop routing, which makes data exchanges among WBASNs complicated. When only data uploading is considered, the second radio needs to increase its radio sphere of influence to reach the gateway, which causes even sever competition for bandwidth across the network. There are also WBASN application scenarios where WPAN infrastructure is not existed, e.g., the WBASN user is travelling in a metropolis area, other wireless technologies, e.g. Wi-Fi or WiMAX, can be employed to facilitate continuous ambulatory monitoring. In such a system, collision is less likely to occur as the number of WBASNs competing for bandwidth in radio sphere of influence is limited. As a tradeoff, power consumption and communications cost will be increased. However, this topic is out of the scope of this paper. The following of this paper focuses on the WBASN-WPAN approach for deployment in a hospital environment.

2.2 WBASN Topology

When we zoom in to examine network structure of sensor nodes of a WBASN on one's body, there are basically two alternatives, namely flat topology and multi-hop topology. Fig. 2 illustrates these two approaches.

Fig. 2. Two WBASN topologies: flat topology and multi-hop topology

For a flat WBASN topology, all wearable sensor nodes are equipped with no routing capability. They are all directly connected to router node around the WBASN*. Senor nodes differ from each other in sensory functionalities, but are all treated the same in network structure. Communications between sensor nodes in the WBASN and gateway are through router node. See the left-side figure in Fig. 2.

A multi-hop topology, in comparison, supports router nodes on body. These router nodes could be sensory devices themselves. As a benefit, ultra-low-power sensor node can transmit its packets with lower power to nearby router, which relays the data. Multiple routers, including those on-body and off-body, can be involved before the data gets to its destination. See the right-side figure in Fig. 2.

Above are two basic topologies when we examine one WBASN with one router. If we zoom out to see the system as a whole, network structure gets complicated considering the existence of multiple WBASNs and corresponding mobility. When one WBASN is moving around, sensor nodes may lose connection to the router node at different time, and thus start look for new router and rejoin the network at different time. This results in nodes of one WBASN connecting to two or more different router nodes.

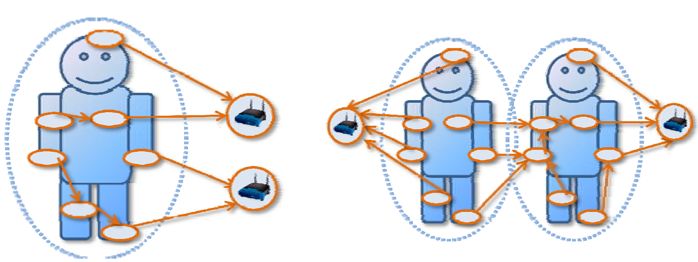


Fig. 3. Example of network structure for mobile WBASN and multi-WBASN cases

* Some application scenario may employ a coordinator node on body to coordinate communications between sensor nodes and help data aggregation. This makes WBASN itself organize as a star topology. However, there is no counterpart for such a WBASN-WPAN structure in ZigBee network. And thus this topic is out of the scope of this paper.

When a WBASN with multi-hop topology meets another WBASN, wearable nodes with routing capability may help route packets from the other WBASN, which adds volatility to the network. In Fig. 3, examples of these two cases are shown respectively.

3 ZigBee Network

Three types of devices exist in a ZigBee network, i.e. coordinator, router and end device. The coordinator is responsible for network establishment, and together with routers, it is responsible for devices joining/leaving the network, network address assignment and routing [1]. An end device represents sensor/actuator node in a WSN, which is equipped with no routing functionality and supposed to be sleeping a large portion of time with the intent to save power. When Aligning ZigBee devices to those in a WBASN-WPAN system, coordinator and routers in ZigBee correspond to router nodes in WBASN-WPAN, and end devices in ZigBee correspond to sensor nodes on body. A coordinator is more likely to take the responsibility as the gateway server in a WBASN-WPAN as shown in Fig. 1, though it is not mandatory.

End devices are automatically portable in the sense that when it loses connection to the parent router, rejoin procedures will be initiated. First, an orphan-scan request is sent to look for an existing parent router; if fail, a network rejoin request shall be broadcast to scan for new potential parent routers. However, even when end devices are not mobile, they may lose connection to their parent routers when network is overloaded. This results in orphan-scan and rejoin processes, which may lead to restructured network as shown in Fig. 3. It has been observed during our simulation evaluations.

