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Performance Analysis of Priority Queuing Model for Low Power Wireless Body Area Networks (WBANs)

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Abstract

Wireless Body Area Network (WBAN) has been an active area of research over the past few years due to its tremendous benefits particularly related to healthcare systems. Through WBAN, the physicians can get real time updates for a long period of time in an inexpensive way about their patients who are suffering from different kinds of chronic diseases such as diabetes, asthma and myocardial infarction etc. A number of issues need to be addressed in the area of WBAN. There is a very strong need to develop scalable and low power MAC protocols. Further, novel and sophisticated queuing models are also needed to develop in order to provide guaranteed QoS to different classes of traffic generating from different types of events in WBAN.

This paper focuses to analyze a three queues priority model for low power WBAN, which enables to provide guaranteed QoS to different types of traffic generated from different events. We extract closed form expressions of various QoS parameters such as queue length, queuing delay, throughput and packet loss rate. We also simulate the behaviour of traffic in WBAN to further evaluate the proposed analytical framework.

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Keywords: QoS ; PQ; Queuing model; WBAN;

1. Introduction

Since 1900, the cardiovascular disease is the famous reason of death in most countries. More than nine million in Europe and two million persons in US are having some sort of heart problem. In 2020 the number is expected to be triple than now. The healthcare cost increased in US from \$3 trillion to \$5

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trillion in the period between 2009 and 2010 [1]. This growing cost has introduced new difficulties and challenges for healthcare industry and governments. For supporting remote patient monitoring, the researchers have introduced some new technologies which are based on small and low-cost battery operated sensing devices. In addition to support remote monitoring, these devices also provide personalized services to patients. This area is known as Wireless Body Area Network (WBAN), which is a specialized type of Wireless Sensor Networks (WSNs). A WBAN consists of removable sensors that monitor the body activities for emergency applications. The main demand for WBAN is power efficiency (low power consumption). The wireless communication in Body Area Network (BAN) is power consuming to a large extent. The dimensions and weight of the battery responsible for storing the energy is the most important issue for the sensor device. Over the past few years, the development of a low-power WBAN that may achieve reliable and fast information delivery has been an interesting hot research topic. Data collecting in WBAN in a timely fashion has got a lot of attraction from the researchers and health care industry particularly related to different critical health applications. The traffic generated in case of emergency situation has established more challenges in this area. It is utmost important to consider the time constraints for critical applications in WBAN. However, the area of providing guaranteed Quality of Services (QoS) to delay sensitive applications in WBAN is quiet new and currently the research related to performance modeling of WBANs has not been established yet. In this paper, we aim to develop novel analytical framework for WBAN to achieve timely and reliable communication.

