Using M/G/1/N Queueing Model and Hold Mode for Cross-Layer Approach to Transmit Data in Bluetooth-Based Body Area Networks

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Abstract. In this paper, a novel approach is proposed to transmit data in a Bluetooth-based medical body area network (BT-MBAN). The characteristics and requirements analysis of MBANs indicate that the rate of data transfer in an MBAN is low, for most medical application scenarios, compared to the capabilities of Bluetooth. As such, the Bluetooth polling system wastes energy and hence a cross-layer interaction is proposed based on queueing theory and hold mode in Bluetooth. The core idea is that Bluetooth devices buffer data and enter hold mode with an estimated hold duration till the state of buffer reaches a set threshold, and then transmit data over an estimated active time before the next hold mode, determined by the application data profile. The analysis shows that the employment of an M/G(M/M)/1/N queueing model and hold mode in Bluetooth can improve power efficiency significantly for data transmission in many MBAN scenarios. Simulation results of the power consumption savings are given. Finally, optimization of parameters and related issues about the approach are discussed.

Keywords: Bluetooth-based medical body area networks, Queueing theory, Hold mode, Cross-layer, Power efficiency.

1 Introduction

During the past few years, many medical companies or research groups have developed wireless health devices which can provide a more flexible platform for monitoring a patient's physiological data, primarily in health care facilities. These health devices typically work by connecting wireless sensors placed on (or even under) a patient's skin to create "medical body area networks" (MBAN).

As one of the most popular short-range wireless communications system, Bluetooth [1] operates in the unlicensed 2.4 GHz ISM (Industrial Scientific Medical) band and is being more and more applied in MBANs. In [2], the authors describe how the Bluetooth Park mode can be utilized to connect a large number of resource-constraint devices while reducing power consumption in Bluetooth network. In [3-4], various solutions are published for Bluetooth-based medical

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body area networks (BT-MBAN). However, using Bluetooth to make body sensor networks is limited in many cases due to its energy consumption problem, and associated battery issues. This paper presents a cross-layer approach to transmit data in Bluetooth-based MBANs, by which the power consumption of Bluetooth can be significantly reduced.

The paper is structured as follows. Section 2 gives a short summary of related Bluetooth technology. Section 3 discusses the characteristics and requirements of MBANs and the core issues are raised. Section 4 gives the mathematical expression of a M/G(M/M)/1/N queueing mode in Bluetooth. In section 5, the cross-layer approach is described in detail. Section 6 evaluates the new approach and section 7 gives the optimization design parameters of BT-MBAN system with a model for power consumption. Finally, section 8 analyses related issues and presents the conclusion.

2 Related Bluetooth Technology

The Bluetooth core system consists of a Host and one or more Controllers [1]. A Host is defined as all of the layers below the usage profiles and above the Host Controller Interface (HCI). A Controller is defined as all of the layers below the HCI. The Bluetooth protocol stack is shown at Fig.1.

As Fig.1 shows, the baseband of Bluetooth includes a BR/EDR/LE Controller and an optional AMP Controller. The Link Manager (LM) controls how the Bluetooth networks, known as piconets and scatternets are established and

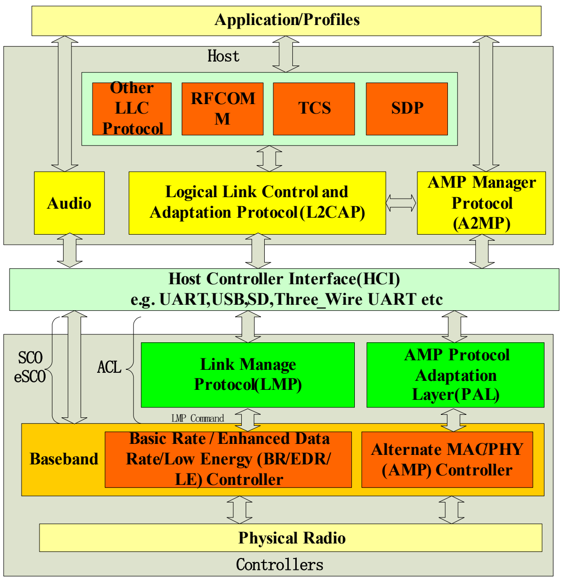

Fig. 1. Bluetooth protocol stack

maintained by the Link Control commands. The Host Controller Interface (HCI), with UART, USB, SD and three wire UART transport options, provides a uniform command method of accessing controller capabilities.

