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Energy Modeling and Optimization for BSN and WiFi Networks Using Joint Data Rate Adaptation

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In this paper, we propose to model and optimize the communication energy consumption of devices in BSN and WiFi (BSN-WiFi) networks by using a method of joint data rate adaptation. First, we detail the BSN-WiFi network system in four consecutive phases. Then, we analyze the communication energy consumption, illustrate throughput and time delay constraints, and derive mappings of signal-to-noise ratio to packet delivery ratio (SNR-PDR) of BSN and WiFi networks. Next, we build an energy optimization model with constraints of SNR-PDR mappings, throughput, and time delay, which minimizes the communication energy consumption. With cvx, we solve this model with inputs of SNR values to obtain optimal data rates, which are used for online data rate adaptation. Finally, from a specific BSN-WiFi network system, we collect 20-minute traces for performance evaluation, and our results demonstrate that our solution achieves up to 86% energy savings compared to solutions using fixed data rates, and saves 10% energy than the optimal packet size solution.

Keywords: Energy consumption, modeling and optimization, joint data rate adaptation, BSN and WiFi networks.

1 INTRODUCTION

In our daily life, wireless devices are becoming more and more important and indispensable by providing an array of practical applications, such as

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elder fall detection [1], personal health care monitor [2], smartphone upload and download, and more. However, in most of these applications, the rapid depletion of batteries on wireless devices is a crucial problem. For instance, energy-constrained motes collecting and transmitting data rapidly deplete the battery in personal health care system, and smartphones connecting to the Internet via WiFi for downloading files or watching videos excessively consume battery. There are a lot of approaches provided to reduce the energy consumption of wireless devices, such as transmission power and rate control [3], which have been investigated in the context of network stability [4], average throughput [5], average delay [6] and packet drop probability [7]. In these approaches, data rate adaptation not only reduces energy consumption, but also meets time delay and avoids congestion. More concretely, data rate can dynamically switch data rate to adapt channel conditions, thereby optimizing energy consumption [8]. Therefore, data rate adaptation is increasingly attracted to pursue energy efficiency in wireless networks.

Two types of wireless networks have been widely studied and deployed: wireless sensor networks (WSNs) especially body sensor networks (BSNs), and WiFi networks. To pursure energy efficiency, we build a BSN and WiFi (BSN-WiFi) network system that consists of a BSN and a WiFi network. More specifically, a BSN is typically composed of an array of small and low power sensors and a resource-rich data aggregation device (referred to as an aggregator) [9]. There are a wide range of applications of BSNs, such as physical fitness assessment [10], and emergency response [11]. On the other hand, a WiFi network typically consists of an aggregator, and a wireless access point (AP). For instance, people browse web sites or send/receive emails with smartphones [12]. The BSN-WiFi network system has been deployed for many applications, such as battle field monitoring and real-time healthcare. For these scenarios, it typically starts from the aggregator for data transfer over BSN-WiFi networks. With current channel condition, the aggregator broadcasts a polling message carrying required information. Then the corresponding mote responds to the aggregator with a packet. After receiving a number of packets, the aggregator combines them into a bigger packet which is then transferred to the AP over WiFi networks. As for real-time patient health care, the state of the patient can be monitored by on-body motes, and then be transmitted to the aggregator by ZigBee, and finally be delivered to the doctors' patient information management system via WiFi. It is greatly efficient and useful for the doctor to adjust his treatments. As for battle field monitoring, motes are deployed in the battle field to track the position of moving targets. Motes first transmit the gathered information to a base station via ZigBee, and then the base station transfers them to a military control center by WiFi. Therefore, the extensive practical and useful applications motivate us to investigate the BSN-WiFi network system. Since wireless devices are usually powered by energy-constrained batteries, how to improve energy efficiency has become more and more important.

A wide range of works focus on data rate adaptation in WSNs or WiFi networks, but not both. On the one hand, some energy-efficiency based algorithms are proposed [13-15] and PHY-metric based algorithms are provided as well [16-18] in WSNs. In particular, the authors in [13] present an addition to 802.15.4 specification adding three data rates to the existing rate with a minor hardware modification. The addition to 802.15.4 specification makes variable data rates available in BSN. On the other hand, some statistics based algorithms are provided [19-22] and several PHY-metric based algorithms are proposed as well [8,23-26] in WiFi networks. In addition, some works consider BSN-WiFi network coexistence [27-30], but they are not for energy efficiency. The authors in [31,53] propose an adjustable packet size solution for energy efficiency, but we are different in that we adopt data rate adaptation solution for energy optimization in BSN-WiFi networks.

As we discussed earlier, data rate adaptation can reduce energy consumption, meet time delay and avoid congestion. Hence, we adopt the joint data rate adaptation solution to optimize the communication energy consumption of BSN-WiFi networks [32]. In this paper, we first describe a BSN-WiFi network system that consists of a BSN and a WiFi network, and then regard the system as four consecutive phases. Next, we analyze the energy consumption, illustrate throughput and time delay constraints, and derive SNR-PDR mappings of the BSN and the WiFi networks. Then, we build an energy optimization model with constraints of SNR-PDR mappings, throughput and time delay. With *cvx* [46], we solve this model with inputs of SNR and obtain optimal data rates. Then, we tabulate SNR values and associated data rate values for online data rate adaptation. Finally, we collect 20-minute traces from a specific BSN-WiFi network system for performance evaluation, and the results demonstrate that our solution can save up to 86% energy, compared to the solutions that use fixed data rates, and 10% energy than the optimal packet size solution.

Our main contributions can be summarized as follows:

- We are among the first to present a joint data rate adaptation approach to optimize the total communication energy consumption in BSN-WiFi networks.
- We analyze the communication energy consumption, throughput, time delay, and SNR-PDR mappings for BSN and WiFi networks, respectively, and then build an energy optimization model with constraints of SNR-PDR mappings, throughput, and time delay, which is then solved by the software of *cvx*.
- We collect 20-minute traces for performance evaluation and the results demonstrate that the optimal data rate solution can achieve up to 86% energy savings comparing with the solutions using fixed data rates.