2. Background of Wireless Body Area Network (WBAN) and Related Work

A Body Area Networks (BANs) is composed of small network nodes, each of them qualified to sense physiological signals or physical activity. They can sense for one or more of the following: heart rate, body temperature, blood glucose, blood oxygen saturation and level body posture etc. If nodes are able to communicate with each other wirelessly, the system is called as Wireless Body Area Network (WBAN) [3]. Since WBAN provide continuous monitoring for the patients, so there is no need for them to stay in bed permanently, rather they can live normally like other people. In WBAN several sensors are inserted to measure the temperature, heart rate, blood pressure, Electrocardiography (ECG), Electroencephalography (EEG), etc. The sensing devices are either wearable or implanted. The wearable devices can be placed on the skin, or at a very close proximity to the user [4]. The implantable medical devices or (in-body) are integrated inside human body. Both of the two types of sensor devices sense different information from the human body and then send it wirelessly to a control device which is placed on the body or at a near location [5, 6]. Protocols in WBANs are depending on the communication type. The first type is between the sensors devices on the body and the second type is communication to a data centre being connected to the Internet. To make it simpler, two modes of communication such as intra-body communication and extra-body communication have been proposed. The intra-body communication controls the information handling between the sensors or actuators and the sink; whereas, the extra-body communication ensures the communication between the sink and an external network" [2]. There are many applications for WBANs in different fields (e.g. remote medical examination, Lifestyle and Sports). The most common examples of In-body applications are monitoring changes for pacemakers, implantable cardiac defibrillators, restoration of limb movement, and control of bladder function etc. On the other hand, the most popular applications for On-body applications are monitoring blood pressure, heart rate, respiration and temperature etc. On-body non-medical applications are monitoring missing person or things and assessing military soldier. Wireless Sensor Networks have huge number of applications in real world. Timely and reliable data delivery in wireless sensor networks has introduced new challenges to meet real-time requirements of different applications. Some work has been conducted for reliable data delivery in WSNs [15-17]. Unfortunately, these researches are not supporting different classes of traffic that have many variable time constraints. Along with this, queuing at MAC layer in Wireless Sensor Networks has been a hot research topic and widely studied in recent years. In [18], the authors proposed techniques for energy efficient Weighted Fair Queuing (WFQ) in wireless communication systems for fair packet scheduling. Some people proposed an analytic model for evaluating the MAC layer queuing delays in wireless nodes [19, 20]. To analyze the performance of wireless ad-hoc networks they have used G/G/1 queuing system. Unfortunately, the available results in this area are not able to provide guaranteed QoS in WBAN. The first reason is that; the results are just approximations. Secondly, the considered traffic assumptions are unrealistic. The authors in [21] present an energy-aware QoS routing protocol for WSN. They support in their proposed work two types of traffic. Each of the two different types of traffic can access to bandwidth from each other. Based on the cost function defined for each link, the protocol return real-time data with least cost and delay path. Here, we would also like to introduce the formal definition of Network Calculus which is "a theory of calculus for deterministic queuing systems that allows assignment of service guarantees by traffic regulations and deterministic scheduling" [22]. The current results of network calculus are not fully explored for wireless sensor networks. At the moment, it is limited for wired networks because it is based on fixed link capacity and static topologies. In our earlier effort [12, 13], we proposed an analytical framework based on M/G/1 queuing system to provide guaranteed QoS in wireless sensor networks. But we have used Poisson distribution to analyze the behaviour traffic in WSNs [12, 13]. Poisson distribution is unable to capture the real phenomenon of bursty traffic. Hence, we presented a novel framework [14] based on G/M/1 queueing system for multimedia sensor networks. But in [14] we were only able to extract the analytical results. In the current paper, we extend our prior effort and analyze three queues priority model based on G/M/1 queuing system with multiple classes of traffic of WBAN being generated from different events. The traffic in WBAN is either event driven or application driven. In both cases, it generates bursty traffic. Hence it is necessary to consider the bursty nature of traffic while modeling the behaviour of different applications of WBAN. To the best of our knowledge, here for the very first time, we present QoS parameters such as queue length and throughput for G/M/1 queuing system with multiple classes of bursty (self-similar) traffic input in WBAN. We also simulate the behaviour of corresponding traffic classes to validate the analytical framework. We would like to refer the readers to [7-11] to get the basic understanding of queuing, scheduling and queuing networks.

3. Analytical Framework

Here, we describe the analytical framework being developed for low power body area networks. We consider a traffic model that is able to capture the bursty nature of self-similar traffic [26]. We feed multiple classes of self-similar traffic into G/M/1 queuing system to develop the analytical framework. We build the Markov chain and extract closed form expressions for various QoS parameters such as delay, PLR, queue length and bandwidth. We make some assumptions for the sensor node of WBAN. We assume that there are three kinds of traffic coming to the sensor node, the first one is the critical traffic (having the highest priority), second one is streaming traffic (having second highest priority) and the third one is non-critical traffic (having lowest priority). A model of three queues based on G/M/1 has been considered. Since there is three type of traffic so we assume the service time distribution for these three types have rate μ_1, μ_2 and μ_3 respectively.

3.1. SS/M/1 with three classes: non-preemptive priority service

For this priority model, we build the Markov chain of G/M/1. To build the Markov chain, we observe the system at the time of arrival instants, right before an arrival [23]. The total number of packets in the system at the arrival instants is the packets in queue plus the packet in service if any. The main point to consider is that; we need to exclude the newly arriving packet to build the Markov chain. At the arrival instants, we denote the Markov chain by $\{X_n : n \geq 0\}$. To obtain the queuing time for any newly arrived packet, it is important to consider the type of packet in service because the scheduler of the sensor node is serving three queues in a priority fashion. We define the state space as follows:

$$S = \{(i_1, i_2, i_3, a, s) : a \in \{a_1, a_2, a_3\},$$
$$s \in \{s_1, s_2, s_3, I\}, i_1, i_2, i_3 \in Z_+\}$$