The host of Bluetooth includes a series of protocols to implement various applications. The Logical Link Control and Adaptation Protocol (L2CAP) provides connection oriented and connectionless data services to upper layer protocols with protocol multiplexing capability and segmentation and reassembly operation.

The Version 3.0+HS Specification of the Bluetooth system, which was released on 21st April, 2009, added an Alternate MAC/PHY (AMP) Controller including AMP Protocol Adaptation Layers (PALs) and AMP Manger Protocol (A2MP). The AMP provides the operation for incorporating an extraneous device, for example an 802.11 device compliant with the 2007 edition of the IEEE 802.11 Standard.

The Bluetooth Low Energy controller was first introduced by the Bluetooth Core Specification Version 4.0 in December 2009, which included the related Low Energy physical and link layers, as well as enhancements to the HCI for Low Energy, Low Energy direct test mode and AES encryption.

2.1 Bluetooth SCO and ACL Logic Link

Bluetooth's physical link represents a baseband connection between Bluetooth devices, which were described as the asynchronous connection-oriented (ACL) and Synchronous connection-oriented (SCO) links in Core Specification, Version 1.1. The Core Specifications define these as logical transport types, which carried different application data for different types of logical link.

The SCO and enhanced SCO links are designed to transport real-time audio signals; The ACL logical transport provides a packet-switched connection between the master and all active slaves participating in the piconet. Both asynchronous and isochronous services are supported. Between a master and a slave only a single ACL logical transport shall exist. For most ACL packets, packet retransmission is applied to assure data integrity.

The ACL logical link includes ACL-C and ACL-U logical link. The ACL-C logical link carries control information exchanged between the link managers of the master and the slave(s). The ACL-U logical link carries L2CAP asynchronous and isochronous user data.

2.2 Bluetooth Clock Synchronization and Polling System

A Bluetooth device has a native clock (CLKN) which is the reference to all other clocks used [1]. One device provides the synchronization reference and is known as the master. All other devices in a network, known as a piconet, are known as slaves. The master clock (CLK) shall never be adjusted during the existence of the piconet.

When a slave gets packets from a master, the CLKN of the slave will be synchronized by a synchronization sequence. To maintain clock synchronization when there is no active traffic from L2CAP and above, the master sends a POLL packet to the slave who shall send back a NULL immediately to acknowledge; after ten immediate POLL-NULL pairs, the master sends a POLL to the slave using the selected poll interval, which has a default value of 40 slots. Therefore, it can be seen that POLL-NULL packets are still consuming device power even when there is no active traffic to transmit.

2.3 Bluetooth Low-Power Operations and Hold Mode Review

Bluetooth provides various low-power operations to manage power consumption. At the microscopic level, the operation of packet handling and slot occupancy must be minimized but in accordance with the core specification. The basic idea is to reduce information exchange between the Bluetooth devices, and allow the transmitter and receiver to return to sleep if possible. At the macroscopic level, the basic idea which realizes low power is to adopt low power operation that reduces the active duty cycle of the Bluetooth devices. Consequently, there are three low power operation modes: sniff, hold and park, all of which are optional.

In sniff mode, the master and slave agree periodic anchor points where they will communicate. A slave in Park mode does not need to participate on the piconet's channel, but still needs to remain synchronized to the channel.

In hold mode, the master slave link becomes inactive and does not support ACL packets on the piconet's channel. A timer is initialized with the timeout value holdTO (hold duration) and the slave device can enter a sleep state. When the timer expires, the slave wakes up, synchronizes to the traffic on the channel and waits for further master transmissions.