The rest of this paper is organized as follows: Section 2 details the BSN-WiFi network system, and Section 3 analyzes the communication energy consumption, illustrates the throughput and time delay constraints, and derives SNR-PDR mappings. Then, Section 4 builds an energy optimization model with constraints of SNR-PDR mappings, throughput and time delay for the BSN-WiFi network system. In Section 5, we evaluate the joint data rate adaptation solution and conclude the paper in Section 6.

2 BSN-WIFI NETWORK SYSTEM

In this section, we first interpret the notations used in this paper in Table 1. Then, we illustrate the BSN-WiFi network system with data flow diagram as shown in Fig. 1. As shown in Fig. 1, the BSN-WiFi network system consists of a BSN, and a WiFi network. We focus on how to coordinate the communication between the BSN and WiFi networks. In the system, each sensor on motes generates data packets and sends them to the aggregator (referred to as a sink mote) in BSN under IEEE 802.15.4 standard (ZigBee) [40]. Then the aggregator (the smartphone) reforms the received data and forwards them to the AP via WiFi under IEEE 802.11 standard (WiFi) [34]. In particular, the aggregator is constructed by a smartphone connected with a sink mote through a USB [33]. As for the aggregator, the sink mote is responsible for communicating with all the motes and sending data to the smartphone, while the smartphone is in charge of delivering data to the AP. To elaborate the BSN-WiFi network system, we regard the data flow as four consecutive phases: Data Generation, BSN Transmission, Data Aggregation, and WiFi Transmission.

2.1 Data Generation

All sensors on motes generate data in this phase. We use b_n to represent data generation rate of mote $n(n \in \{1,2,...,N\})$. Then, $\sum_{n=1}^{N} b_n$ is the data generation rate for all motes and $\sum_{n=1}^{N} b_n / N$ denotes the average data generation rate. Therefore, the expected time for a mote generating one bit data can be calculated as $N / \sum_{n=1}^{N} b_n$.

2.2 BSN Transmission

In this phase, all the sensors on motes in BSN attempt to send the sampled data to the aggregator [54,55]. For data transmission, the aggregator first broadcasts a polling message, and then the associated mote responds a BSN data packet. The polling message carries mote ID and data rate information, where mote ID is to identify which mote that can transmit BSN packets and data rate is used by mote to transmit BSN packet. Denote a BSN data packet length by l_m, header length for both polling message and BSN data packet by

Notations	Meanings
N	The number of motes used in BSN
M-1	The number of potential contenders sharing the same AP with the aggregator
R	The maximum number of backoff retries
D	The required time delay by real time application
b_n	The data generation rate of mote n
l_m	The length of a BSN packet
l_a	The length of a WiFi packet
l_p	The length of a polling message
h_m	The header length of a polling message or a BSN data packet
h_a	The header length of a WiFi packet
r_m	The data rate in BSN
r_a	The data rate in WiFi network
cw	The backoff time period
t_{cw}	The expected backoff time period for a packet transmission
p_{r_m}	The PDR of data transmission between all the motes and the aggregator in both directions when using data rate r_m
p_{r_a}	The PDR of data transmission from the aggregator to the AP when using data rate r_a
S_{r_m}	The current SNR under the data rate r_m
S_{r_a}	The current SNR under the data rate r_a
e_{11}	The total energy consumed by N motes to receive polling messages from the aggregator and to transmit BSN data packets to the aggregator, including retransmissions of polling messages and packets, over any time period t
e_{12}	The total energy consumed by the aggregator to broadcast polling messages to all the motes and receive BSN data packets from the assigned mote, including the retransmission, over any time t
e_{21}	The energy spent for carrier sensing, including the situation of WiFi packet transmission failure, over any time period t
e_{22}	The energy spent by the aggregator, including retransmission, over any time period t
P_{mr}	The power needed by the mote to receive polling messages
P_{mt}	The power needed by the mote to transmit BSN data packets
P_{as}	The power of the aggregator for carrier sensing
P_{at}	The power of the aggregator to transmit WiFi data packets
E_{BSN}	The total energy consumed by all the motes and the aggregator over any time period t
E_{WiFi}	The total energy consumption of the aggregator to transmit WiFi data packets to the AP
θ_{BSN}	The throughput of BSN
θ_{WiFi}	The throughput of WiFi networks
r_{BSN}	The set of data rate r_m in BSN
r_{WiFi}	The set of data rate r_a in WiFi networks
$\tau_{BNS-WiFi}$	The total time period from the time when data is generated to the time when a WiFi data packet is delivered to the AP

TABLE 1
Notations and their semantic meanings

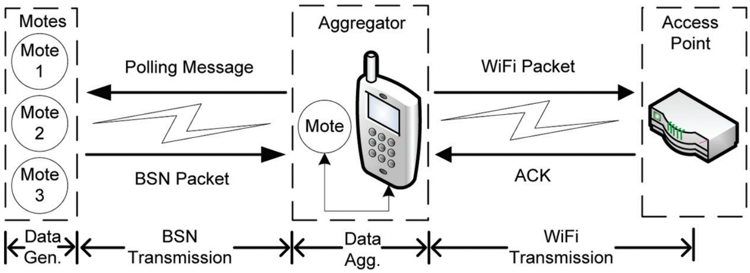

FIGURE 1
The BSN-WiFi network system.

h_m, and the data rate in BSN by r_m. Furthermore, we let l_p denote a polling message length, which consists of information of h_m-byte header, 1-byte mote ID, and 2-byte data rate, namely, $l_p = h_m + 1 + 2$ (bytes). Thus, the time needed by the aggregator broadcasting a polling message is l_p / r_m , while the time required by the mote to send a BSN data packet back is l_m / r_m. In addition, we let p_{r_m} indicate data transmission PDR between motes and the aggregator in both directions under data rate r_m. Since packet transmission in BSN is one polling message for one BSN data packet, the failure of either a polling message itself or BSN data packet will trigger polling message retransmission, while the failure of a BSN data packet only causes the BSN data packet retransmission. Hence, expected retransmission number of a polling message delivery is $1/p_{r_m}^2$ while expected retransmission number of a BSN data packet delivery is $1/p_{r_m}$. Therefore, the expected time delay of a BSN data packet delivery from the assigned mote to an aggregator can be calculated as $\frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2} + \frac{l_m}{r_m} \times \frac{1}{p_{r_m}}$.