As shown above in the state space, we have used a_1, a_2 and a_3 to denote the type of arriving packet. Also s_1, s_2 and s_3 are being used to represent the type of packet in service, whereas; the number of packets in each queue plus a possible packet in service if any are being represented by i_1, i_2 and i_3 for queue 1, 2 and 3 respectively. *I* is the symbol that has been used to show that there is no packet in service or in queue and system is idle. The Markov chain can be build by considering all transition probabilities from one state to another. Also, it is important to note, that we consider idle cases (at least one empty queue) separately from non-idle cases (i.e. non-empty queues).

States (i_1, i_2, i_3, a, s) with $i_1, i_2, i_3 \neq 0$ and $s \neq I$:

The transitions would be distributed to 81 different groups, the reason behind it is the possibility for (a, s) and (p, q) to happen in 3x3=9 different ways, as $a, p \in \{a_1, a_2, a_3\}$ and $s, q \in \{s_1, s_2, s_3\}$. Here we will describe only one state in detail; the others follow the same style.

Transition from $(i_1, i_2, i_3, a_1, s_1) \rightarrow (j_1, j_2, j_3, a_2, s_2)$

In this transition, in the initial state, an arrival of type 1 comes and finds i_1, i_2 and i_3 packets in the system of type 1, type 2, and type 3 respectively. In the next state, a new arrival of type 2 comes and finds j_1, j_2 and j_3 packets in the system of type 1, type 2, and type 3 respectively. It also finds that upon its arrival, a type 2 packet is in service. Based on the priority logic, a new arrival of type 2 packet can find a type 2 packet in service only, when all type 1 packets including the packet that arrived in the previous state have been served. Hence, there is no other possible value for j_1 except 0. Also the numbers of packets that have been served from queue 1 are exactly $i_1 + 1$. On the contrary, we can say that number of packets which are served from queue 2 is *k*, which may have value between 0 and $i_2 - 1$. Because, when the new class 2 packet arrives, there is at least one type 2 packet in the system, the one being in service to fulfil this transition. We can write this transition probability as follow:

$$P\{X_{n+1} = (0, i_2 - k, i_3, a_2, s_2) \mid X_n = (i_1, i_2, i_3, a_1, s_1)\} = \int_0^{\infty} \int_0^{t} \int_{t-x}^{\infty} f_{S_2}(s)\, f_{S_1^{i_1+1} + S_2^{k}}(x)\, f_{T_{12}}(t)\, ds dx dt$$

By following the same style, we can write all possible transitions.

3.2. Limiting Distributions and QoS Parameters

By solving $\pi P = \pi$ we can calculate the steady state distribution π, where P represents the transition matrix of the Markov chain as mentioned earlier. It is a known fact that the queue size in a sensor node is limited, hence Markov chain is finite and we can easily solve the steady state distribution. Our analysis is relying on arrival instances but it is also valid and logical for any G/M/1 queueing model, where the limiting distribution π at the arrival instances can be computed. First of all, we write down the queue length for three queues priority model. To the best of our knowledge, we have been the first to present the queue length results for G/M/1 queueing model in this paper for three queues priority model. In our earlier work on G/M/1 queueing system, we have just produced the results of waiting time and packet loss rate [25]. Queue length for class 1 packet will be simply the number of packets waiting in the system that must depart before this newly arrived type 1 packet. It can be written as follow:

$$E[QL_1] = \sum_{j_1=1}^{J_1-1}\sum_{j_2=0}^{J_2}\sum_{j_3=0}^{J_3} j_1\pi(j_1, j_2, j_3, a_1, s_1) +$$
$$\sum_{j_1=0}^{J_1-1}\sum_{j_2=1}^{J_2}\sum_{j_3=0}^{J_3} (j_1+1)\pi(j_1, j_2, j_3, a_1, s_2) +$$
$$\sum_{j_1=0}^{J_1-1}\sum_{j_2=0}^{J_2}\sum_{j_3=1}^{J_3} (j_1+1)\pi(j_1, j_2, j_3, a_1, s_3)$$

It clearly shows that the there are three possibilities when a new class 1 packet arrives.