To enter hold mode, both the master and slave can start a request or the master can force hold mode through the Link Manager Protocol (LMP) messages, commonly referred to as LMP protocol data units (PDUs). The process is initiated by sending an LMP_hold_req PDU or LMP_hold PDU containing a parameter hold duration. The LMP sequence for a master to force a slave into hold mode is shown at Fig. 2.

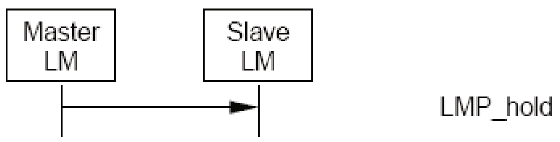

Fig. 2. Master forces slave into hold mode [1]

The host can use a HCI_Hold_Mode command to place a device into hold mode. The Controller may do this by either negotiating the hold mode parameters or forcing hold mode. Hold mode will automatically end after the negotiated length of time [1]. Note the HCI_Hold_Mode parameters include a min and max hold interval, allowing the LMP a degree of flexibility in selecting the hold time

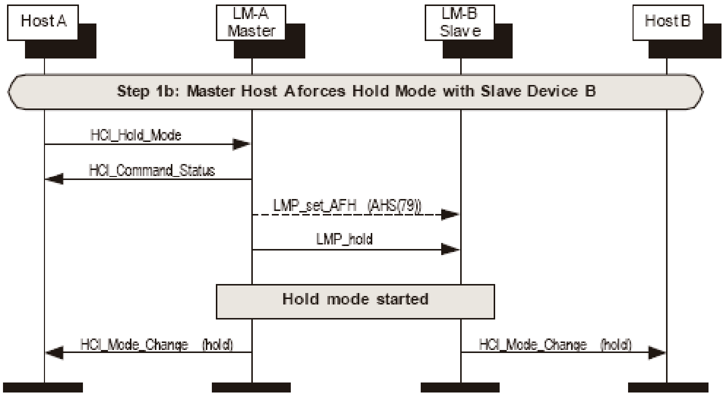

Fig. 3. Master forces hold mode [1]

(hold duration). An example of a hold mode forced by a master is shown in Fig.3. The optional LMP_set_AFH command can be used to adapt the set of active frequencies hopping channels.

2.4 Attribute Protocol and Generic Attribute Profile

The Bluetooth SIG has developed new operating modes and protocols to address Bluetooth for low data rates and asynchronous data. The Attribute protocol (ATT) [6] provides a method to communicate small amounts of data over a fixed L2CAP channel. The attribute protocol has notification and indication capabilities that provide an efficient way of sending attribute values to a client without the need for them to be understood. The Attribute protocol is also used by devices to determine the services and capabilities of other devices.

The Generic Attribute Profile (GATT) defines a service framework using the Attribute Protocol. This framework defines procedures and formats of services and their characteristics. The definition includes discovering, reading, writing, notifying and indicating characteristics, as well as configuring the broadcast characteristics. Fig. 4 shows the place of Attribute protocol and profile in Bluetooth

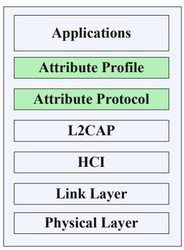

Fig. 4. The place of Attribute protocol and profile in Bluetooth stack

stack. Thus, the ATT and GATT can be a common method to complete applications info exchange between Bluetooth devices, which improve the compatibility and interoperability of medical sensors.

3 The MBANs Characteristics and Requirements Analysis

The medical body area networks (MBANs) has special characteristics and requirements which can be inferred as follows. First of all, although the applications of medical sensor are varied, the actual bit rates of MBAN are far below the capacity of a Bluetooth network. For example, the sustainable raw data rates of a fall and activity sensor [4], which is a medical monitoring sensor, is 9.6 kbps and many other devices have significantly lower aperiodic data rates. The classic Bluetooth supports asynchronous connections with data rates of 721.2 kbps for Basic Rate, and 2.1 Mbps for Enhanced Data Rate.

