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Bluetooth Energy-Saving Optimization: A Queuing Theory Analysis

CUI Yi-dong[1,2], XIAO Zhi-qing[2], WANG Xiao-yue[2], YANG Bao-xing[2]

1. State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing, 100876, China
2. School of Information and Communication Engineering, Beijing University of Posts and Telecommunications, Beijing, 100876, China

Abstract

Bluetooth on mobile terminal can be used to scan the surroundings to discover other Bluetooth-enabled devices. However, with energy limitations, the scanning actions must be well arranged to reduce power consumption. In this paper we propose an energy-saving strategy that turns on and off the Bluetooth device at a configured time. The scenario of Bluetooth scanning is modeled as an *M*/*M*/1 vacation queue with special impatient customers and startup expenses. In the *M*/*M*/1 queue, the terminal with Bluetooth device is the only server which scans its nearby customers, and the on-off state of Bluetooth device is indicated as vacation behaviors. The aim of the paper is to find the best vacation strategy, or equivalently, the most energy-effective rules. Simulations demonstrated that the best strategy depends on the intended error rate, startup time and expenses and many other factors. Generally, the performance of the multiple vacation strategy is satisfactory on most conditions.

Keywords: energy-saving, vacation queuing, Bluetooth, environment discover

1 Introduction

With the rapid deployment of mobile terminals in our life scenes, we are able to use wireless communication to discover the environment where we are being. Some technologies, such as GPS and cellular base-station positioning, have been developed to locate people geographically. Besides, WiFi and Bluetooth can also be used to discover the nearby peers and communicate with them. Based on these technologies, more and more fascinating applications have emerged, such as MobiClique [1] which provides social network services.

In this paper, we just focus on Bluetooth communications. Consider such a scenario: a mobile terminal uses Bluetooth to exchange information with other terminals in its scanning range. More concretely, John walks along the road and use Bluetooth of his mobile phone to scan nearby Bluetooth-enabled phones; once his phone find a peer (for example, Jenny's phone), the phones will exchange information to find whether they share same favorite friends in the phone address books. In such a scenario, the power of the terminal is limited, and once the Bluetooth device starts to scan or communicate, it will consume a considerable amount of precious energy. If the terminal continues scanning without break, the battery exhausts soon. In order to save the energy, the Bluetooth device should be turned off or be set into idle mode. However, while the Bluetooth device is inactive, the terminal will fail to discover the peers passed by closely. Hence, this paper aims to provide an energy-saving strategy by turning on the Bluetooth device intermittently while minimizing the opportunities of missing discovering the peers (briefly, missing rate).

In recent decades, queuing theory is widely used in energy-saving optimization problems [2-3]. A project about lightweight ad-hoc network [4] introduces queuing system into the similar network performance analysis. At the same time, many models of queuing systems with service interruptions have been published. Please see reference [5] for an updated and comprehensive description. The classic and simpler models of server vacations are those of exhaustive service, that is, the server goes out on vacation only when the queue is empty. However, their studies do not exploit a solution to the problem in this essay. We need to investigate on the compromise between energy-consuming and the missing rate.

The paper is organized as follows. We first outline the Bluetooth scanning scene as an M/M/1 queuing system with extreme impatient customers in Sect. 2. In Sect. 3, the energy-saving approach is mathematically described as a problem of vacation strategy. In Sect. 4, the time-invariable vacation strategies are discussed. Some simulation results are shown to compare some mature vacation strategies. Further, we have a discussion on the feasibility of the time-varies

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Corresponding author: Cui Yidong, E-mail: cyd@bupt.edu.cn

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vacation strategy, which makes an outlook into the future work in Sect. 5. Finally, we conclude in Sect. 6.

2 The energy-saving model

According to the scenario described in Section 1, the system includes one terminal (namely, the server) which scans/serves other peers and some moving terminals (namely, the customers) which are scanned/served. All the terminals, including the server and the customers, are moving around. Without loss of generality, we can fix the server, then the customers' relative velocity vectors to the server can be calculated with their absolute velocity vectors and the server's velocity vector. We assume that all the terminals have the same Bluetooth communication range, which is a circle area with the radius R. Only those customers within the communication range of server will be served. **Fig. 1** shows an example. In this example, C_1 and C_2 are in the communication range of S; C_4, C_5, C_6 are out of the range; C_3 is moving into the range and C_7 is moving out of the range.