2.3 Data Aggregation

In this phase, the aggregator will collect multiple BSN data packets from motes, remove these packet headers, and then aggregate the payloads into a WiFi data packet with a new header. If we let l_a and h_a indicate the length and header of a WiFi data packet, then a WiFi data packet can be constructed by $\frac{l_a - h_a}{l_m - h_m}$ BSN data packets. Since transmissions in BSN and data aggregation in WiFi network are processed in parallel, the net delay in aggregation is the transmission time of the remaining $\frac{l_a - h_a}{l_m - h_m} - 1$ BSN data packets after the first. Therefore, the time delay in data aggregation phase can be given by $\frac{l_m - h_m}{\sum_{n=1}^{N} b_n} \times \left(\frac{l_a - h_a}{l_m - h_m} - 1 \right)$.

2.4 WiFi Transmission

In this phase, the aggregator in WiFi network transmits the reorganized WiFi data packets to an AP under IEEE 802.11 standard [34]. The aggregator first carrier senses the channel condition and then sends a WiFi data packet to the AP until the channel is clear. The AP will reply an ACK when the channel is clear, after receiving the packet.

We first briefly introduce the CSMA protocol used in existing WiFi devices [56]. Based on default settings on commercial WiFi devices, we simply turn off the RTS-CTS exchange in CSMA protocol. In the protocol, the aggregator first carrier senses the conditions of wireless channels. If the channel is idle, it sends out the WiFi data packet immediately; otherwise, it randomly selects a time interval within [0, *cw*] as a backoff time counter before transmission, where *cw* indicates the backoff time. The backoff time counter decrements as long as the channel is sensed idle, stops when a transmission is detected, and reactivates when it is sensed idle again. The aggregator sends out WiFi data packets when the backoff counter reaches zero and the channel is idle. Otherwise, it backs off again. Therefore, the expected backoff time for a packet transmission can be computed as $t_{cw} = cw/2 \times \min\{(M-1)/2, R\}$ [35], where M-1 denotes the number of potential contenders that share the AP with the aggregator, and R indicates the maximum number of backoff retries.

Then, if let r_a denote the data rate in WiFi network, the time the aggregator needed to transmit a WiFi data packet to the AP until the channel is clear is l_a / r_a. Since the ACK message is tiny compared with the WiFi data packet, we assume there is no ACK failure. If we let p_{r_a} indicate the PDR from the aggregator to the AP under data rate r_a, the expected retransmission number of a WiFi data packet delivery is $1/p_{r_a}$. Therefore, the expected time delay of a WiFi data packet delivery from the aggregator to the AP can be given by $(t_{cw} + \frac{l_a}{r_a}) \times \frac{1}{p_{r_a}}$.

3 SYSTEM MODELING

Energy efficiency is a critical issue in energy-constrained wireless devices. In this section, we first detail the communication energy consumption, then illustrate throughput and time delay constraints, and finally derive the SNR-PDR mappings.

3.1 Energy Consumption

Communication consumes major battery energy in wireless devices. In this section, we formulate communication energy consumption issues of BSN and WiFi networks, respectively.

3.1.1 BSN energy consumption

In BSN, energy is consumed by motes and the aggregator, where motes transmit BSN data packets and receive polling messages, and the aggregator broadcasts polling messages and receive BSN data packets. If let E_{BSN} indicate the energy consumed by motes and the aggregator over time period t, we obtain:

$$E_{BSN} = e_{11} + e_{12} \tag{1}$$

where e_{11} denotes the energy consumed by motes and e_{12} represents the energy consumed by the aggregator. The total energy consumed by N motes that receive polling messages and transmit BSN data packets, including retransmissions, over time period t can be formulated as:

$$e_{11} = (N \times \frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2} \times P_{mr} + \frac{l_m}{r_m} \times \frac{1}{p_{r_m}} \times P_{mt}) \times \frac{\sum_{n=1}^{N} b_n \times t}{l_m - h_m} \tag{2}$$

where P_{mr} and P_{mt} denotes the power by the mote receiving polling messages and transmitting BSN data packets, respectively. Furthermore, $\frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2}$ represents the expected time for a mote successfully receiving a polling message, while $\frac{l_m}{r_m} \times \frac{1}{p_{r_m}}$ indicates the expected time required by a mote successfully transmitting a BSN data packet. Hence, the sum of energy consumption for both reception and transmission in the parentheses is that of a BSN data packet delivery. In addition, if we let $l_m - h_m$ indicate the payload of a BSN data packet, then $\frac{\sum_{n=1}^{N} b_n \times t}{l_m - h_m}$ denotes packet number generated by the N motes over time t.

On the other hand, the energy consumed by the aggregator broadcasting polling messages and receiving BSN data packets, including the retransmission, over time t, is computed as:

$$e_{12} = \left(\frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2} \times P_{mt} + \frac{l_m}{r_m} \times \frac{1}{p_{r_m}} \times P_{mr} \right) \times \frac{\sum_{n=1}^{N} b_n \times t}{l_m - h_m} \tag{3}$$

where P_{mt} and P_{mr} denote the power of the sink mote on the aggregator broadcasting polling messages and receiving BSN data packets, respectively. Since motes are unable to communicate with the smartphone directly, we explore the sink mote broadcasting and receiving packets instead of a smartphone. As a result, we connect a sink mote with a smartphone through a USB [33] as the aggregator.

