Performance Study on ZigBee-Based Wireless Personal Area Networks for Real-Time Health Monitoring

Bernard Kai-Ping Koh and Peng-Yong Kong

ABSTRACT—When multiple ZigBee wireless personal area networks (WPANs) are in close proximity to each other, contentions and collisions in transmissions will lead to increased packet delays. However, there is no existing study on how delay performance would be affected in a crowded real-life environment where each person walking down a busy street would be wearing a ZigBee WPAN. This letter studies the use of ZigBee WPANs in such a real-life environment for real-time heart beat monitoring. To be pragmatic, we derived a mobility pattern from the analysis of a real-life video trace. Then, we estimated the delay performance from the video trace by combining data collected from ZigBee experiments. The results show that the 300 ms packet delay requirement will not be met for only 11% of the time. When failure occurs, it will last for an average duration of 1.4 s.

Keywords—WPAN, health monitor, ZigBee.

I. Introduction

With rapid improvements in medical research, more and more health sensors have been developed to assist medical doctors in monitoring their patients' conditions. These sensors have been getting smaller, making it possible for the sensors to be worn or to be implanted into the human body [1]. Hence, there may come a day when governments require every citizen to wear a sensor to track their condition for proactive healthcare. The sensors worn by individuals can be interconnected through a network for efficient multi-modal monitoring. In the literature, wireless personal area networks (WPAN), such as Bluetooth and ZigBee, have been proposed for connecting the various health sensors [2].

A WPAN is required to deliver sensor data regularly so that changes can be detected promptly. The level of regularity and promptness required depends on the types of health conditions being monitored. This letter specifically concerns heart beat monitoring. Heart attack has become the number one killer in the United States. However, if help is given within 10 minutes of an attack occurring, there is a chance that heart attack will not cause death.

We envisage a system that is integrated with a heart beat monitor. In the event of a heart attack, the system will alert a remote monitoring station to dispatch help or simply sound an alarm to alert people nearby that immediate medical attention is needed.

In detecting a heart attack, one of the early symptoms is irregular heart beat. A heart beat monitor has to take readings of the systole and the diastole which occur every 0.30 and 0.55 seconds, respectively [3] in order to determine a heart beat pattern. As such, for real-time heart beat monitoring, a WPAN needs to ensure a 300 ms packet delay so that a systole reading can be captured before the next one is generated. Packets with excessive delay may be dropped or lost, and thus lead to inaccurate monitoring. However, as far as we know, there is no existing study on the feasibility of using a WPAN in such an environment.

In this letter, we study the use of ZigBee WPANs [4] for real-time heart beat monitoring. To make this study relevant for practical application, we consider the performance of a WPAN system in which each individual wears a WPAN while walking

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down a busy street. In such an environment, individual WPANs may frequently collide and interfere with one another, resulting in performance degradation.

II. Setup and Environment

The major challenge of this study is to find a way to estimate the WPAN performance in the target environment while, in practice nobody today wears health sensors in daily life. Our approach was to first determine the mobility pattern in a real-life environment by analyzing some video traces captured on a busy street. This analysis provided an estimate of the number of people around the subject and the distances between them. Next, we carried out experiments to estimate how the packet delay of a ZigBee node is affected by the number of interfering (that is, disruptive) nodes and their distances. Finally, we combined the experimental results with the video traces to determine the packet delay performance of a subject WPAN for each video frame. Given the packet delay performance at each video frame, the ability of ZigBee to meet the packet delay requirement could then be determined.

1. Mobility Pattern

To find the number of people around a subject and the distance between them, one idea is for the subject to wear a distance finder that has the ability to take distance readings of every nearby person around the subject at high accuracy and frequency. However, currently available infra-red distance finders can only take one distance measurement at a time and the time taken to record the reading greatly exceeds the 300 ms packet delay requirement. This is not desirable as it may result in an inaccurate estimation of the packet delay for each reading.

Our approach comprised taking video footage from directly above the subject in a real-life environment and rendering the video traces at 30 frames per second. By analyzing each of the video frames, distances between other people and the subject could be estimated. One drawback of this method is that the interval between two consecutive frames is about 33 ms which is the smallest time scale we can achieve in estimating changes in time. The other drawback is that the maximum measurable distance in each video frame is limited by the view angle of video camera. Fortunately, it was found later in our ZigBee experiments that nodes transmitting at a distances larger than 5.0 m from the subject had little effect on their packet delay performance.

We installed a video camera as illustrated in Fig. 1 alongside a busy street. At the installation, there was a wall behind the video camera and thus, the camera could only view people on one side of the wall. However, this was the best location we

Fig. 1. Video camera setup and installation.

