Energy Modeling and Optimization through Joint Packet Size Analysis of BSN and WiFi Networks*

Yantao Li‡†, Xin Qi†, Zhen Ren†, Gang Zhou†, Di Xiao‡ and Shaojiang Deng‡
†Department of Computer Science, College of William and Mary, Williamsburg, VA 23187, USA
† {*yantaoli, xqi, renzh, gzhou*}@*cs.wm.edu*
‡College of Computer Science, Chongqing University, Chongqing 400044, China
‡{*yantaoli, dixiao, sj_deng*}@*cqu.edu.cn*

Abstract

In this paper, we propose to optimize energy consumption in heterogeneous wireless networks through joint packet size optimization. Specifically, we consider a two-hop data communication system composed of a body sensor network (BSN) and a WiFi network. Within the system, we formulate an energy consumption optimization problem with the constraints of both throughput and time delay. Mathematically, we convert this problem into a geometric programming (GP) problem, which is then numerically solved. The solutions can be used by both the BSN and the WiFi network to dynamically change their packets' payload sizes based on their current packet delivery ratios (PDRs). Since the PDRs are time-varying, we tabulate an offline payload size lookup table for online packet size selection using PDRs as indices. Finally, we collect PDRs from a deployed two-hop BSN-WiFi network and simulate the energy consumption. The performance evaluation results show that our solution achieves up to 70% *energy savings compared with solutions that use fixed packet sizes.*

1 Introduction

With the advancement of both hardware and software in wireless communication, the cost of deploying wireless instruments dramatically decreases and wireless networks become more and more common in our daily life. The pervasive existence of wireless networks provides the feasibility of many human-centered applications, such as *eCoupon* [1], *CenceMe* [2]. Although wireless networks enable us to enjoy many daily conveniences, their designs face two main challenges. First, the wireless devices' energy capacity is limited. Any node in the wireless network running out of energy may cause the malfunction of the whole network. Second, the current designs of heterogeneous wireless networks, such as ZigBee and WiFi, are separate. The designers of one specific network rarely consider how to achieve system improvement as a whole with other coexistent networks. To jointly tackle the above two challenges, this paper aims to address the problem of optimizing energy consumption in heterogeneous wireless networks. Particularly, we consider a system composed of a body sensor network (BSN) and a WiFi network.

Within the system, the BSN consists of a group of wireless sensor motes, which are either wearable on or implanted into a human body to monitor vital physiological parameters and body movements. It has attracted significant interests from a wide range of applications, including assisted living [3], emergency response [4], athletic performance evaluation [5], interactive controls [6] and victim monitoring [7]. In the BSN, the data collected by sensors is delivered by motes to an aggregator (e.g., a cell phone [8]). The aggregator reorganizes the received packets and delivers them through WiFi to a data center like in a hospital. For applications like health care, real-time and reliable data delivery is usually required for this two-hop wireless communication. The main source of energy consumption in this system is communication. In communication, it is known that longer packets experience reduced reliability and suffer increased time delay, while shorter packets suffer increased overhead. Thus, with the consideration of the throughput and time delay, our work is to jointly determine the optimal packet sizes for both the motes and the aggregator in the two-hop system with the purpose of optimizing communication energy consumption.

To address this problem, we first abstract the two-hop communication system as a three-phase pipeline and analyze the time delay in each phase. Then, taking the throughput and time delay constraints into account, we formulate an energy optimization problem with the packet sizes in the

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BSN and WiFi networks as the variables. We mathematically convert the energy optimization problem into a problem of *Geometric Programming* (GP) [9] and solve it with *cvx* [10]. In our design, the optimal solutions are also tabulated on the aggregator. With packet delivery ratios (PDRs) as indices, the aggregator looks up the table and gets the optimal packet sizes for both BSN and WiFi networks. Finally, to evaluate the optimal solutions, we prototype a two-hop BSN-WiFi network that is composed of TelosB motes and a laptop as an aggregator. With collected PDRs, the communication energy in the network is simulated and the performance evaluation results support our theoretical study.

To pursue energy efficiency, many works have been done in both wireless sensor network and WiFi network separately. In wireless sensor network, several energy-efficient synchronous duty-cycling MAC protocols [11, 12] and asynchronous duty-cycling MAC protocols [13, 14] have been proposed. Algorithms for scheduling packet transmissions [15, 16, 17] or optimizing homogeneous networks' packet sizes [18, 19, 20, 21] are also developed to achieve energy efficiency. In WiFi network, energy efficiency for smart devices (e.g. smart phones) has also been studied [22, 23, 24, 25]. However, these works do not consider the joint energy optimization in both the BSN and WiFi networks. Although *WISE* [26] and *BuzzBuzz* [27] consider network coexistence, they only focus on collision minimization and throughput maximization, rather than the joint energy optimization under throughput and time delay constraints.