3.1.2 WiFi energy consumption

After AP receives a WiFi data packet, it will reply an ACK, according to IEEE 802.11. Since the ACK is tiny, we assume the aggregator does not consume any energy to receive it. In WiFi network, energy is consumed by the aggregator carrier sensing the channel condition and transmitting WiFi data packets to the AP. The aggregator should receive $\sum_{n=1}^{N} b_n \times t$ payload from BSN data packets, which is then delivered to the AP in the form of WiFi data packets. If we let E_{WiFi} represent the energy consumption of the aggregator transmitting WiFi data packets to the AP, we have:

$$E_{WiFi} = e_{21} + e_{22} \tag{4}$$

where e_{21} and e_{22} denote the energy consumed for carrier sensing and transmitting WiFi data packets, respectively.

Before each packet transmission, the aggregator will carrier sense the channel condition for an expected time period t_{cw}. Thus, the energy spent for carrier sensing, including WiFi packet failures, over any time period t, can be calculated as:

$$e_{21} = t_{cw} \times \frac{1}{p_{r_a}} \times P_{as} \times \frac{\sum_{n=1}^{N} b_n \times t}{l_a - h_a} \tag{5}$$

where P_{as} represents the power consumed by the aggregator carrier sensing. Furthermore, $t_{cw} \times \frac{1}{p_{r_a}}$ denotes the expected carrier sensing time for a WiFi data packet delivery, and $l_a - h_a$ indicates the payload of a WiFi data packet.

Once the channel is clear, the aggregator sends out a WiFi data packet immediately. Thus, the energy consumed by the aggregator, including retransmission, over any time period t, can be computed as:

$$e_{22} = \frac{l_a}{r_a} \times \frac{1}{p_{r_a}} \times P_{at} \times \frac{\sum_{n=1}^{N} b_n \times t}{l_a - h_a} \tag{6}$$

where P_{at} represents the power of the aggregator transmitting WiFi data packets, and $\frac{l_a}{r_a} \times \frac{1}{p_{r_a}}$ indicates the expected time for a WiFi data packet delivery.

3.2 Throughput Constraint

In this section, we make sure that the data throughput is less than or equal to the optimal data rate [36-38]. We analyze the throughput for BSN (θ_{BSN}) and WiFi network (θ_{WiFi}), respectively.

3.2.1 BSN throughput constraint

Over a unit time period (e.g., 1 second), polling messages and BSN data packets are transmitted in the BSN. Hence, the throughput constraint of BSN can be expressed as:

$$l_p \times \frac{\sum_{n=1}^{N} b_n}{l_m - h_m} \times \frac{1}{p_{r_m}^2} + \sum_{n=1}^{N} b_n \times \frac{l_m}{l_m - h_m} \times \frac{1}{p_{r_m}} \le r_m \tag{7}$$

where $\frac{\sum_{n=1}^{N} b_n}{l_m - h_m}$ indicates the number of polling messages from the aggregator, and $l_p \times \frac{\sum_{n=1}^{N} b_n}{l_m - h_m}$ denotes the data amount in polling messages, and $\sum_{n=1}^{N} b_n \times \frac{l_m}{l_m - h_m}$ represents the total amount of data in BSN data packets, including the header data of each packet. Taking the retransmission of polling message and BSN data packets into account, the total amount of data transmitted per unit time should be less than or equal to the current data rate r_m, namely, $\theta_{BSN} \le r_m$.

3.2.2 WiFi throughput constraint

Over a unit time period, WiFi data packets are delivered in the WiFi networks; therefore, the throughput constraint of WiFi network can be formulated as:

$$\sum_{n=1}^{N} b_n \times \frac{l_a}{l_a - h_a} \times \frac{1}{p_{r_a}} \le r_a \tag{8}$$

where $\sum_{n=1}^{N} b_n \times \frac{l_a}{l_a - h_a}$ indicates the amount of WiFi data packet. The data amount delivered including retransmissions per unit time should be less than or equal to the current data rate r_a, that is, $\theta_{WiFi} \le r_a$.

3.3 Time Delay Constraint

Time delay is a rigorous requirement for some real time applications [39], such as Voice over IP (VoIP). Therefore, time delay constraint of BSN-WiFi networks can be calculated as:

$$\begin{aligned}&\frac{l_m - h_m}{\sum_{n=1}^{N} b_n / N} + \frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2} + \frac{l_m}{r_m} \times \frac{1}{p_{r_m}} + \\ &\frac{l_m - h_m}{\sum_{n=1}^{N} b_n} \times \left(\frac{l_a - h_a}{l_m - h_m} - 1\right) + \left(t_{cw} + \frac{l_a}{r_a}\right) \times \frac{1}{p_{r_a}} \le D\end{aligned} \tag{9}$$

where D indicates the required time of a real time application. We regard the total time delay of BSN-WiFi networks $\tau_{BSN-WiFi}$ as a pipelined data flow: (i) first, since all motes spend time on generating packets, the average time needed to generate a BSN data packet is $\frac{l_m - h_m}{\sum_{n=1}^{N} b_n / N}$; (ii) then, within time $\frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2} + \frac{l_m}{r_m} \times \frac{1}{p_{r_m}}$ under data rate r_m, a BSN data packet is transmitted to the aggregator; (iii) next, the aggregator collects $\frac{l_a - h_a}{l_m - h_m} - 1$ BSN data packets from motes and then composes a WiFi data packet within the time $\frac{l_m - h_m}{\sum_{n=1}^{N} b_n} \times \left(\frac{l_a - h_a}{l_m - h_m} - 1\right)$; (iv) finally, the aggregator delivers the WiFi data packet to AP within time $\left(t_{cw} + \frac{l_a}{r_a}\right) \times \frac{1}{p_{r_a}}$.

3.4 SNR-PDR Mappings

We attempt to find a map of one SNR for one optimal data rate through analyzing SNR-PDR mappings of BSN and WiFi networks, respectively, in this section.