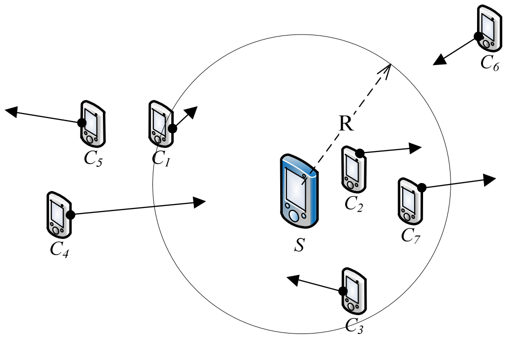

Fig. 1 Example of the mobile terminal topology

Generally, the system can be modeled as a queuing system. When a new mobile terminal (e.g. C_3) comes into the communication range of the server, a customer is pushed into the queue. We suppose that the distribution of the interarrival time is the negative exponential distribution with a parameter λ.

When a terminal has been finished serving, then a customer is popped out of the queue, or passes the server. The serving time for each terminal is different. For example, if the server wants to search someone in others' contacts, the serving time depends on the length of the contact list. We assume that the distribution of service time is negative exponential distribution with the parameter μ.

The customers in this queue is 'extreme' impatient. We say 'extreme' because both the customers waiting in the queue and the one being served are impatient. That is to say, even the customer who is being served may leave. Hence, all the customers leave at probability δ.

The queueing system is dipicted in **Fig. 2**.

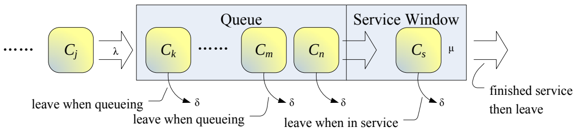

Fig. 2 The queueing system for Bluetooth energy-saving model

Obviously, if a terminal wants to serve as many terminals as possible, it should keep the Bluetooth device working all the time. Or equivalently, the server should always on duty. On this condition, the queuing system can be modeled as a birth-death process $N(t)$ (see **Fig. 3**).

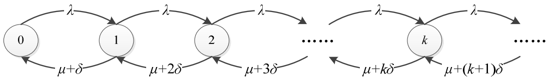

Fig. 3 M/M/1 queuing with extreme impatient customers

Assume $p_k(t)$ is the probability to have a queue length k at time t. From the state flow chart, we can find that

$$\frac{dp_0(t)}{dt} = (\mu + \delta) p_1(t) \tag{1}$$

$$\frac{dp_k(t)}{dt} = \lambda p_{k-1}(t) + [\mu + (k+1)\delta] p_{k+1}(t) - (\mu + \lambda + k\delta) p_k(t) \quad k \geq 1 \tag{2}$$

Two major factors we concerned are: 1. How many terminals have been missed, or equivalently, leave the queue without being served? 2. How much energy does the server need? The first factor can be denoted by the missing rate M. During the time interval Δt, if there are $N_{enter}(\Delta t)$ customers coming into the queue and $N_{miss}(\Delta t)$ impatient customers leaving without being served (including those leave when serving), then

$$M = E\left[\frac{N_{miss}(\Delta t)}{N_{enter}(\Delta t)}\right] = \delta \sum_{k=1}^{\infty} k p_k \tag{3}$$

In stable state,

$$p_k = \frac{\dfrac{\lambda^k}{\prod_{j=1}^{k}(\mu + j\delta)}}{1 + \sum_{k=1}^{\infty} \dfrac{\lambda^k}{\prod_{j=1}^{k}(\mu + j\delta)}} \tag{4}$$

So in the queuing system,

$$M=\delta\sum_{k=1}^{\infty}\left(\frac{\dfrac{k\lambda^{k}}{\prod_{j=1}^{k}(\mu+j\delta)}}{1+\sum_{i=1}^{\infty}\dfrac{\lambda^{i}}{\prod_{j=1}^{i}(\mu+j\delta)}}\right)\square M_0 \qquad (5)$$

The second factor can be denoted by the expense index E. The energy consumed by the Bluetooth device varies when the device is busy or not. If the device does not serve any terminal, the energy consumed per time unit is denoted by e_i (i.e. the idle period expense per time unit). Otherwise, it needs more energy which can be denoted by e_b (i.e. the busy period expense per time unit). The energy cost index E is mathematical expectation of their weighted mean, or equivalently,

$$E=\mathrm{E}\left[\frac{t_b e_b+t_i e_i}{t_b+t_i}\right]=\mathrm{E}\left[\frac{t_b}{t_b+t_i}\right]\left(e_b-e_i\right)+e_i\ \square\ E_0 \qquad (6)$$

The distribution of t_b is identical to $d\tilde{p}_0/dt$ in the following differential equations:

$$\frac{d\tilde{p}_0}{dt}=(\mu+\delta)\tilde{p}_1 \qquad (7)$$

$$\frac{d\tilde{p}_1}{dt}=(\mu+2\delta)\tilde{p}_2-(\mu+\lambda+\delta)\tilde{p}_1 \qquad (8)$$

$$\frac{d\tilde{p}_k(t)}{dt}=\lambda\tilde{p}_{k-1}(t)+[\mu+(k+1)\delta]\tilde{p}_{k+1}(t)-(\mu+\lambda+k\delta)\tilde{p}_k(t)$$
$$k\geq 1 \qquad (9)$$

and the idle period length t_i obeys negative exponent distribution with parameter λ.