Our main contributions can be summarized as follows:

• We are among the first to optimize the communication energy consumption in heterogeneous wireless networks. Based on a particular two-hop communication system that is composed of a BSN and a WiFi network, we formulate a communication energy optimization problem through joint packet size analysis with throughput and time delay constraints.

• We convert the energy optimization problem into a GP problem, which is then numerically solved by cvx. We also tabulate the optimal solutions for online packet size selection with PDRs being as indices.

• We collect PDRs from a real deployed two-hop BSN-WiFi network and simulate the communication energy consumption. The results show that our solution can achieve up to 70% energy savings than the solutions that use fixed packet sizes.

The rest of this paper is organized as follows. Section 2 summarizes existing works that improve energy efficiency in wireless communication. In Section 3, we formulate and solve the communication energy optimization problem with constraints of throughput and time delay. Finally, performance evaluation based on trace-driven simulation and conclusions are given in Sections 4 and 5, respectively.

2 Related Work

Many research works that pursue energy efficiency have been done in wireless sensor network, especially in BSN area. There are some works achieving energy efficiency through the design of MAC protocols [11, 12, 13, 14]. In [12], authors introduce *DW-MAC*, which is a new low-overhead scheduling algorithm that allows nodes to wake up on demand during the sleep period of an operational cycle and ensures that data transmissions do not collide at their intended receivers. In [13], authors propose *PW-MAC*, which minimizes sensor node energy consumption by enabling senders to predict receiver wakeup times through an on-demand prediction error correction mechanism. Besides, some energy-efficient scheduling algorithms for packet transmissions are proposed [15, 16, 17]. In [17], authors propose a packet transmission scheduling algorithm, which is primarily based on the well-known tradeoff between the expected number of data packets that are successfully received by the sink and the transmission power consumed in the system. In addition, energy efficiency is also achieved through packet size optimization [18, 19, 20, 21]. In [18], authors address optimal fixed packet size for data communication in energy constrained wireless sensor networks by maximizing the energy efficiency metric. In [20], authors maximize the throughput and energy utilization in noisy wireless channels by adapting the packet length to the instant network statistics. In [21], authors optimize energy consumption in BSN by dynamically adjusting packet size, and examine the effects of error control schemes on energy efficiency under different propagation phenomena.

Energy efficiency has also been largely studied in WiFi network [22, 23, 24, 25]. In [22], authors present *Cell2Notify*, an energy management architecture that leverages the presence of multiple radios on the WiFi smartphone to reduce the idle energy consumption of the WiFi radio. In [23], authors propose *NAPman*, a network-assisted power management for WiFi devices that leverages AP virtualization and a new energy-aware fair scheduling algorithm to minimize client energy consumption. In [24], authors design *WiFisense*, a mobile-centric WiFi sensing system that maximizes the usage of open WiFi access opportunities via the salient features including sensor-based mobility detection, disconnected sensing and connected sensing. In [25], authors present *SiFi*, silence prediction based WiFi energy adaptation that examines audio streams from phone calls, tracks when silence periods start and stop and then places the WiFi radio to sleep during these periods.

However, these aforementioned works improve the energy efficiency in wireless sensor network and WiFi network separately. We are different in that we jointly optimize the energy consumption in both the BSN and WiFi networks. Our novelty also lies in that we achieve this en-

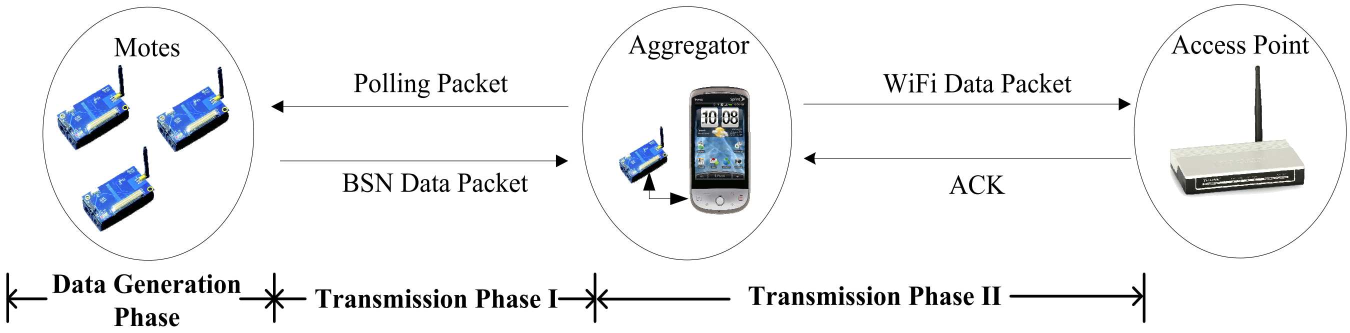


Figure 1: The Two-hop Communication System

ergy efficiency with a joint packet size optimization.