Next, long data delays in MBANs can be tolerated (seconds to minutes range), but there maybe specified low delay constraints when an emergency happens.

The third is based on network configuration; the MBANs topology is point to point or point to multi-point and it does not dynamically change. Therefore, the topology is simple and Bluetooth's piconet meets the requirements but is typically constrained to a master and up to seven active slaves.

Finally, the central node of a MBAN might have an uninterruptible power supply or high capacity battery, but the slave nodes usually just have a low capacity battery for power supply. Therefore, to reduce the power consumption and prolong the usable time of slave nodes, each slave node should just acquire and transmit the data and the central node shall process the data in most cases.

As mentioned above, the arrival rate of data in an MBAN is slow in most scenarios. Moreover, hold mode in Bluetooth can pause the ACL logical link and reduce the polling operation between Bluetooth devices which means power saving. If a BT-MBAN slave device buffers data when Bluetooth enters hold mode and transmits the buffered data with the FIFO rule when Bluetooth exits hold mode, the power consumption can be reduced.

4 M/G(M/M)/1/N Queueing Model in Bluetooth

Queueing theory [7] has its roots early in the twentieth century in the early studies on telephone networks. Today it is one of the primary tools used to deal with questions involving trade-offs between the amount of resources allocated to provide a telecommunications service and the quality of service [8].

In [9], the performance of a single Bluetooth piconet is analyzed using the theory of M/G/1 queues with vacations. Therefore, the Bluetooth-based MBAN systems can be also considered as an M/G(M/M)/1/N queueing model. The M means the "Markovian" queue is distinguished by a Poisson arrival process and exponential service times. The G means the arrivals are again Poisson but the service times are described by an arbitrary (or general) probability distribution. The '1' indicates that the number of servers in the queue is a Poisson process. N is the amount of queue space, which means the size of the buffer.

As Fig.5 shows, the data arrival average rate from medical applications is denoted λ bps. The service average rate is μ bps. The transmit rate of data of Bluetooth has two processes (M/M). Process 1 is $\mu_h = 0$ bps when Bluetooth enters hold mode till the buffer's threshold is reached; Process 2 is μ_a bps when Bluetooth exits hold mode to become active and transmits data till the buffer is empty.

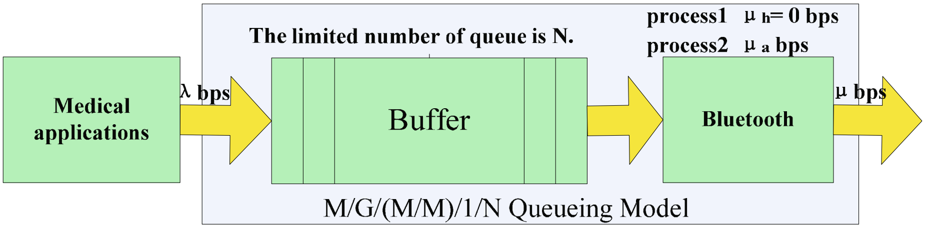

Fig. 5. M/G(M/M)/1/N Queueing model in Bluetooth

The variables t_h and t_a are holdTO (hold time) value in process 1 and ActiveTO (transmit time) value in process 2, when the BT-MBAN system enters steady state. Based on queueing theory, BT-MBAN system utilization ρ can be defined:

$$\rho = \frac{\lambda}{\mu} = \frac{\lambda(t_h + t_a)}{\mu_h t_h + \mu_a t_a} = \frac{\lambda}{\mu_a}(1 + \frac{t_h}{t_a}) \qquad (\rho \leq 1) \tag{1}$$

Therefore, the probability that the system is empty is

$$\mathrm{P}(0) = 1 - \rho = 1 - \frac{\lambda}{\mu_a}(1 + \frac{t_h}{t_a}) \tag{2}$$

The expected amount of data L in system and expected queue length of data L_q are

$$L = \frac{\rho}{1-\rho} = \lambda W, \ L_q = \frac{\rho^2}{1-\rho} = \lambda W_q \tag{3}$$

The total expected waiting time W in system and the expected waiting time W_q in queue are

$$W = \frac{1}{\mu - \lambda}, \ W_q = \rho W \tag{4}$$

5 The Operation Analysis

Our operation analysis, as already shown in the previous section, includes hold mode, applications rate, buffer data and BT transmit data with different rates, which are good indicators for the operations in a BT-MBAN. The specific operations between Bluetooth devices are given as follows.