3.4.1 SNR-PDR mapping in BSN

Through a minor hardware changes, data rates 500*kbps*, 1000*kbps* and 2000*kbps* are added to the existing data rate 250*kbps* in IEEE 802.15.4 specification [13,57]. Hence, the data rate r_m in BSN can be valued in set $r_{BSN} : \{250kbps, 500kbps, 1000kbps, 2000kbps\}$, that is, $r_m \in r_{BSN}$. Based on [13], we obtain SNR to PDR map under data rate r_m in BSN:

$$p_{r_m} = \left(1 - \frac{2^k - 1}{2} \times \exp\left(-\sqrt{\left(u \times \frac{S_{r_m}}{2}\right)}\right)\right)^v \tag{10}$$

where S_{r_m} indicates SNR under data rate r_m and p_{r_m} denotes PDR under data rate r_m. The exponent v is a BSN data packet length in symbols. k and u are parameters in coding scheme, which indicates that k bits are encoded together into a u chip signal. We define SNR-PDR mappings in BSN as $p_{r_m} = f(S_{r_m})$, and just list the parameters under different data rates in Table 2.

The SNR in BSN typically range in [1dB, 30dB] [13,41], therefore, based on Eq. 10 and Table 2, we plot Fig.2 to show the correlation between SNR and PDR under r_{BSN}. As illustrated in Fig.2, PDRs of data rates rise when SNR increases. Hence, we can deduce that $p_{r_m} = f(S_{r_m})$ is a monotonically increasing function. The other observation is that a lower data rate grows faster than a higher one as SNR increases. The reason is that when the link quality is poor (low PDR or small SNR), a lower data rate is preferred; while when it is good, a higher data rate has priority. In particular, for a specific SNR value, there are $|r_{BSN}| = 4$ PDR values associated with $|r_{BSN}| = 4$ data rates, where $|r_{BSN}|$ indicates the number of elements in set r_{BSN}.

k(bit)	u(chip)	r_m(kbps)
4	32	250
4	16	500
4	8	1000
1	1	2000

TABLE 2
Parameters for SNR-PDR Model in BSN

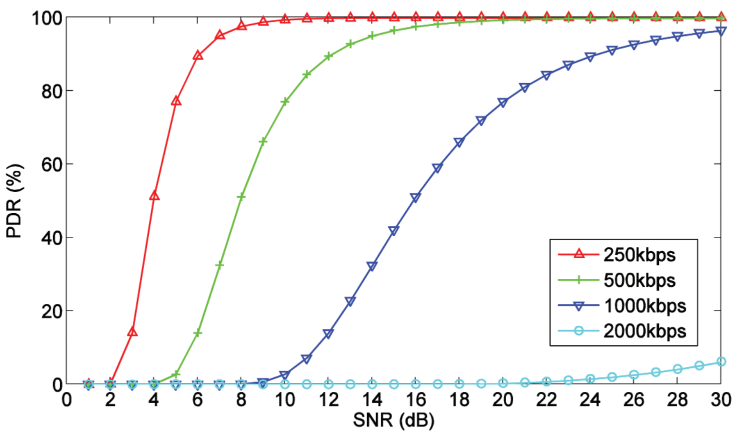

FIGURE 2
SNR-PDR mapping of BSNs.

3.4.2 SNR-PDR mapping in WiFi network

The available values of data rate r_a in WiFi networks lie in set r_{WiFi}: {6*Mbps*, 12*Mbps,* 18*Mbps,* 24*Mbps,* 35*Mbps,* 48*Mbps,* 54*Mbps* [23,42], that is, $r_a \in r_{WiFi}$. The SNR in WiFi networks usually lie in [1dB, 40dB] and based on the values in Fig. 5 of [42], we replot a color Fig. 3 that demonstrates the correlation between SNR and PDR under r_{WiFi}. We define the PDR-SNR mapping of WiFi networks as a function of $p_{r_a} = f(S_{r_a})$. As illustrated in Fig. 3, PDRs for all the data rates increase as SNR grows. Thus, we deduce $p_{r_a} = f(S_{r_a})$is a monotonic increasing function. The other observation is that with the increase of SNR, PDRs of lower data rates grow faster than that of higher ones. In particular, there are $|r_{WiFi}| = 7$ PDR values associated with $|r_{WiFi}| = 7$ data rates for each SNR value, where $|r_{WiFi}|$ indicates the number of elements in set r_{WiFi}.

3.4.3 SNR measurements

For BSN, we refer to a method in [41]: each mote is equipped with an IEEE 802.15.4 compliant Chipcon CC2420 radio, and the received signal strength indicator (RSSI) of CC2420 on the aggregator contains the measurement of signal power P_{sm} in *dBm*, if there is no incoming packet. RSSI value is the signal power of environmental noise P_{nm} in *dBm*. Therefore, the SNR in BSN can be calculated as: $S_{BSN} = \frac{P_{sm} - P_{nm}}{P_{nm}}$.

On the other hand, for WiFi networks, we refer to an approach provided in [43,47]: RSSI values reported by network interface cards (NICs) give an estimate of the signal power denoted as P_{sa} in *dBm* for each received packets. If there is no incoming packet, the signal power of environmental noise can be

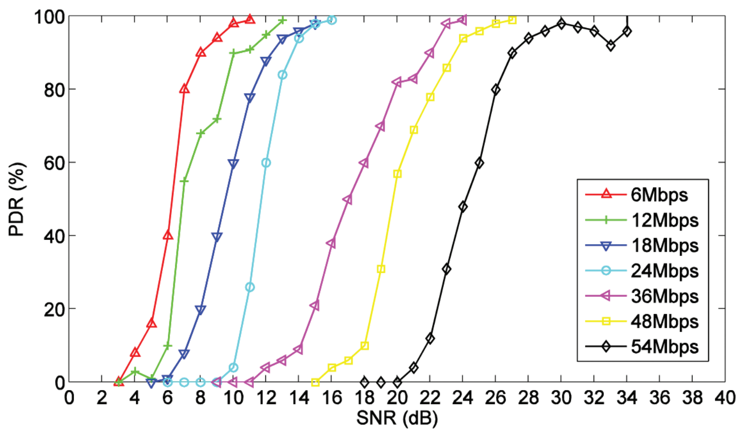

FIGURE 3
SNR-PDR mapping of WiFi networks.

expressed as P_{na} in *dBm*. Thus, the SNR in WiFi networks can be computed as: $S_{WiFi} = \frac{P_{sa} - P_{na}}{P_{na}}$.