When a new class 1 packet arrives and finds a class 1 packet in service then it's queue length is simply equal to the total number of class 1 packets waiting ahead of it in queue 1.When a class 1 packet comes and it finds a class 2 packet in service, then its queue length is equal to the number of packets (j1) waiting in queue 1 plus a type 2 packet, which is in service. When a class 1 packet comes and it finds a class 3 packet in service, then it's queue length is equal to the number of packets (j1) waiting in queue 1 plus a type 3 packet, which is in service.

Similarly, we can directly write down the queue length for class 2 and class 3 packets as follows:

$$E[QL_2] = \sum_{j_1=1}^{J_1}\sum_{j_2=0}^{J_2-1}\sum_{j_3=0}^{J_3} (j_1 + j_2)\pi(j_1, j_2, j_3, a_2, s_1) +$$
$$\sum_{j_1=0}^{J_1}\sum_{j_2=1}^{J_2-1}\sum_{j_3=0}^{J_3} (j_1 + j_2)\pi(j_1, j_2, j_3, a_2, s_2) +$$
$$\sum_{j_1=0}^{J_1}\sum_{j_2=0}^{J_2-1}\sum_{j_3=1}^{J_3} (j_1 + j_2 + 1)\pi(j_1, j_2, j_3, a_2, s_3) + j_1 E[QL_2]$$

Where the last term in the above equation $j_1 E[QL_2]$ indicates that number of class 1 packets that arrive during the waiting time of newly arrived class 2 packet and because of high priority, those class 1 packets will depart before this newly arrived class 2 packet.

$$E[QL_3] = \sum_{j_1=1}^{J_1}\sum_{j_2=0}^{J_2}\sum_{j_3=0}^{J_3-1} (j_1 + j_2 + j_3)\pi(j_1, j_2, j_3, a_3, s_1) +$$
$$\sum_{j_1=0}^{J_1}\sum_{j_2=1}^{J_2}\sum_{j_3=0}^{J_3-1} (j_1 + j_2 + j_3)\pi(j_1, j_2, j_3, a_3, s_2) +$$
$$\sum_{j_1=0}^{J_1}\sum_{j_2=0}^{J_2}\sum_{j_3=1}^{J_3-1} (j_1 + j_2 + j_3)\pi(j_1, j_2, j_3, a_3, s_3) + (j_1 + j_2)E[QL_3]$$

Another QoS parameter that can be readily available is the bandwidth (throughput). The average throughput that a packet will experience is equal to the length of packet divided by the mean delay. So the expected bandwidth for a class 1 packet will be:

$$E[BW_1] = \frac{L}{E[D_1]}$$

Where $E[D_1]$ is the expected total delay across a sensor node. The total delay is equal to processing plus queueing plus transmission delay. The processing delay and transmission delay are fixed; whereas queueing delay is the only type of delay which is variable. We have already reported the three queues priority model results (queuing delay and packet loss rate) for G/M/1 system in [25]. For details, the readers are referred to [25].

4. Simulation Results

In order to evaluate the analytical framework, we have developed a discrete-event simulator. We implement the Priority Scheduler to analyze the behaviour of three different kinds of traffic. Also, a traffic generator is implemented. For simulations, we used the same template design as given in [24]. We use the traffic model [26] which is able to capture the real behaviour of traffic in WBAN. The traffic model generates packets for all the three queues (i.e., Q1, Q2 and Q3). The session arrival rate for the class 1 traffic in Q1 (i.e., highest priority class) is set to $\lambda_1 = 6s^{-1}$, the in-session packet arrival rate to $\alpha_1 = 50s^{-1}$ and service rate to $\mu_1 = 5000s^{-1}$. For symmetry between all the three queues, we consider the session arrival rate for Q2 and Q3 (i.e. low priority queues) as $\lambda_2 = \lambda_3 = 50s^{-1}$, the in-session packet arrival rate as $\alpha_2 = \alpha_3 = 6s^{-1}$ and the service rate as $\mu_2 = \mu_3 = \mu_1$. The total traffic load for the system is 900 packets per second (pps) (i.e. 300 pps for each queue). With 95% confidence interval, we present the QoS results from the simulation studies. Fig. 1 and 2 show delay vs. Hurst parameter and queue length vs. Hurst parameter for three queues priority model respectively. We can clearly observe that as soon as the Hurst parameter increases (i.e. burstiness of the traffic increases); there is an increase in QoS parameters particularly for low priority queues. Just for comparison, we also present the simulation results for two queues priority model under same traffic load (i.e. the total traffic input load that has been taken in three queues model (i.e. 900 pps), here the same traffic load has been considered for two queues model). Fig. 3 shows the delay vs. Hurst parameter for two queues priority model. We can clearly observe that the delay for low priority queue (queue 2) in two queues model has been significantly decreased even at Hurst parameter = 0.9 as compared to three queues model. Whereas; the delay for high priority queue (queue 1) is almost same in both models.