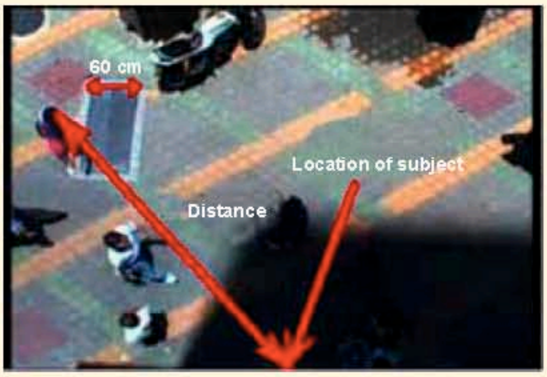

Fig. 2. One sample video frame.

could find as it enabled the camera to be suspended directly above the subject without any obstruction in a crowded area and covering a video range of up to 5.5 m.

Video footage was captured during lunchtime when there were many people walking around. The captured video was converted into MPEG-4 format using InterVideo WinDVD Creator™ software. The MPEG-4 video was then loaded into Adobe After Effect™ so that the video frames could be analyzed one-by-one. The process of measuring distances from the subject to its surrounding people was done manually because there is no software that will automatically detect people in the video and calculate the distance. For the purpose of accurate measurement, we used the metal drain cover (see Fig. 2) in the video frame as a reference to determine the scale.

Each video frame yielded data about the number of people a certain distance away from the subject where the distance is rounded to the nearest 0.5 m. The video traces may be requested from the authors.

2. ZigBee Experiments

We used MPR2400 MICAz motes from Crossbow Technology Inc. [5], which follow the ZigBee standard at 2.4 GHz. The experiment setup is depicted in Fig. 3. It simulates the scenario in which the subject WPAN meets its surrounding WPANs and the heart beat monitor in each WPAN transmits to its own central node. The subject WPAN is represented by the sender and receiver nodes while each of the surrounding WPANs is represented by one disruptive node.

The sender was placed 1.74 m away from the receiver. The distance chosen is the average height of a human being and the distance was intended to simulate the scenario in which the transmitting node would be at the head and the central node would be at the feet of the subject. This scenario has the largest possible propagation of delay, which translates into the largest possible period in which a transmitted packet can be affected by interference. Disruptive nodes were placed at different distances from the central (that is, receiver) node, and the delays were recorded for all possible combinations of distances and numbers of disruptive nodes.

The distance between the receiver and a disruptive node is an experiment variable. The average social distance for interaction within arms length is about 0.5 m and people tend to keep a distance greater than 3 m when walking if there is no space constraint. Therefore, 0.5 m was used as the step size for the distance variable. The maximum distance was 5.0 m because we found that performance of the subject WPAN was no longer affected by the disruptive nodes beyond this distance. Due to lack of equipment, only five disruptive nodes were used in this study.

In the experiments, packet delay was calculated as the difference between the time when a packet arrived at the sender and the time when it was received at the receiver. A new packet is generated at the sender only when the current packet has been transmitted successfully or dropped after retransmitting 10 times. A successful transmission is indicated by an acknowledgment packet from the receiver. A packet will be retransmitted if an acknowledgment is not received after a timeout period of 900 ms from the packet transmission time.

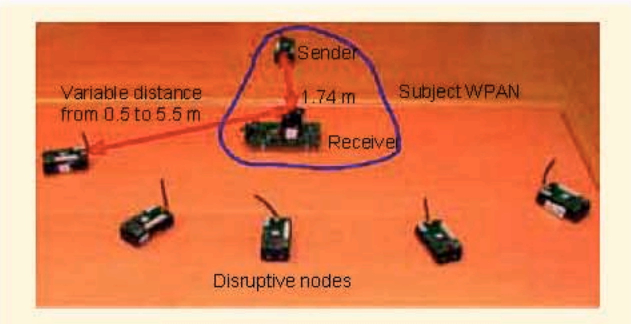

Fig. 3. Experiment setup for ZigBee WPAN.

III. Results and Analysis

Figure 4 shows how the average packet delays were affected by the number of disruptive nodes and their distances. From the figure, the average packet delay converges to 9.26 ms after distance from the subject grows to 5.0 m regardless of the number of disruptive nodes. The largest delay occurs when the distance between the disruptive nodes and the receiver is small and it increases non-linearly with the number of disruptive nodes. When there are less than 3 disruptive nodes, the delay is almost not affected by them at any distance. This is an important finding as it means, in practice, the WPAN performance will not be affected if there are only 1 or 2 persons around each individual.