There are some works on coexistence of BSN and WiFi networks [26, 27, 7]: In [26], authors propose a *WISE* protocol that enables ZigBee links to achieve assured performance in the presence of heavy WiFi interference. In [27], authors examine the interference patterns between ZigBee and WiFi networks at the bit-level granularity and then design *BuzzBuzz* to mitigate WiFi interference through increased header and payload redundancy to ZigBee. Although these works reduce the packet collision, they do not consider the energy optimization with throughput and time delay constraints. In [7], authors shortly study energy minimization with the focused victim monitoring scenario.

3 Offline Energy Optimization

Energy constraint is an important issue in wireless communications since wireless devices usually have limited battery power. The main source of energy consumption in wireless sensor network is communication. In this paper, we aim to tackle the communication energy optimization problem in heterogeneous wireless network system through joint packet size analysis. Specifically, we consider a two-hop heterogeneous wireless communication system that is composed of motes (equipped with sensors), one aggregator (connected to a sink mote) and one WiFi access point (AP) (see Figure 1). The first hop in the system is a BSN that consists of the motes and the aggregator. In this hop, each mote tries to transmit packets to the aggregator following the IEEE 802.15.4 standard [28]. The second hop is composed of the aggregator and the AP, communicating with each other through WiFi following the IEEE 802.11 standard [29]. In this hop, the aggregator aggregates packets received from the first hop and forwards the new packets through WiFi to the AP.

In the following subsections, we first abstract the two-hop network system as a three-phase pipeline system and analyze the time delay in each phase. Second, we analyze how the energy is consumed in the two-hop heterogeneous wireless networks. Third, we formulate an energy optimization problem with constraints of throughput and time delay and then we solve the optimization problem by transforming it into an already known convex problem - GP problem. Finally, we analyze the solutions that an offline payload size lookup table is tabulated for online packet sizes selection with PDRs being as indices.

3.1 Two-hop System As a Pipeline

To formulate the communication energy consumption problem, we first abstract the two-hop heterogeneous wireless network system as a pipeline described in Figure 1. The pipeline contains three phases:

• Data Generation Phase. In this phase, data is generated by motes. We use b_n ($n \in \{1, 2, ..., N\}$) to denote all motes' data generation rates with *bits/second* being as the unit. In the pipeline, all motes together are viewed as one data generation group and its data generation rate or throughput is $\sum_{n=1}^{N} b_n$. Thus, it takes $\frac{1}{\sum_{n=1}^{N} b_n}$ time for the group to generate one bit data.

• Transmission Phase I. In this phase, generated data is transmitted from motes to the aggregator through the BSN. For one BSN data packet transmission, we suppose a polling packet is first sent from the aggregator to all motes and the selected mote replies to the aggregator with a BSN data packet. If we use S_p and θ_1 to denote the size of the polling packet and the network throughput in the first hop, respectively, then the time to send a polling packet can be computed by $t_{1p} = \frac{S_p}{\theta_1}$. Furthermore, if we use S_{h1} and S_{d1} to denote the sizes of a BSN packet's protocol overhead and data payload in the first hop, then the time for the mote to send a BSN data packet is $t_{1d} = \frac{S_{h1}+S_{d1}}{\theta_1}$.

Taking retransmission into account, we assume the PDRs of all motes in both directions in the first hop are the same and use p_1 to denote them. The failure of transmitting either a polling packet itself or a data packet will lead to the polling packet retransmission, while only data packet transmission failure will cause the data packet retransmission. Thus, to successfully deliver a polling packet and a following BSN data packet, the first hop, on average, needs to transmit the polling packet for $\frac{1}{p_1^2}$ times and the data packet for $\frac{1}{p_1}$ times. Therefore, on average, it takes $t_{1p}\times\frac{1}{p_1^2}+t_{1d}\times\frac{1}{p_1}$ time to successfully deliver one data packet from one mote to the aggregator.

• Transmission Phase II. After receiving packets from the BSN, the aggregator reorganizes the packets' payloads into a WiFi data packet. Since a WiFi data packet's generation process overlaps with Transmission Phase I and with the assumption that the aggregator transmits the new generated packet immediately after it is constructed, the time spent on the packets reorganization by the aggregator is already included in the time delay in Transmission Phase I.