5.1 Slave's Operation

Generally, the slave's functions in BT-MBAN are receiving and performing control commands from the master and to complete data collection, storage and transmission to the master. As the slave has energy restrictions, many special operations, for example to initiate hold mode or process data, shall be dealt with by the master.

Furthermore, the current medical application attributes can be stored in slave's generic attribute profile, which contains the normal rate λ and buffer size N, even the acceptable maximal data delay t_{delay} and suggestion hold time parameters t_{hold} etc. When the ACL link between Bluetooth devices is established, the attributes shall be exchanged by attribute protocol. Therefore, the slave operation in active mode can be minimized.

5.2 Master's Operation

The master must take more actions in the BT-MBAN. When the master receives the necessary information from the slave in connection state, it will decide when the slave's state shall be transferred to hold mode with hold duration t_{hold}. The simplest method for the master is to accept the suggested policy or parameters from the slave by the attribute protocol and generic attribute profile. However, the master must consider the current network. For example, if the master has more than one slave in the piconet, it must maintain fairness.

When the slave leaves hold mode and enters active mode, a new timer shall be initialized with activeTO value (active time t_a), which is a new parameter. When the timer expires, the master shall transfer the slave's state to hold mode with the calculated t_{hold}. The active time t_a shall be decided by the amount of data in the buffer for transmission and current channel conditions with appropriate redundancy. As described above, Bluetooth devices shall do periodic state-transition between active and hold mode, which is shown in Fig.6.

6 Analysis and Discussions

From Fig.6, it can be seen that the key parameters of the system are the hold duration t_{hold} and the active duration t_a. In an actual system, the hold duration t_{hold} is determined by the BT-MBAN system acceptable maximal data delay t_{delay}, the buffer size N and the rate λ. The t_{hold} is

$$t_h \in [0, \min(t_{delay}, \frac{N}{\lambda})] \tag{5}$$

From (1), t_a is

$$t_a = \frac{\lambda t_h}{\rho\mu_a - \lambda} = \frac{t_h}{\frac{\rho\mu_a}{\lambda} - 1} \tag{6}$$

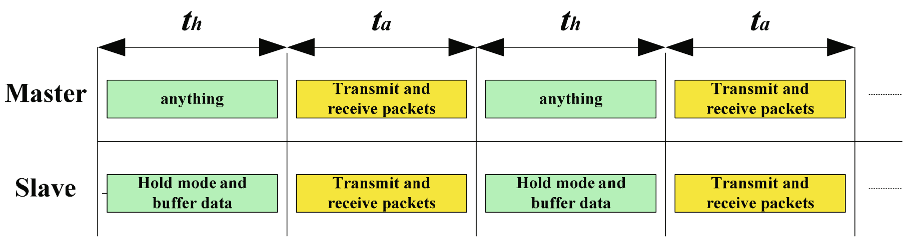

Fig. 6. The hold based approach to transmit data

The μ_a is the actual transmit data rate of Bluetooth, which is determined by the transmission packet types selected and current channel conditions. For the DM1 and the 3-DH5 packets in Bluetooth, it is 108.8 kbps and 2178.1 kbps, respectively.

Fig.7 shows, when the BT-MBAN system utilization ρ is increased, the active duration t_a is reduced when the hold duration t_h is fixed through (6).

The BT-MBAN system utilization ρ cannot be equal to 1 because the wireless channel error exists. In fact, the Bluetooth devices negotiate hold mode also takes up data transmit channel time, which reduces the system utilization and increases the active duration t_a.