When an end device rejoins the network through another parent router, a new 16-bit network address may be assigned depending on network address assignment scheme. If distributed address assignment is employed, new parent device will assign a network address from its address block to rejoining end device. Every time a new network address is assigned, a message is broadcast across the whole network to announce the update. If stochastic address assignment mechanism is employed, however, end device can retain its formal address, assuming there is no address conflict. The overhead involved for address conflict detection each time an end device rejoins the network is a tradeoff for keeping its network address. As end devices are usually the source of sensory data, data sending can be resumed after rejoining the network. However, as destinations of command packets, a huge delay may be involved for assigning new network address and processing device discovery.

4 Performance Evaluations

The following of this paper conducts extensive simulation experiments to evaluate ZigBee's support for WBASN-WPAN in an indoor environment. OPNET Modeler 14.0 with ZigBee models is used [10]. In the simulations, we evaluate system's average reception ratio, throughput, latency and fairness of WBASN sensor nodes by varying number of WBASNs and distance from WBASNs to the gateway. Mobility support of ZigBee for WBASNs is also studied based on our planned trajectory.

4.1 Simulation Setup

We set a 100 m x 100 m area to simulate one floor of a hospital, as shown in Fig. 4. At the centre of this floor sits the ZigBee coordinator. It also acts as gateway server, collecting data from different WBASNs. Routers are equally distributed (20 meters apart) across this floor. Transmit power of devices are configured based on the data-sheet of CC2420 radio chip [11], to reflect different roles in the network, i.e., end devices transmit at a lower power level and thus last for a longer time. In order to mimic practical deployment of routers along hallways and simulate the signal propagation along them, path loss model and radio sensitivity are specifically configured, i.e. although it is an square area, signal is more likely to reach the most nearby neighbor routers, and thus travels perpendicularly or horizontally along the lines shown in Fig 4 (These lines indicate hallways on the floor.).

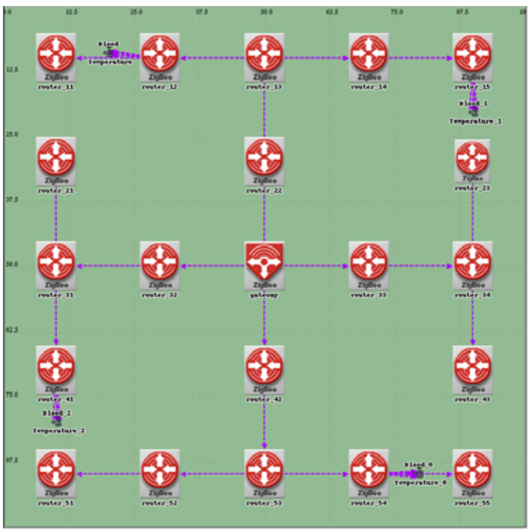


Fig. 4. Deployment in a hospital environment with four WBASNs

Table 1. Simulation Parameters

Parameter	Value
Simulation Area	100 m x 100 m
Number of Coordinator	1
Number of Router	20
Tx. Power (coordinator/router)	1 mW (< 25m)
Tx. Power (end device)	0.05 mW (< 20m)
Maximum Routers per Device	8
Maximum Children per Device	30
Maximum Network Depth	5
Simulation Time	10 minutes

Table 2. Application Parameters

Application	Data Rate
Control	200 bits/0.5 s
Respiration	200 bits/0.5 s
Blood Analysis	400 bits/1 s
Temperature	200 bits/1 s
ExG (ECG/EEG)*	800 bits/0.2 s

* ExG refers to either ECG or EEG sensor nodes in the WBASN.

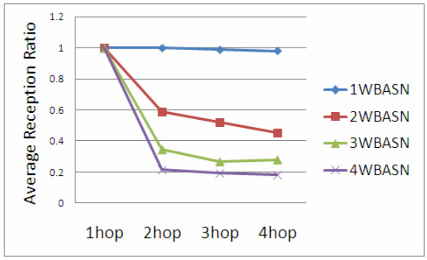
In order to simulate a WBASN, each five end devices are grouped together at one location. They represent sensor nodes, supposedly worn by one person. There are propagation models for in/on-body transmission, which are different from general indoor/outdoor models. We consider no such model in this paper, which should be addressed in future work. Details of simulation parameters are listed in Table 1. Table 2 lists simulated applications for sensor nodes and corresponding data rates. As ExG sensors generate relatively larger data rate, we evaluate in the following simulations by including and excluding these sensor nodes respectively, to see their effects.