To simplify the analysis, we assume that the RTS-CTS exchange is turned off, which is the default setting for commercial WiFi devices. Thus, to send a WiFi data packet, the aggregator only needs to use a CSMA-like mechanism to make sure the channel is clear. In CSMA, the aggregator first carrier senses the wireless channel. If the channel is idle, it sends out the packet immediately. Otherwise, it randomly selects a time period within [0, CW] as a backoff time counter before transmitting. Here CW denotes the backoff window size, which is composed of time slots with the length of $t_{sl} = 20\,\mu$s. The backoff time counter is decremented as long as the channel is sensed idle, stopped when a transmission is detected on the channel, and reactivated when the channel is sensed idle again. The aggregator propagates packets when the backoff time reaches zero and the channel is clear; otherwise, it backs off again. The average backoff time period for one packet transmission can be approximated as $t_{2i} = CW \times t_{sl}/2 \times min\{(M-1)/2, R\}$ [30]. Here $M-1$ is the number of potential contenders sharing the same AP with the aggregator and R is the maximum number of backoff retries.

After sending out a WiFi data packet, the aggregator waits for an ACK from the AP. Compared with the WiFi data packet, the ACK is very short. Thus, we assume there is no ACK failure. If we use S_{h2}, S_{d2} and θ_2 to denote the sizes of the WiFi packet's protocol overhead, data payload and network throughput in the second hop, respectively, then the time for the aggregator to send a data packet is $t_{2d} = \frac{S_{h2}+S_{d2}}{\theta_2}$. Furthermore, if we use p_2 to specify the PDR, the expected number of transmissions for one successful packet delivery is $\frac{1}{p_2}$. Therefore, the second hop on average takes $(t_{2i}+t_{2d})\times\frac{1}{p_2}$ time to successfully deliver one WiFi data packet from the aggregator to the AP.

3.2 Energy Consumption in Two-hop Network System

The wireless devices consume energy mainly for three tasks: transmission, reception and idle sensing. Thus, in each hop, we sum the energy consumed for the above tasks to obtain the total energy consumption.

3.2.1 Energy Consumption in the BSN

In the BSN hop, energy is consumed for communication between N motes and one aggregator. It begins with the aggregator broadcasting polling packet, and then the selected mote transmits a data packet to the aggregator. A successful delivery includes the consecutively successful delivery of both the polling packet and the following data packet. In this process, all motes consume energy to receive every polling packet, and each selected mote spends energy on transmitting the polled data packet back to the aggregator. In addition, the aggregator spends energy on broadcasting polling packets and receiving data packets from motes.

We assume that the polling packet has a fixed length, that is composed of the protocol overhead and the value of S_{d1} - the assigned packet size for motes. The total energy consumed by N motes for receiving polling packets and transmitting data packets, under consideration of retransmissions over any time period t can be formulated as:

$$E_{11} = (N\times\rho_{mr}\times t_{1p}\times\frac{1}{p_1^2}+\rho_{mt}\times t_{1d}\times\frac{1}{p_1})\times\frac{\sum_{n=1}^{N} b_n\times t}{S_{d1}} \quad (1)$$

Here ρ_{mr} and ρ_{mt} denote the power spent by a mote for receiving polling packets and for transmitting data packets, respectively. Besides, $t_{1p}\times\frac{1}{p_1^2}$ is the expected time needed to successfully receive a polling packet, while $t_{1d}\times\frac{1}{p_1}$ is the expected time to successfully deliver a packet (see Section 3.1). In short, the summation of the two items inside the parentheses is the average energy consumed for successfully delivering one packet. Furthermore, during any time period t, there are $\frac{\sum_{n=1}^{N} b_n\times t}{S_{d1}}$ packets to be transmitted in total.

Symmetrically, the total energy consumed by the aggregator for broadcasting polling packets and receiving all packets from N motes, with consideration of retransmissions over any time period of t can be expressed as:

$$E_{12} = (\rho_{mt}\times t_{1p}\times\frac{1}{p_1^2}+\rho_{mr}\times t_{1d}\times\frac{1}{p_1})\times\frac{\sum_{n=1}^{N} b_n\times t}{S_{d1}} \quad (2)$$

Here, ρ_{mt} and ρ_{mr} are still the power consumed by the mote for packet transmission and reception, because we assume the aggregator is connected to a sink mote and works under the host mode [31]. To transmit or receive a packet, the sink mote needs to extract energy from the aggregator.

Therefore, the whole energy consumed by N motes and one aggregator over any time period t in the BSN hop is expressed as:

$$E_1 = E_{11} + E_{12} \quad (3)$$

3.2.2 Energy Consumption in the WiFi Network

In the WiFi network hop, energy is consumed by the aggregator for transmitting packets and being idle. With the received data packets from BSN, the aggregator reorganizes multiple BSN packets into a new WiFi packet and then transmits it to the AP. When the packet is received by the AP, it replies an ACK to the aggregator. A successful delivery includes consecutively successful delivery of the data packet from the aggregator and the ACK from the AP. Since an ACK is tiny, we assume it is always successfully delivered and ignore the energy consumption for the ACK reception on the aggregator side. Over any time period t, the total amount of data generated by N motes is $\sum_{n=1}^{N} b_n \times t$. With retransmission mechanism, the aggregator should successfully deliver all the data to the AP.