3 Vacation queuing – an energy saving approach

Keeping a server on duty all the time may cost more than necessary. Non-stop Bluetooth device will consumes a lot of energy of the mobile terminal. Do we have other smarter way to save some energy while the missing rate M is controlled in a tolerable value? Obviously, a strategy that turns on and turns off the Bluetooth device in a configurable time will work.

If the Bluetooth device is turned off, we may say the server is on vacation. A server who is on vacation does not know anything except the situation before he closes the service-window. The server needs some energy or expense and a certain amount of time to reopen the service-window. The expense to open a window and close window is called Startup Expense e_{st}, (that is the energy to start and stop a Bluetooth device) and the time to close window then restart a window is called Startup Time t_{st}. Notice the cost includes the closing procedure, which always appears in pair with the starting service. The on-duty time t_{on} is the time interval where the Bluetooth device is on, while vacation time t_{off} is where the device is off. When the server is on-duty, he is either in busy period or in idle period. So $t_{on}=e_b+e_i$.

Our goal is to find the best vacation strategy to minimize both the missing rate M and the expense index E, where

$$M=E\left[\frac{N_{miss}\left(t_{on}+t_{off}+t_{st}\right)}{N_{enter}\left(t_{on}+t_{off}+t_{st}\right)}\right]\square\ 1-E\left[\frac{\mu t_b}{\lambda\left(t_{on}+t_{off}+t_{st}\right)}\right] \qquad (10)$$

$$E=E\left[\frac{t_b e_b+t_i e_i+e_{st}}{t_{on}+t_{off}+t_{st}}\right] \qquad (11)$$

It's obvious that M is always less than M_0 that is the missing rate of non-vacation system. But E sometimes can be greater than E_0, which indicates that the vacation strategy is meaningless.

4 Time invariant vacation strategy

There are a lot of mature vacation strategy, such as exhaustive service and non-exhaustive service, gated service, limited service, Bernoulli vacation rule, multiple vacation, single vacation, decrementing service, threshold vacation and so on. Different kinds of vacation rules, which specify their triggers and ending methods [6], acquire different analysis tool. So we do not analyze them mathematically one by one, we just show some of our simulation results.

We suppose to sample $N=16$ points in every time unit (for convenience sake, let one time unit be 1 second) , and $\delta=\lambda=0.2$ erl/s , $\mu=0.5$ erl/s , $e_b=e_i=1$, and $t_{st}=1$ s . Here we show the simulation result when $e_{st}=5$ and $e_{st}=7$. According to the simulation result, some smoothed $E\ \square\ M$ curves are plotted in the figure, where two parameters are unified separately by E_0 and M_0.

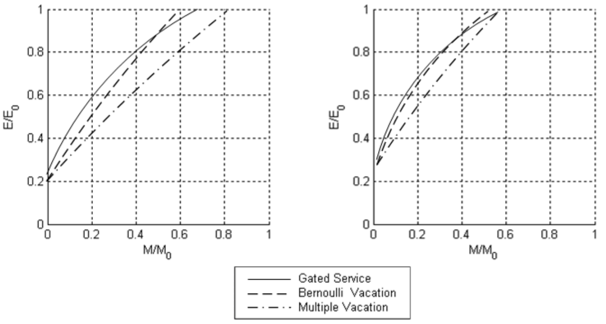

Fig. 4 *E-M* relationship with different setup costs

The simulation result indicates that the multiple vacation rule is a good strategy for most of time. As to other vacation rules, the rank among them vary with different system requirements.

5 More discussions – cognitive time variant vacation strategy

The time invariant vacation strategy sometimes seems quite rigid. In time invariant vacation, arguments are constant. But during some periods of observation, we can get new knowledge about the newest value and tendency of arguments. We can bring up some more flexible ways [7]. For example, if the average queue length is under the threshold, a larger vacation probability may utilize the system.

6 Conclusions

In this paper we bring up an energy-saving strategy for Bluetooth device application. First, we build an M/M/1 queuing system with special impatient customers. Second, we specify the optimistic option: the vacation strategy – trigger strategy and ending strategy. Third, we provide some simulation results of some mature vacation strategy then mention a smarter way to improve the vacation strategies.

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