Next, we discuss combinations of SNRs as well as data rates in BSN and WiFi network, respectively. Since S_{r_m} falls in the range [1dB, 30dB] while S_{r_a} lies in [1dB, 40dB], there will be 30×40 combinations of (S_{r_m}, S_{r_a}). On the other hand, r_m lies in set r_{BSN} with 4 elements and r_a falls in set r_{WiFi} with 7 elements. Therefore, each combination of (S_{r_m}, S_{r_a}) associates with 4×7 combinations of (r_m, r_a). Next, we try to obtain one out of 28 combinations of (r_m, r_a) for each SNR combination (S_{r_m}, S_{r_a}) through solving a communication energy optimization model with constraints of SNR-PDR mappings, throughput, and time delay.

4 ENERGY OPTIMIZATION

Energy efficiency is also a critical issue in energy-constrained BSN-WiFi networks. In this section, we optimize the communication energy in BSN-WiFi networks via a method of joint data rate adaptation. Through the model, we attampt to input the SNR values (S_{r_m}, S_{r_a}) and output the corresponding optimal data rates (r_m, r_a). More concretely, we build an energy optimization model for BSN-WiFi networks with constraints of SNR-PDR mappings, throughput, and time delay. Then, we solve it by a software *cvx* and tabulate the offline results for online usage.

4.1 Energy Optimization Modeling

We build an energy optimization model with constraints of SNR-PDR mappings, throughput, and time delay for BSN-WiFi networks. With inputs of SNR values and outputs of optimal data rates through solving the model, we aim to obtain a map of SNR values (S_{r_m}, S_{r_a}) and optimal data rate (r_m, r_a), meanwhile minimize communication energy consumption:

$$Minimize \quad E = E_{BSN} + E_{WiFi} \tag{11}$$

Subject to

$$p_{r_m} = f(S_{r_m}) \tag{12}$$

$$p_{r_a} = f(S_{r_a}) \tag{13}$$

$$\theta_{BSN} \leq r_m \tag{14}$$

$$\theta_{WiFi} \le r_a \tag{15}$$

$$\tau_{BSN-WiFi} \le D \tag{16}$$

$$r_m \in r_{BSN}, r_a \in r_{WiFi} \tag{17}$$

where r_m and r_a are optimal variables.

Eq. 11 is an objective function, and Eqs. 12-17 are constraints. For objective function (Eq. 11), inputs are one SNR combination (S_{r_m}, S_{r_a}) associated with 28 combinations of (r_m, r_a) while outputs are optimal data rates (r_m, r_a) exactly associated with (S_{r_m}, S_{r_a}).

For constraints, Eq. 12 is a map of SNR S_{r_m} associated with data rate r_m and PDRs p_{r_m} in BSN, while Eq. 13 is a map of SNR S_{r_a} associated with data rate r_a and PDRs p_{r_a} in WiFi networks. Eqs. 14 and 15 are throughput constraints in BSN and WiFi networks, respectively. Eq. 16 is time delay required by a specific application, where $\tau_{BSN-WiFi}$ indicates the time period from the time data is generated to the time a WiFi data packet is delivered. Eq. 17 denotes data rates r_m and r_a are discrete values in sets of r_{BSN} and r_{WiFi}, respectively.

4.2 Offline Solution and Online Usage

We set up parameters in the model, then solve it by a software *cvx*, and finally tabulate the offline results for online dynamic data rate adaptation.

Based on BSN-WiFi network system, we exploit three TelosB motes with MSP430F1611 micro controller and CC2420 radio [44,48-50], use a Sprint HTC Hero smartphone connected with a sink mote via a USB as an aggregator, and employ a router connected to Internet through cables as an AP. The parameters in the model are presented in Table 3. Note that the parameters in the table are just a specific application setup, therefore, the model is not con-

Parameter	Value	Parameter	Value	Parameter	Value
N	3	l_a	272B	P_{as}	$1.15W$
M	5	h_m	$20B$	cw	640µs
R	5	h_a	$46B$	D	$177ms$
t	$1s$	P_{mt}	$35mW$	b_1	$4kbps$
l_p	$23B$	P_{mr}	$38mW$	b_2	$5kbps$
l_m	$133B$	P_{at}	$1.65W$	b_3	$5kbps$

TABLE 3
Parameter Setup

fined to these parameters, and the corresponding results are just used to validate the model.

From the table, l_p consists of fields of h_m-byte header, 1-byte mote ID, and 2-byte data rate. We set the length of WiFi data packet payload as $l_a - h_a = 226$ *bytes*, so that it is in multiple length of BSN data packet payload $l_m - h_m = 113$ *bytes*. We assign the time delay $D = 177ms$, from a specific application of VoIP [51-52].