The energy consumed by the aggregator for transmitting the WiFi packets including retransmissions over any time period t is described as:

$$E_{21} = \rho_{at} \times t_{2d} \times \frac{1}{p_2} \times \frac{\sum_{n=1}^{N} b_n \times t}{S_{d2}} \tag{4}$$

Here, ρ_{at} denotes the aggregator's transmission power and $t_{2d} \times \frac{1}{p_2}$ specifies the average time for the aggregator to successfully deliver one packet (see Section 3.1). Moreover, $\frac{\sum_{n=1}^{N} b_n \times t}{S_{d2}}$ is the total number of packets that the aggregator needs to send to the AP during any time period t.

In addition, for any packet transmission, the aggregator needs to stay in the idle state for a time period of t_{2i}. Thus, the energy spent in the idle state over any time period t is formulated as follows:

$$E_{22} = \rho_{ai} \times t_{2i} \times \frac{1}{p_2} \times \frac{\sum_{n=1}^{N} b_n \times t}{S_{d2}} \tag{5}$$

where ρ_{ai} is the power that the aggregator spends during the idle state for carrier sensing.

Therefore, the whole energy consumed by the aggregator for packet transmissions and being idle during any time period t in the WiFi network is expressed as:

$$E_2 = E_{21} + E_{22} \tag{6}$$

3.3 Energy Consumption Optimization

In this subsection, we start with formulating an energy optimization problem of the two-hop heterogeneous networks with constraints of throughput and time delay. Then we find that this energy optimization problem is a nonlinear, non-convex problem. Finally, in order to take advantage of the existing convex optimization programming technique to solve it, we convert it to a nonlinear but convex optimization problem - GP problem [9].

First, the energy optimization problem with constraints of throughput and time delay is formulated as follows:

$$\text{Minimize } E = E_1 + E_2 \tag{7}$$

Subject to

$$S_p \times \frac{\sum_{n=1}^{N} b_n}{S_{d1}} \times \frac{1}{p_1^2} + \sum_{n=1}^{N} b_n \times \frac{S_{d1} + S_{h1}}{S_{d1}} \times \frac{1}{p_1} \leq \theta_1 \tag{8}$$

$$\sum_{n=1}^{N} b_n \times \frac{S_{d2} + S_{h2}}{S_{d2}} \times \frac{1}{p_2} \leq \theta_2 \tag{9}$$

$$\begin{aligned} &\frac{S_{d1}}{\sum_{n=1}^{N} b_n / N} + t_{1p} \times \frac{1}{p_1^2} + t_{1d} \times \frac{1}{p_1} + (t_{2d} + t_{2i}) \times \frac{1}{p_2} \\ &+ \frac{S_{d1}}{\sum_{n=1}^{N} b_n} \times (\frac{S_{d2}}{S_{d1}} - 1) \leq D \end{aligned} \tag{10}$$

$$S_{d1}, S_{d2} > 0 \tag{11}$$

In the objective function (Eq.7), only the packet sizes S_{d1} and S_{d2} in two hops are variables. All other parameters have constant values and their meanings are presented here: (i) θ_1 and θ_2 in InEqs.8 and 9 denote the network throughput of the BSN and the WiFi network, respectively. (ii) D in InEq.10 is the maximum time delay allowed between the point at which data is generated on motes and the point when data is successfully delivered to the AP.

InEqs.8 and 9 capture network throughput constraints in the BSN and the WiFi network, respectively. InEq.8 means that the first hop's throughput is larger than the total amount of data (polling packets plus data packets) that needs to be sent per unit time. This amount of data contains the extra data that is incurred as a result of retransmission. Similarly, InEq.9 represents that the second hop's throughput is larger than the total amount of data (without considering ACKs) that needs to be sent per unit time.

InEq.10 captures the delay constraint in the two-hop heterogeneous networks. The left hand side of InEq.10 is the total time latency between the point at which data is generated on motes and the point when the data is received by the AP in the form of a WiFi packet. It can be understood as follows: (i) $\frac{S_{d1}}{\sum_{n=1}^{N} b_n / N}$ is the average time for one mote to generate one packet. (ii) Then, this packet is transmitted to the aggregator with time delay $t_{1p} \times \frac{1}{p_1^2} + t_{1d} \times \frac{1}{p_1}$. (iii) After receiving the data, the aggregator reorganizes the data into a WiFi packet, senses the channel, and sends it to the AP with time delay $(t_{2d} + t_{2i}) \times \frac{1}{p_2}$. (iv) The last term $\frac{S_{d1}}{\sum_{n=1}^{N} b_n} \times (\frac{S_{d2}}{S_{d1}} - 1)$ denotes the time for all motes to generate the extra data that are necessarily used to compose one WiFi packet on the aggregator. We don't include the transmission time for the extra data because the system can be abstracted as a pipeline, in which the data generation on motes and data transmission in the BSN happen in parallel. InEq.8 ensures that the first hop's network throughput is large enough to support the data generation rates of all motes with consideration of retransmissions.