4.2 Average Reception Ratio and Throughput

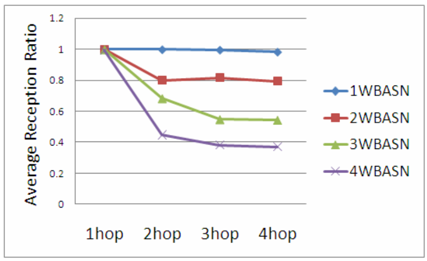
Firstly, we evaluate average reception ratio and throughput of the whole network. For all scenarios, we position each WBASN along one certain route to the gateway, as indicated by the line in Fig. 4. For each scenario, all WBASNs are positioned with equal distance to gateway, with the intent to set the same number of hops for them. Devices are not mobile in these cases. Fig. 4 gives an example of deploying four WBASNs with four hops away from the gateway. We do observe during simulations that the network structure changes, i.e., end devices in one WBASN occasionally join two different routers. This complies with our analysis in Section 3, and results in different hop counts for sensor nodes in WBASNs. Simulation results are shown in Fig. 5 and Fig. 6.

Fig. 5 depicts the average reception ratio for both including and excluding ExG sensor nodes. Fig. 5 (a) and (b) both exhibit a trend of getting smaller average reception ratio when there are more WBASNs in the system. This is as expected since more WBASNs, meaning more sensor nodes, are competing for the limited bandwidth. Average reception ratio shows its largest value, i.e., nearly 100%, when WBASNs are directly connected to gateway and tends to be stable when WBASNs are distanced further away. As in multi-hop cases, routers have to compete with upstream and downstream peers, resulting in collisions and packet drops; on the other hand, more hops in middle does not have critical effect as throughput reaches the network bandwidth and every WBASN has steady data rate. Comparing (a) and (b) in Fig. 5, it is clear to see in the figure that high data rate sensors (ExG sensors) lead to the performance degradation when there is more than one WBASN competing for the bandwidth. About 20% to 40% more packets are dropped when ExG sensor is equipped with each WBASN.

Complementing the average reception ratio, Fig. 6 depicts the throughput for above two WBASN setups. When WBASNs are directly connected to the gateway, like a star network, almost all packets have reached the destination, exhibiting a throughput

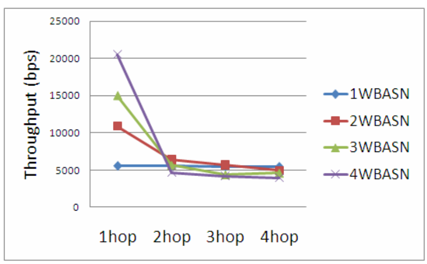


(a) average reception ratio for WBASNs with ExG sensors

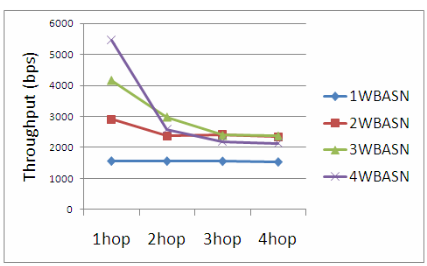


(b) average reception ratio for WBASNs without ExG sensors

Fig. 5. Average reception ratio for WBASN-WPAN



(a) throughput for WBASNs with ExG sensors



(b) throughput for WBASNs without ExG sensors

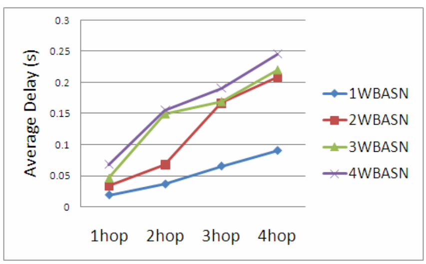
Fig. 6. Throughput for WBASN-WPAN

up to over 20 Kbps. However, when one more hop is introduced into gateway and WBASNs, network throughput degrades to 5 Kbps and 1.5 to 3 Kbps in Fig. 6 (a) and (b) respectively. The throughput of both tends to be stable. These observations comply with those in Fig. 5. For multi-hop scenarios, we note there is only a minor difference in throughput when different numbers of WBASN are in connection. This is likely due to the limitation of throughput for the last hop of routes, i.e., the routers close to gateway, because they experience more severe competition in bandwidth.

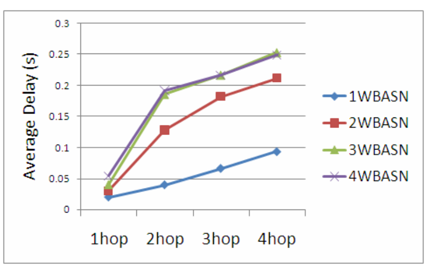
4.3 Latency

We examine in this subsection how the ZigBee network performs in terms of average delay. Simulation results are shown in Fig. 7.