Then, we solve the energy optimization model. We rewrite the standard form of energy optimization model as:

$$\begin{aligned} Minimize \quad E &= E_{BSN} + E_{WiFi} \\ &= \frac{P_{as} t_{cw}}{p_{r_a}\left(l_a - h_a\right)} \sum_{n=1}^{N} b_n t + \frac{\left(N l_p + p_{r_m} l_m\right) P_{mr} + \left(l_p + p_{r_m} l_m\right) P_{mt}}{p_{r_m}^2 \left(l_m - h_m\right)} \\ &\sum_{n=1}^{N} b_n t \times r_m^{-1} + \frac{l_a P_{at}}{p_{r_a}\left(l_a - h_a\right)} \sum_{n=1}^{N} b_n t \times r_a^{-1} \end{aligned} \tag{18}$$

Subject to

$$\frac{l_p + p_{r_m} l_m}{p_{r_m}^2 \left(l_m - h_m\right)} \sum_{n=1}^{N} b_n \times r_m^{-1} \le 1 \tag{19}$$

$$\frac{l_a}{p_{r_a}\left(l_a - h_a\right)} \sum_{n=1}^{N} b_n \times r_a^{-1} \le 1 \tag{20}$$

$$\left(\frac{(N-1)\left(l_m - h_m\right) + l_a - h_a}{D \sum_{n=1}^{N} b_n} + \frac{t_{cw}}{D p_{r_a}} \right) + \frac{p_{r_m} l_p + l_m}{D p_{r_m}^2} \times r_m^{-1} + \frac{l_a}{D p_{r_a}} \times r_a^{-1} \le 1 \tag{21}$$

where r_m and r_a are optimization variables, and t is any time period. According to [45], the model is a GP problem if its standard form satisfies: (i) the coefficients of the functions are any positive numbers; and (ii) the exponents are any real numbers. All coefficients of the objective function (Eq. 18) and all constraint inequalities (Eqs. 19-21) are positive numbers, and all exponents of the optimization variables belong to $\{-1, 0\}$ that are real numbers, and the objective function and the left side of constraint inequalities are all polynomial functions. Therefore, we conclude that the model is a GP problem. We exploit an efficient solution for a GP problem *cvx* [46] to solve the energy optimization model, and we can obtain the offline results of optimal data rates r_m for motes in the BSN and r_a for the aggregator in WiFi networks for all combinations of (S_{r_m}, S_{r_a}). We plot Fig. 4 to illustrate optimal data rates r_m and r_a with all SNR combinations (S_{r_m}, S_{r_a}), that shows data rates increase as both SNRs increase. More concretely, optimal data rate r_m in BSN increases when SNR S_{r_m} increases as depicted in Fig. 4(a). This is because when SNR S_{r_m} increases, that is, PDR p_{r_m} is increasing, a higher data rate is adapted, which consumes less power. However, there is an exception that when S_{r_m} is extremely low, the data rate is the highest one $2000 kbps$. The reason is the mote tries its best to send data out in the extreme condition. On the other hand, the optimal data rate r_a in WiFi networks increases when SNR S_{r_a} rises, as illustrated in Fig. 4(b). The same exception is that when S_{r_a} is extremely low, the data rate is the highest one $64 Mbps$.

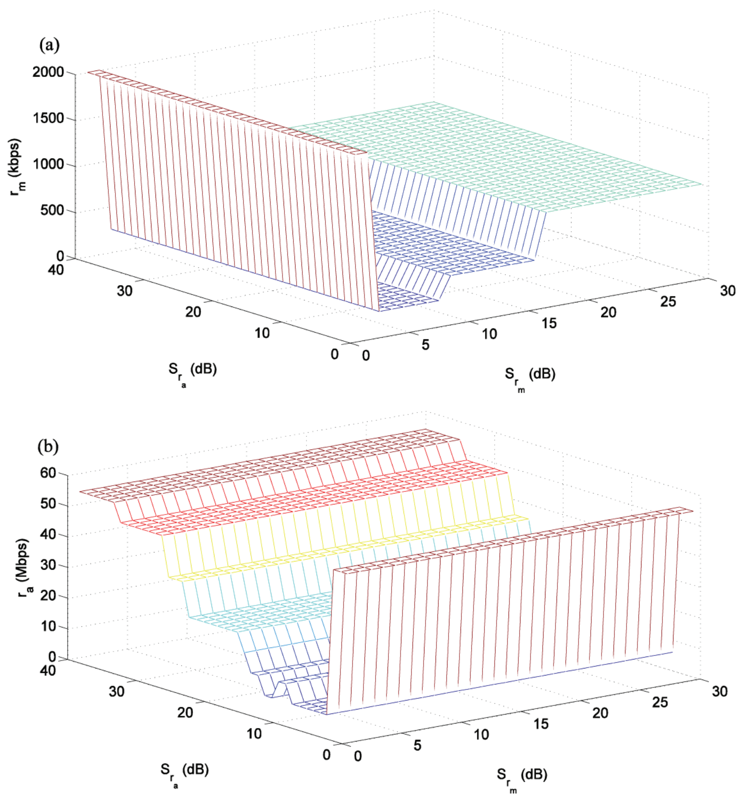

FIGURE 4
The optimal data rate solution. (a) optimal data rate r_m; (b) optimal data rate r_a.

We tabulate the optimal results with 4 columns and 30×40 rows. The columns are composed of S_{r_m}, S_{r_a}, r_m and r_a and the rows are the corresponding combinations of S_{r_m} and S_{r_a}. The offline optimal solution table can be loaded on the aggregator for online data rate adaptation. More specifically, according to real-time SNRs, the aggregator assigns data rate for motes in BSN via polling messages and specifies the data rate for itself in WiFi network. Note that the optimal solutions are solved on a laptop offline, and then we install the results on the aggregator for online usage. That is why we say the solution is offline and the usage is online.

5 PERFORMANCE EVALUATION

We first specify the evaluation setup that collects traces, and then evaluate our solution in terms of energy savings, throughput and time delay, cost analysis, and comparison with optimal packet size solution, respectively.

5.1 Evaluation Setup

Our BSN-WiFi network system mimics a typical assisted living facility, where the BSN is in charge of monitoring a patient's physiological readings and transmitting these data to a portable device (such as a smartphone), then the WiFi network is responsible for delivering these data to an AP, and the AP finally transmits the data to a data center in a hospital by Internet. In the experiment, we use one TelosB mote, a laptop connected with a TelosB mote through a USB as an aggregator, and an AP connected to Internet via cables. We collect about 20-minute PDR traces where the aggregator polls every $20ms$ and computes PDR every $5s$. Then, we convert PDR traces into SNR traces based on SNR-PDR mappings to evaluate our optimal data rate solution.