To solve the above energy optimization problem, we convert it into the standard form of the GP with unknown variables S_{d1} and S_{d2} as follows:

$$\begin{aligned} \text{Min } E = &(\frac{\rho_{mt} + \rho_{mr}}{p_1 \theta_1} + \frac{\rho_{at}}{p_2 \theta_2}) \sum_{n=1}^{N} b_n t \\ &+ \frac{(N\rho_{mr} + \rho_{mt}) S_p + (\rho_{mt} + \rho_{mr}) p_1 S_{h1}}{p_1^2 \theta_1} \sum_{n=1}^{N} b_n t \times S_{d1}^{-1} \\ &+ \frac{\rho_{at} S_{h2} + \rho_{ai} \theta_2 t_{2i}}{p_2 \theta_2} \sum_{n=1}^{N} b_n t \times S_{d2}^{-1} \end{aligned} \tag{12}$$

Subject to

$$\frac{\sum_{n=1}^{N} b_n}{p_1 \theta_1} + \frac{(S_p + p_1 S_{h1}) \sum_{n=1}^{N} b_n}{p_1^2 \theta_1} \times S_{d1}^{-1} \leq 1 \tag{13}$$

$$\frac{\sum_{n=1}^{N} b_n}{p_2 \theta_2} + \frac{S_{h2} \sum_{n=1}^{N} b_n}{p_2 \theta_2} \times S_{d2}^{-1} \leq 1 \tag{14}$$

$$
\begin{aligned}
&(\frac{p_1 S_{h1} + S_p}{D p_1^2 \theta_1} + \frac{S_{h2} + \theta_2 t_{2i}}{D p_2 \theta_2}) \\
&+ \frac{(N-1) p_1 \theta_1 + \sum_{n=1}^{N} b_n}{D p_1 \theta_1 \sum_{n=1}^{N} b_n} \times S_{d1} \\
&+ \frac{p_2 \theta_2 + \sum_{n=1}^{N} b_n}{D p_2 \theta_2 \sum_{n=1}^{N} b_n} \times S_{d2} \leq 1 \qquad (15)
\end{aligned}
$$

Here, t is any constant value. According to [9], if the form of an optimization problem is in conformity with standard form of GP (the coefficients are any positive numbers and the variables' exponents are any real numbers), then it is a GP problem. As we can see, all the coefficients for objective function (Eq.12) and constraint inequalities (InEqs.13 - 15) are positive numbers. Besides, all the exponents belong to {-1,0,1} that are real numbers; thus, the objective function and the left hand side of constraint inequalities are all posynomial functions. Therefore, we can confirm that the energy optimization problem is a GP problem.

The main approach to efficiently solve the GP problem is to convert it to a nonlinear but convex optimization problem, which is a problem with convex objective and inequality constraint functions. Efficient solution methods for general convex optimization problems are well formulated [9, 10]. We choose *cvx* [10] which is a modeling system for disciplined convex programming, to solve our GP problem. *cvx* is developed by Stanford University, and effectively turns Matlab into an optimization modeling language.

Through solving this optimization problem by *cvx*, we can obtain the solutions of the packet sizes S_{d1} for motes in the BSN and S_{d2} for the aggregator in the WiFi network, with the objective of minimizing the whole energy consumption over any time period t.

3.4 Analyzing and Tabulating the Optimization Solutions

With *cvx*, we solve the energy optimization problem in the form of GP under a particular two-hop system configuration. The system's hardware is mainly composed of TelosB motes with MSP430F1611 micro controller [32] and CC2420 radio and the Sprint HTC Hero smart phone [25] with Android 3.1. One mote is connected to the phone through USB and works as a sink node in the BSN where we suppose 3 motes exist and their data generation rates are $b_1 = 4$kbps, $b_2 = 5$kbps and $b_3 = 5$kbps, respectively [33]. The values of the above three parameters are just used in this particular two-hop system configuration. However, our energy optimization problem and solutions to them are general, and hence should not be constrained by the detailed parameter settings here. The setup of other parameters is shown in Table 1.