Assume that the average power of Bluetooth in MBAN during t_h and t_a is 0 and P_{active}. The new approach's power consumption is $P_{active} * t_a$. Considering the sustainable data rates from applications and regardless of Bluetooth parameter POLL interval, the conventional power consumption during t_h and t_a is $P_{active} * (t_a + t_h)$.

Due to (6) the new approach's power consumption saving utilization ρ_{saving} is defined as follows:

$$\rho_{saving}=1-\frac{P_{active} * t_a}{P_{active}(t_h + t_a)} = 1 - \frac{\lambda}{\rho\mu_a} \quad (\rho_{saving} \leq 1) \tag{7}$$

From (7), the ρ_{saving} is related with ρ, μ_a. The Fig.8 shows the impact of ρ and μ_a for ρ_{saving}.

If the power consumption saving utilization ρ_{saving} equates to zero, there is no power saving in BT-MBAN. Therefore, the power control should make the power consumption saving utilization ρ_{saving} close to 1 as much as possible. In Fig.6, when μ_a = 9.6 kbps, the simulation results show the proposed cross-layer queueing theory based approach can improve power consumption saving utilization ρ_{saving}, which means saving energy. With the increasing of BT-MBAN system utilization, the power consumption saving utilization is increased and more energy is saved. For the same BT-MBAN system utilization, the higher the data transmission rate, the more energy can be saved.

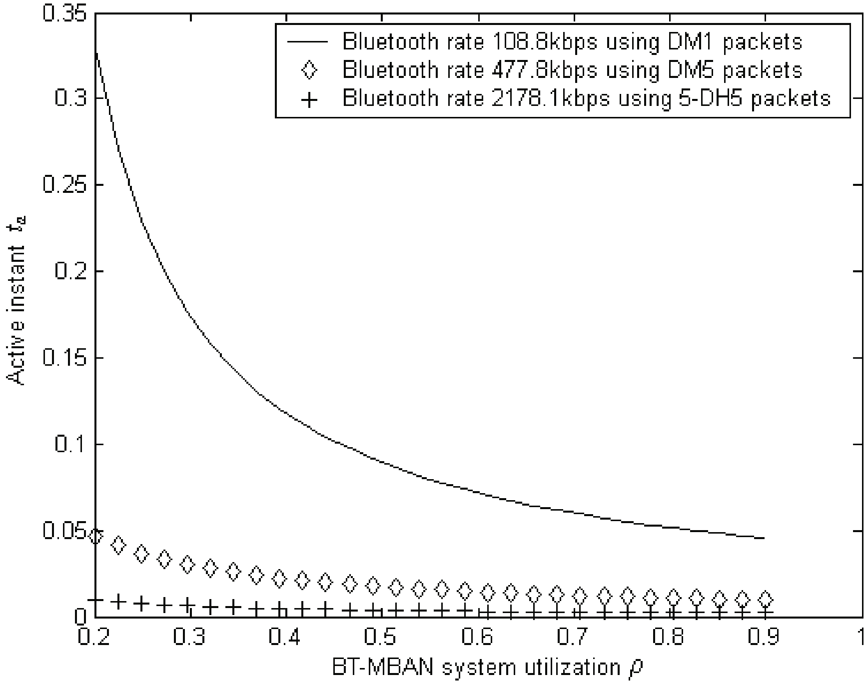

Fig. 7. The new approach's system active duration t_a, based on different BT-MBAN system utilization ρ and Bluetooth transmit data rate μ_a, when set λ= 9.6 kbps, $N =$ 4 Kbit, $t_h = \frac{N}{\lambda}$

7 Optimization of Parameters by Queueing Mode

Using queueing mode to optimize and design the parameters of BT-MBAN, for instance buffer size and hold duration, is very important and can reduce the BT-MBAN system costs.