We note the results show a varying of average delay from 0.02 to 0.25 second. This is promising as such a delay is acceptable to most WBASN applications. It is obvious in both Fig. 7 (a) and (b) that larger number of hops results in longer delay. This is as expected due to the time taken for each router. More WBASNs in connection in the system generally exhibit larger average delay but the difference is only prominent between scenarios with one WBASN and multiple WBASNs. Also, when comparing Fig. 7 (a) and (b), we note there is little difference for the same WBASN and multi-hop setup. These are due to the disconnections of WBASNs and consequently the drops of packets. More WBASNs with higher data rates normally result in more packet drops. This leads to frequent disconnection of WBASNs to the network, which causes more packet drops. These dropped packets, spends much less time on route compared to those delivered packets, contribute to smaller averaged delay.



(a) delay for WBASNs with ExG sensors



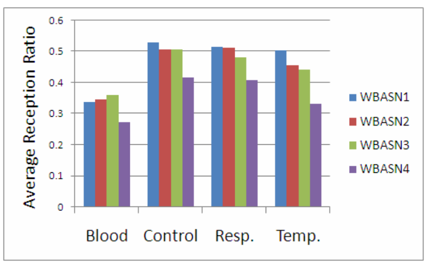
(b) delay for WBASNs without ExG sensors

Fig. 7. Delay for WBASN-WPAN

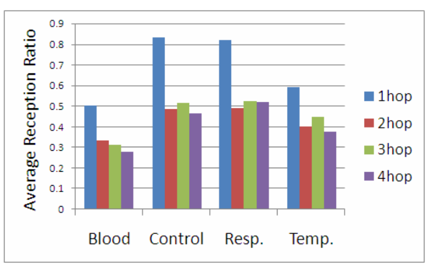
4.4 Fairness

After investigating the overall system performance, in this subsection, we evaluate the fairness across the network. Without any QoS protocols implemented in the ZigBee network, it is important to see whether there is any biasness for certain sensor nodes in one WBASN or for certain WBASNs in a system. Specifically, we compare the average reception ratio and throughput of each sensor node for certain network setup. Two scenarios are studied, and both have four WBASNs in the network. One has all WBASNs positioned two hops from the gateway; the other one sets four WBASNs at different distances away, i.e., one to four hops respectively, from the gateway. In order to better evaluate the fairness under a situation where the whole network performs relatively well, ExG sensors are not included in these simulations (otherwise, in the case of a four-WBASN two-hop deployment, overall network reception ratio is near 20% as shown in Fig. 5 (a)). Fig. 8 and Fig. 9 illustrate the results.

We observe in Fig. 8 (a) and Fig. 9 (a), that the same kinds of sensors from different WBASNs perform comparable to each other when all WBASNs are positioned same distance away from gateway. Control, respiration and temperature sensors show similar average reception ratio (temperature sensors have slightly smaller average reception ratio), which is larger than that of blood sensors. This is explained by the longer application data payload blood sensors have, which leads to more collisions and thus packet loss. While having almost the same average reception ratio, temperature sensors are noted to have halved throughput, which can be obviously traced back to the halved application data rate generated.

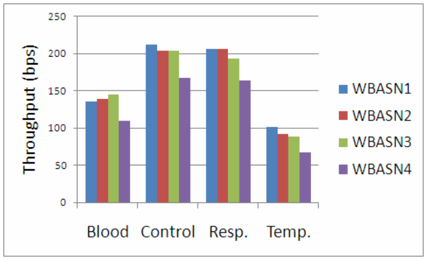


(a) average reception ratio for sensors of WBASNs positioned two hops away

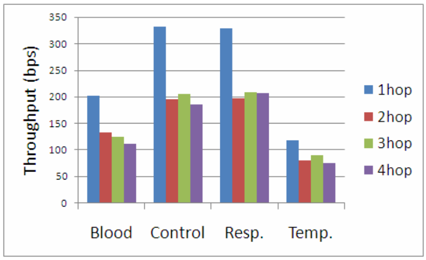


(b) average reception ratio for sensors of WBASNs positioned varying number of hops away

Fig. 8. Average reception ratio for sensors of WBASNs



(a) throughput for sensors of WBASNs positioned two hops away



(b) throughput for sensors of WBASNs positioned varying number of hops away

Fig. 9. Throughput for sensors of WBASNs

Compared to Fig. 8 (b) and Fig. 9 (b), it is clear that all sensors from one-hop WBASN exhibit better performance in average reception ratio (20% to 30% more) and throughput (30 to 150 bps more). The kind of sensors from different WBASNs with varying number of hops away (two to four hops) exhibit same performance as in the other scenario. Except for the one-hop WBASN, other observations in the other scenario explained above also apply.