In Table 1, S_{h1} and S_{h2} are protocol overheads of both physical layer and MAC layer. In addition, S_p is composed

N	3	ρ_{at}	1.65 W
M	5	ρ_{ai}	1.15 W
t	1 s	CW	32
S_{h1}	20 bytes	R	5
S_{h2}	46 bytes	θ_1	250 $\times 10^3$ bps
S_p	23 bytes	θ_2	54 $\times 10^6$ bps
ρ_{mt}	35$\times 10^{-3}$ W	D	177 $\times 10^{-3}$ s
ρ_{mr}	38 $\times 10^{-3} W$		

Table 1: Parameter Setup

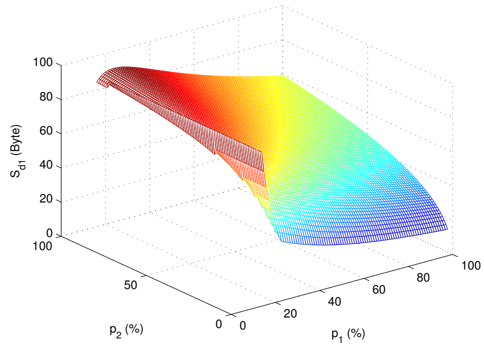
of S_{h1} and 3 bytes which store the selected mote ID (1 byte) and the value of S_{d1} (2 bytes).

Since the wireless communication channels are unstable, the parameters p_1 and p_2 are time-varying, which significantly impact the energy optimization. Therefore, we divide the value range of p_1 and p_2 into 100 bins with a bin size being as 1%. There are 100×100 bin combinations of p_1 and p_2 in total. For each combination, we replace p_1 and p_2 with the values of their bins and then solve the optimization problem to obtain the optimal solutions - packet sizes S_{d1} and S_{d2}.

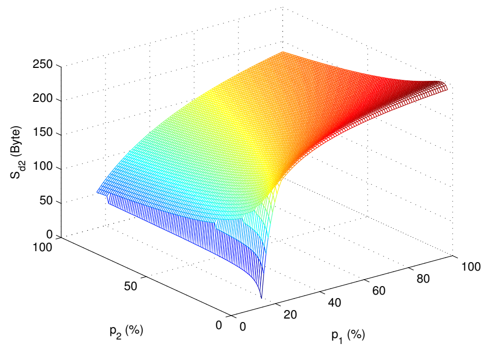
Figures 2(a) and 2(b) show the optimal solutions for S_{d1} and S_{d2} under different p_1 and p_2 combinations, respectively. From them, we first can see that when the communication quality is poor, both hops prefer to use bigger packet sizes. This observation can be explained through the following two aspects: (i) To simplify the problem, we assume the PDR is not affected by the packet length. Thus, When PDR is low, a bigger packet size with a smaller protocol overhead is preferred. (ii) A longer packet indicates a longer packet interval. As indicated in [34], a longer packet interval can attenuate the effect of burstiness, but it cannot be unboundedly large since it needs to satisfy the time delay constraint.

Second, from Figure 2(a) we can also see that if we fix the value of p_1, the packet length in the first hop grows as p_2 increases. The reason can be explained as follows: as the network throughput in the second hop is fixed, a larger p_2 indicates that the aggregator can deliver more data to the AP per unit time, while a smaller p_2 means the opposite. Moreover, when p_1 is fixed, the amount of data that is received and that should be delivered by the aggregator is a monotonically increasing function of the packet size in the first hop. Thus, the packet size in the first hop cannot be large when p_2 is low and vice versa. Similarly, in Figure 2(b), when p_2 is fixed, the packet size in the second hop is a monotonically increasing function of p_1. This is because that the aggregator has more data to deliver per unit time when the communication quality in the first hop is better.

Finally, the optimal solutions obtained from cvx show that the energy optimization problem is solvable only if p_1 ranges in [16%, 100%] and p_2 values in [3%, 100%]. These results indicate that when the communication quality is extremely poor in both two hops, the energy optimiza-



(a) Optimal Solution - S_{d1}



(b) Optimal Solution - S_{d2}

Figure 2: The Optimal Solutions

tion problem does not have an optimal solution. The reason can be either that the large number of retransmissions of the generated data packets makes the time delay unsatisfiable or that the network throughput in both two hops cannot support the transmission and retransmission of data packets. Moreover, in terms of the solvability of the energy optimization problem, the second hop can tolerate worse communication condition (p_2 can be the values between 3% and 16%) than the first hop. This is because the second hop has a much larger network throughput (54Mbps in our configuration) and hence its throughput constraint is easier to be satisfied.

For practical system deployment, we can tabulate the optimal solutions and install the table on the aggregator. The table contains 4 columns: p_1, p_2, S_{d1} and S_{d2}, where p_1 and p_2 are used as indices. The aggregator is in charge of monitoring the two-hop PDRs by: (i) calculating the ratio of the number of received packets over the number of transmitted polling packets to get p_1; (ii) calculating the ratio of the number of ACK packets over the number of transmitted data packets to obtain p_2. With the obtained p_1 and p_2, the aggregator then selects the optimal packet sizes S_{d1} and S_{d2} from the installed table to notify the assigned mote by polling packet and to prepare its own packet, respectively.