The whole power consumption is one of the important measurements of a BT-MBAN. The notations are introduced as follows:

F: whole power consumption in BT-MBAN per unit of time;

f_1: power consumption per unit of time when BT-MBAN is actively running;

f_2: power consumption per unit of time per bit when BT-MBAN system buffer data;

f_3: power consumption when BT-MBAN transfers state from hold to active;

Therefore,

$$F = f_1 + L * f_2 + \frac{f_3}{t_h + t_a} \tag{8}$$

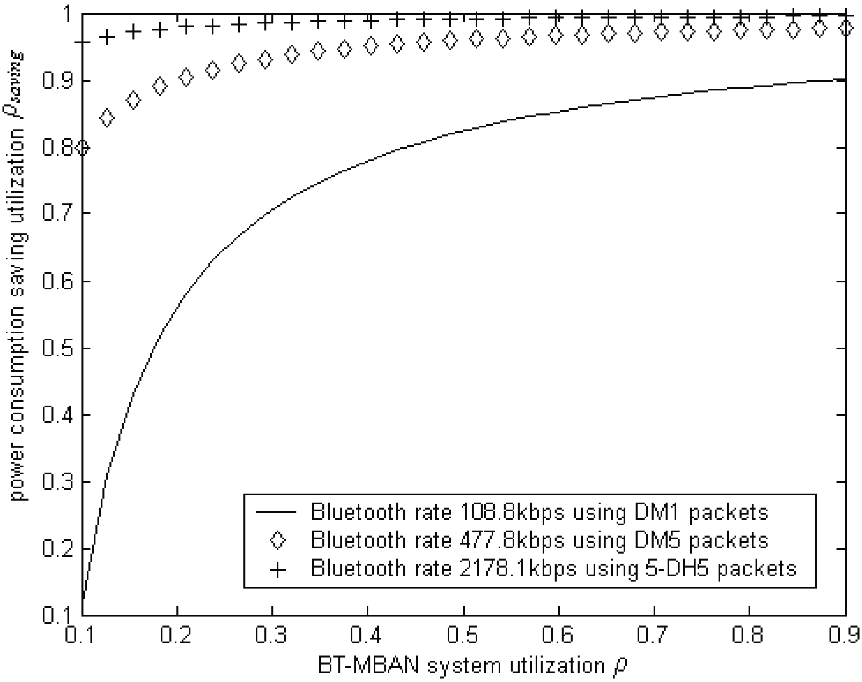

Fig. 8. The power consumption saving utilization ρ_{saving}, based on different BT-MBAN system utilization ρ and Bluetooth transmit data rate μ_a, when set $\lambda = 9.6$ kbps

From (1)-(6),

$$F = f_1 + \lambda W * f_2 + \frac{f_3}{t_h + \frac{\lambda t_h}{\rho\mu_a - \lambda}} = f_1 + \lambda W * f_2 + \frac{(\rho\mu_a - \lambda) f_3}{(\rho\mu_a) t_h} \tag{9}$$

Using (9) and (5) can calculate when $\frac{\partial F}{\partial t_h} = 0$ and $\frac{\partial F}{\partial N} = 0$, or numerically analyses it. From the result, it can be estimated and optimized about the parameters hold time t_h or buffer size N in a given MBAN scenario.

For example, as mention before, the sustainable raw data rates of a fall and activity sensor [4], which is a medical monitoring sensor, is λ=9.6 kbps. We just use DM1 packet (μ_a=108.8 kbps) to transmit data. The task of fall sensor is monitoring and we set that this MBAN system acceptable maximal data delay t_{delay}=5 s. We assume that $f_1 = 0$,$f_2 = 0.1$, $f_3 = 10000$, the expected waiting time $W \approx t_d$ and the BT-MBAN system utilization ρ is 0.99. We can numerically analyses (9) when $t_h \in [0.5, 5]$, which is showed in Fig.9.

From Fig.9, we can see that the whole power consumption per unit of time F can reach the minimum when t_h is equal to about 3.1 s.