To conclude, one-hop WBASN has prominent privilege over multi-hop WBASNs. Application data length plays an important role in determining average reception ratio, and application data rate is crucial in determining throughput. Generally, there is no QoS guarantee for sensors or WBASNs during random deployment.

4.5 Mobility

Following, simulations have been conducted to evaluate the mobility support of ZigBee protocols for WBASN. Preliminary results are shown. One WBASN is set to travel along the periphery of our router deployment. Specifically, it moves along the four sides of the square area as shown in Fig. 4. Starting from the upper left angle, it moves at a speed r m/s and stops at each angle for t seconds, until it gets back to the start point. Fig. 10 shows an example of the bits received verses time when r = 1 m/s and t = 60 seconds.

It is observed in Fig. 10 that a number of packets are lost due to the mobility of WBASN. Large ripples are shown in the figure for the periods when WBASN is moving, indicating the disconnection and re-joining activities of the WBASN to the network. We also note that between two relatively stable periods (indicating the rests at angles),

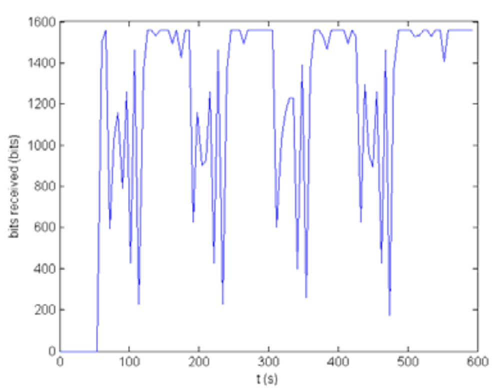


Fig. 10. An example of the bits received verses time when r = 1 m/s and t = 60 seconds

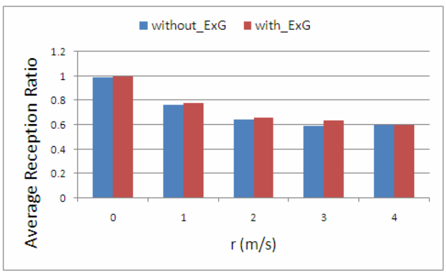


Fig. 11. Average Reception Ratio with varying travelling speeds

there are two to three times of re-joining process happening, as expected. This is because there are three routers deployed in middle of two routers at the angles, and the communication range of the sensor nodes is limited to less than 20 meters.

In Fig. 11, average reception ratios with varying travelling speeds r (t = 10 seconds) are shown for comparison. Both WBASNs, with and without ExG sensors, exhibit similar performance in terms of average reception ratio. With increasing speeds, both WBASNs exhibit larger packet loss, and the average reception ratio tends to be stable at 60%. As even with ExG sensor, a four-hop WBASN's data stream is within the bandwidth, therefore we see comparable performance when a single WBASN, with or without ExG sensor, is moving. This result shows the contribution of up to 40% to the lessened average reception ratio, under a perfect environment, where there is no other collision. It is even worse when we consider the successfully received data are during periods when the WBASN is resting at angles. This shall motivate further research for faster handover mechanisms between routers for WBASNs in a ZigBee network.

5 Conclusion

As defined, WBASNs are used for connecting wearable or implantable sensor devices, while WPANs can be employed to connect peer devices, peripherals and remote controllers in proximity. This differentiation is general; it also largely depends on the application and underlying technology. With the advances of very large scale integration (VLSI), dual and multiple-standard radios can be intergraded into a single chip. This greatly brings down the cost and power consumption, and at the same time, fosters combination as well as merging of technologies. In this paper, we have listed the characteristics of WBASN-WPAN and compared WBASN-WPAN system to a general WSN, as the ground for this paper. We have extensively evaluated the performance of ZigBee technology for WBASN-WPAN system by analysis and computer simulations. Average reception ratio, throughput and latency have been evaluated for the overall system performance; fairness across sensor nodes has been examined; preliminary results regarding mobility support of ZigBee for WBASN have also been shown. We come to the conclusion that ZigBee network supports rather limited throughput with acceptable latency for many WBASN applications. QoS will be a concern when many WBASNs are in the system with different distance to the gateway. Also, mobility support in ZigBee network needs to be improved. All these results indicate that optimizations should be done before applying ZigBee to such a system.

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