4 Performance Evaluation Based on Trace-Driven Simulation

In this section, we evaluate the jointly optimal packet size solution using the collected PDR trace (including p_1 and p_2) from a real prototype system, which is composed of one TelosB mote that is attached on the human body, the laptop to which another TelosB mote (the sink node) is connected through a USB cable, and the AP. Here, we use only one on-body mote's PDR to represent all motes' PDRs because we assume that all motes' PDRs are the same and all motes' packets transmissions are scheduled by the polling packets and hence are free of collision. In the experiment, the mote is attached on the left hand, while the aggregator is put on a chair close to the AP. We set that the aggregator transmits the polling packet every 20ms and calculates the PDRs every 5 seconds.

First of all, we compare our solution with the solutions that use fixed packet sizes. To select reasonable packet size combinations for the competitive solutions, we first notice that the valid range of packet payload size in TinyOS-2.0 [35] is 28$\sim$114 bytes and the valid packet size in WiFi network is at most 2272 bytes (including 46 bytes protocol overhead) [29]. Second, we find that the WiFi packet cannot be longer than 308 bytes; otherwise the data generation duration would already exceed the 177ms time delay constraint. Third, in the system, several BSN packets will be reorganized into a WiFi packet, thus the WiFi packet payload size we select should be an integral multiple of the packets' payload size in the BSN. Therefore, one fixed packet payload size combination we select is 28 bytes in the BSN and 28 bytes in the WiFi network, while the other combination is 70 bytes in the BSN and 140 bytes in the WiFi network (see Figure 3). Figure 3 demonstrates that our jointly optimal packet size solution consumes the least energy compared to the other two solutions. Moreover, the curves have the same trends since the energy consumptions are simulated based on one PDR trace. The huge fluctuation arises from the unstable PDRs. To save energy, our solution adjusts the packet sizes according to the fluctuant PDRs. In comparison with the solutions that use fixed packet payload sizes, our solution, on average, can reduce the energy consumption by 69.99% and 6.41%, respectively.

For other solutions that use fixed packet sizes, we compare our solution with them in terms of the mean energy consumption, minimum time delay and energy savings. The results are presented in Table 2. For each item of the Energy Savings column, it is calculated by the energy that our solution saves over the energy that the corresponding solution using fixed packet sizes consumes. As we can see in Table 2, compared with the solutions using fixed packet sizes, our solution can save up to 69.99% energy while at the same time still meet the user configured maximum time delay

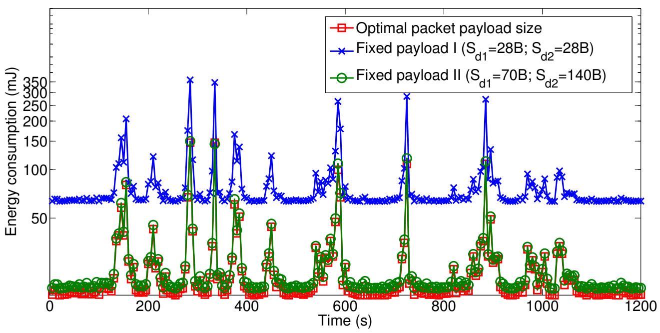


Figure 3: Energy Consumption Comparison

S_{d1} (Byte)	S_{d2} (Byte)	Mean (E) (mJ)	Min (D) (ms)	Energy Savings
28	28	77.3	51	69.99%
28	140	37.9	115	38.87%
28	308	32.6	221	28.8%
70	70	34.6	124.3	33%
70	140	24.8	164.3	6.41%
70	280	19.9	244.3	–
114	114	23.6	201.2	1.88%
114	228	17.6	266.3	–
Optimal Size		23.2	177(max)	N/A

Table 2: Performance Comparison

(177ms). Although some payload size combinations (such as 70 and 280, 114 and 228) consume less energy than our solution (these situations are represented by the *dash* items in the column of Energy Savings), it is worthy of being noticed that their minimum time delays are far beyond the user configured maximum time delay.

5 Conclusions

In this paper, we consider a two-hop data communication system that is composed of motes, an aggregator and an AP. Within the system, we formulate an energy consumption optimization problem with constraints of throughput and time delay through adjusting joint packet sizes. Mathematically, we convert the problem into the numerically solvable GP problem, whose solutions are then used to tabulate a lookup table for online packet size selection. Finally, we simulate the energy consumption based on the PDR trace collected from a deployed two-hop BSN-WiFi network for performance evaluation. The results show that our solution can achieve up to 70% energy savings than the solutions that use fixed packet sizes.

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