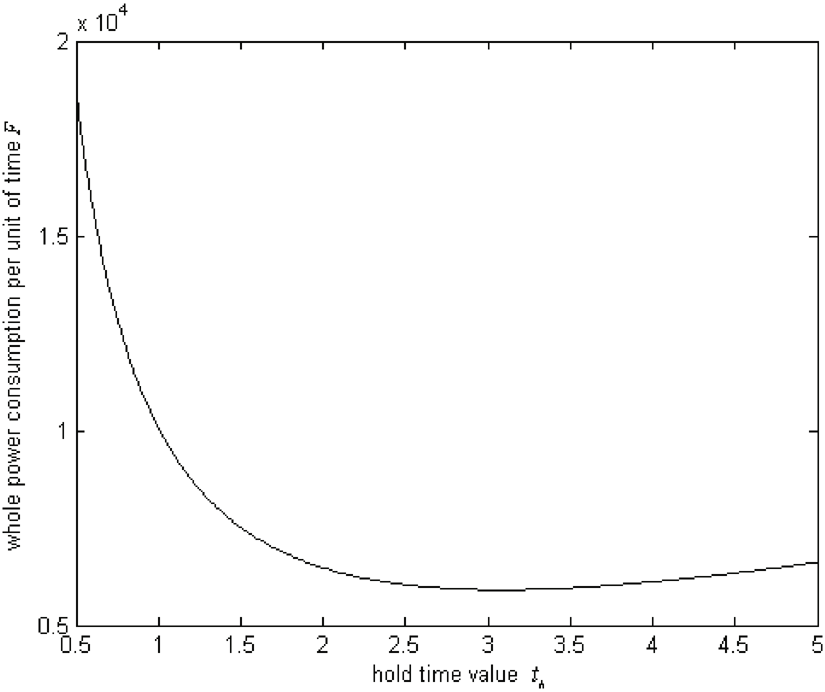

Fig. 9. An example calculation of whole power consumption per unit of time F, based on different hold time value t_h at the specific scenario

8 Conclusions and Related Issues

The paper proposes a cross-layer approach to transmit data with hold mode in BT-MBAN. By employing of M/G(M/M)/1/N queueing model and hold mode in Bluetooth, the power consumption can be significantly reduced.

Realistically, when using the new approach, there are some issues that shall be considered. For one thing, based on the current requirements of an MBAN, the system utilization ρ must be selected to guarantee system round trip, including system stability and reliability.

For another, although the bigger hold duration and active duration could reduce the amount of times into hold mode per unit of time, it shall increase the maximal data delay of application.

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References

1. The Bluetooth Special Interest Group (SIG): Specification of the Bluetooth system, Version 4.0 (2010)
2. Bohn, H., Bobek, A., Golatowski, F.: Bluetooth Device Manager Connecting a Large Number of Resource-Constraint Devices in a Service-Oriented Bluetooth Network. In: Lorenz, P., Dini, P. (eds.) ICN 2005. LNCS, vol. 3420, pp. 430–437. Springer, Heidelberg (2005)
3. Naima, R., Canny, J.: The Berkeley Tricorder: Ambulatory Health Monitoring. In: Sixth International Workshop on Wearable and Implantable Body Sensor Networks, BSN 2009, pp. 53–58 (2009)
4. Van de Van, P., Bourke, A., Nelson, J., Laighin, G.: A Wireless Platform for Fall and Mobility Monitoring. In: Signals and Systems Conference, ISSC 2008, pp. 319–324. IET Irish (2008)
5. Tahat, A.A.: Mobile Personal Electrocardiogram Monitoring System and Transmission using MMS. In: 7th International Caribbean Conference on Devices, Circuits and Systems, ICCDCS 2008, pp. 1–5 (2008)
6. Bluetooth SIG: Attribute protocol V09r11 (2010)
7. Robertazzi, T.G.: Computer Networks and Systems: Queueing Theory and Performance Evaluation, 3rd edn. Springer, New York (2000)
8. Daigle, J.N.: Queueing Theory with Applications to Packet Telecommunication. Springer Science + Business Media, Inc. (2005)
9. Mišić, J., Mišić, V.B.: Modeling Bluetooth piconet performance. IEEE Communications Letters 7(1), 18–20 (2003)