5. Conclusion and Future Work

In this paper, we have presented a three queues priority model to evaluate the behaviour of different kinds of traffic generated from different events in WBAN. We have developed the Markov chain and extracted the QoS parameters such as queuing delay, queue length, bandwidth and PLR for different kinds of traffic. A discrete event simulator has been developed in C++ to simulate the traffic behaviour of corresponding traffic classes of WBAN. In the future, we aim to develop queuing models involving different types of polling schemes such as exhaustive, gated and limited service combined with traditional scheduling schemes. Hence, the main objective behind this work is to come up with novel and more sophisticated queuing models, which must be able to provide guaranteed QoS to all kinds of applications in WBAN according to their requirement.

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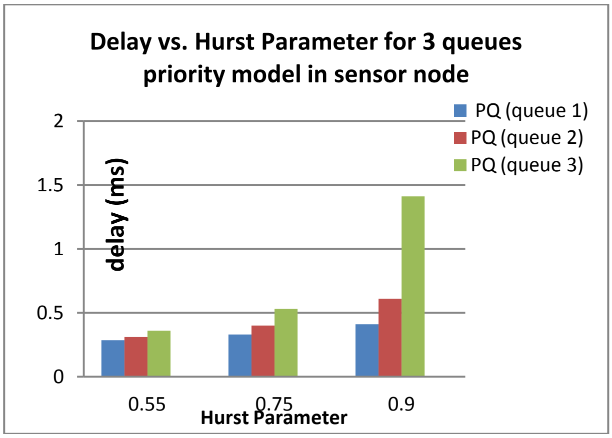

Fig. 1: Delay vs. Hurst Parameter for 3 queues PQ model

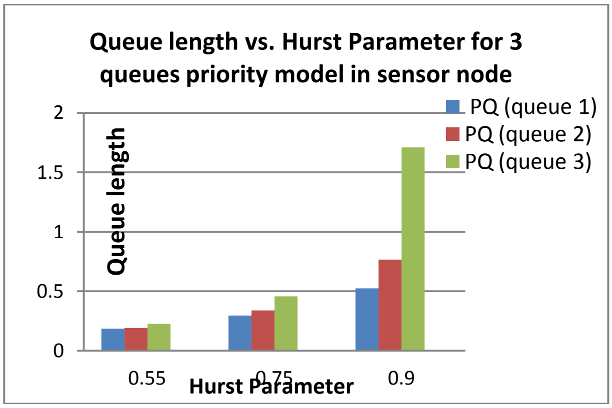

Fig. 2: Queue length vs. Hurst Parameter for 3 queues PQ model

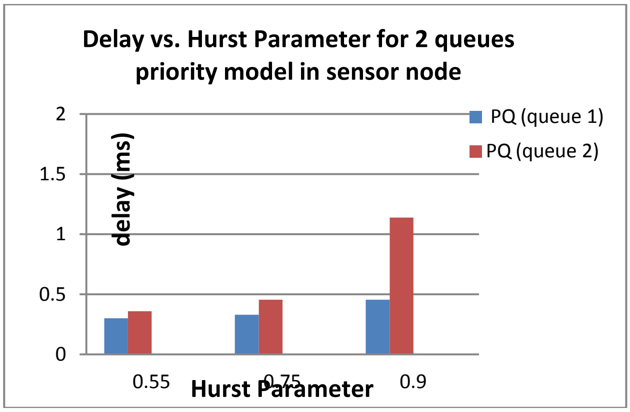

Fig. 3: Delay vs. Hurst Parameter for 2 queues PQ model

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