Although we had only 5 disruptive nodes, there could easily be more than 10 persons surrounding the subject. Hence, we used the DatafitTM software to extrapolate the existing data to produce the best-fit average packet delays when there would be more than 5 disruptive nodes. The extrapolation results imply only an empirical suggestion before being verified through experiments because the effect of multiuser interference on network performance may not be simply extrapolated.

A limitation in these experiment results is that all of the disruptive nodes were at a same distance from the subject WPAN. In practice, any number of people may be around a subject WPAN, each at a different distance. For this case, we

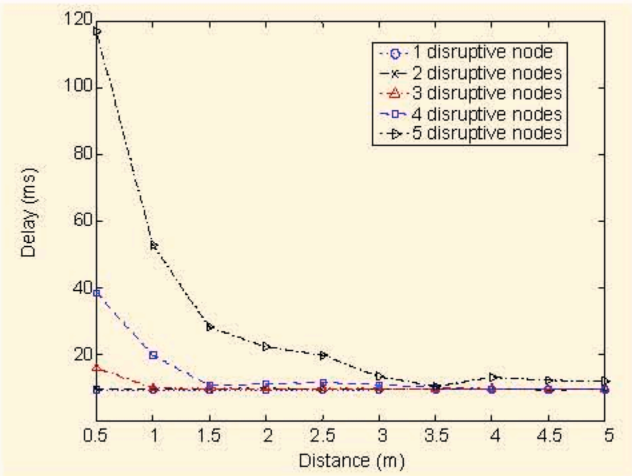

Fig. 4. Average packet delay for different numbers of disruptive nodes at different distances.

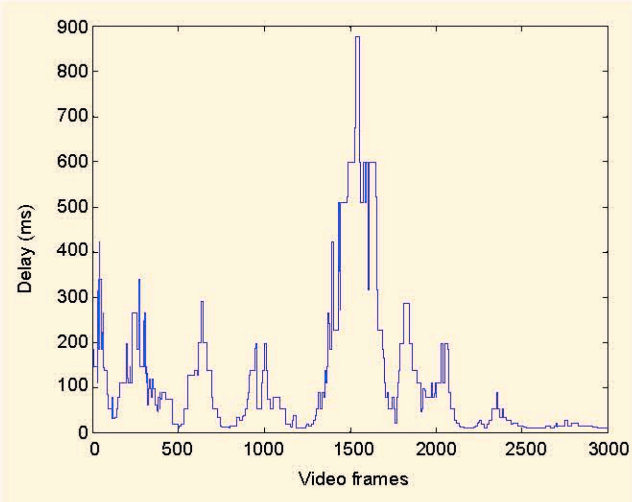

Fig. 5. Average packet delay for 3000 video frames.

Table 1. Packet delay statistics for a subject WPAN

Threshold	Duration above threshold			Prob. of delay exceeds threshold
	Min.	Max.	Avg.	
60 ms	100.7 ms	1.30 s	3.16 s	0.47
130 ms	33.3 ms	1.11 s	1.81 s	0.27
200 ms	100.0 ms	1.01 s	1.27 s	0.15
300 ms	100.0 ms	7.53 s	1.44 s	0.11
340 ms	100.0 ms	5.27 s	1.12 s	0.08

have made the following experiment observations: 1) when there are 3 or more disruptive nodes at a distance, their effect dominates that of a group of 2 or less disruptive nodes, and 2) when there are no more than 2 disruptive nodes grouped at any distance, their aggregate effect is similar to that of all nodes at the average distance of all of the disruptive nodes. Based on our observations, we have calculated the average packet delay for each captured video frame. The calculated delays for 3000 frames are shown in Fig. 5. In the figure, each data point is average packet delay computed for a video frame.

The peaks and valleys in the delay correspond respectively to the scenes of more and fewer people coming close to the subject WPAN. The average packet delay is 114.18 ms, and it is below the 300 ms requirement. However, as shown in Table 1, the probability of the delay being above the 300 ms threshold is about 0.11; and the average duration for delay to exceed and stay above the threshold is about 1.4 s.

IV. Conclusions

In this letter, the authors study the use of ZigBee WPANs for real-time heart beat monitoring to detect heart attacks. In a real-life environment in which every person walking down a busy street is wearing a WPAN, the average packet delay of ZigBee is below the 300 ms requirement. The probability of a packet delay exceeding the 300 ms requirement is about 0.11, and when it occurs the packet delay will stay above the threshold for an average duration of 1.4 s. Thus, ZigBee WPAN may not be a feasible solution for future wearable WPANs for real-time heart beat monitoring, as a network service disruption exceeding 1.4 s is not acceptable. However, as a future work, it would still be useful to study how measurement aggregation, data redundancy and transmission diversity could help improve the WPAN's performance, robustness, and scalability.

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