5.2 Energy Savings

We compare the optimal solution with solutions of fixed data rate to demonstrate energy savings. According to SNR traces, our solution operates on the aggregator that selects optimal data rates from the table for motes and itself, while fixed data rate solutions work on the mote and aggregator delivering packets with prefixed data rates.

Since available data rates are r_{BSN} : {250*kbps*, 500*kbps*, 1000*kbps*, 2000*kbps*}, in BSN and are r_{WiFi} : {6*Mbps*, 12*Mbps*, 18*Mbps*, 24*Mbps*, 35*Mbps*, 48*Mbps*, 54*Mbps*} in WiFi network, we randomly select 250*kbps* for BSN and 24*Mbps* for WiFi network, and 1000*kbps* and 54*Mbps*, respectively, as two fixed data rate solutions for comparison. Based on SNR traces, we plot the energy consumption for our solution and the two fixed data rate solutions. As shown in Fig. 5, our solution consumes the least energy com-

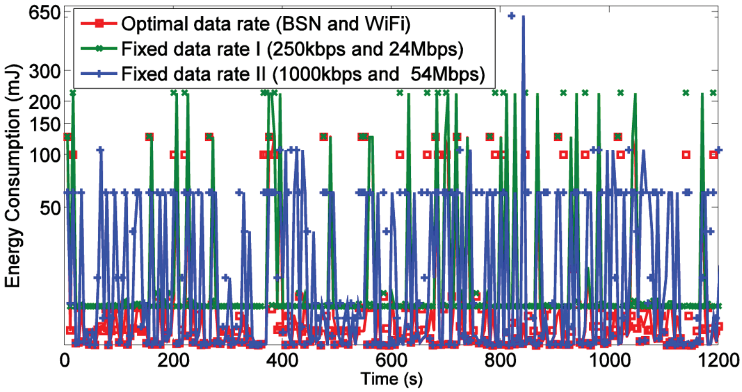

FIGURE 5
Energy consumption comparison.

r_m(kbps)	r_a(Mbps)	Mean(E)(mJ)	Energy Savings
250	6	39.1	42%
250	24	35.4	36%
250	54	34.6	35%
500	18	57.7	61%
500	54	56.6	60%
1000	12	34.2	34%
1000	48	32.4	30%
2000	54	171.6	86%
Optimal Data Rate		22.6	N/A

TABLE 4
Performance Comparison

pared with the other two solutions. In addition, the combination (250*kbps*, 24*Mbps*) consumes more energy than the combination (1000*kbps*, 54*Mbps*). For comparison, our solution saves 36% energy than solution I (250*kbps*, 24*Mbps*) and 30% than solution II (1000*kbps*, 54*Mbps*).

To be general, we compare our solution with more solutions of fixed data rate in terms of mean energy consumption and energy savings, as listed in Table 4. In Table 4, we have columns of data rates r_m in BSN, r_a in WiFi networks, the $Mean(E)$ energy consumption and Energy Savings, where energy savings are calculated by the energy our solution saves over the energy the fixed data rate solution consumes. Compared to all fixed data rate solutions, our solution consumes the least energy 22.6*mJ* and achieves up to 86% energy savings. We note that fixed data rate solutions with higher r_a consume less energy for the same r_m, and energy savings of our solution decreases with increase of r_a. For instance, the mean and energy savings in the first three rows decrease gradually with increase of r_a. This is because the same data amount sent by motes consumes less energy if r_a is higher. The fixed data rate solutions with higher r_m consume more energy, and energy savings of our solution increases with the increase of r_m, for the same r_a value. For example, the mean and energy savings in the third, fifth and eighth rows increase with increase of r_m. The reason is that more data with higher data rate r_m consumes more energy to transmit. Therefore, we conclude that our solution saves energy by dynamically adjusting the joint data rates of BSN and WiFi networks to current SNR.

5.3 Throughput and Time Delay

To evaluate the performance of throughput and time delay, we explore two metrics: (i) delivered throughput ratio, that is, the timely delivered data throughput over the needed data throughput; and (ii) time delay miss ratio, that is, the number of data packets that miss their deadlines over the number of data packets requested to send [36]. We select eight representative fixed data rate solutions, and compute delivered throughput ratios and time delay miss ratios. As shown in Table 5, the delivered throughput ratio of BSN increases as data rate r_m increases. The bigger the data rate is, the higher the throughput ratio is. Throughput supported by IEEE 802.11 is large enough, so WiFi network has a full delivered throughput ratio. Then, the time delay miss ratio relies heavily on the transmission rate r_m in BSN. That is, the faster the r_m is, the less time it takes. Therefore, comparing with fixed packet size solutions, our solution provides a full delivered throughput ratio and zero time delay miss ratio.

r_m (kbps)	r_a (Mbps)	Delivered Throughput Ratio		Time Delay Miss Ratio
		BSN	WiFi network	
250	6	91%	100%	5%
250	24	91%	100%	5%
250	54	91%	100%	5%
500	18	94%	100%	0%
500	54	94%	100%	0%
1000	12	97%	100%	0%
1000	48	97%	100%	0%
2000	54	100%	100%	0%
Optimal Data Rate		100%	100%	0%

TABLE 5
Delivered Throughput Ratios and Time Delay Miss Ratios

5.4 Cost Analysis

In this section, we discuss the cost of BSN-WiFi network system in terms of computation, storage of the lookup table, and networks. The computation cost is the time cost required to generate the optimal data rate lookup table. Our solution takes about 82 minutes to generate a 1200×4 lookup table on a desktop with Intel Core quad 2.8G processor and 2G Memory. The optimal data rate lookup table is generated before loading on the aggregator and once it is loaded, it will work for all the data transmission. Second, the aggregator has a storage of 512MB and supports flash memory cards as well, while the size of the optimal data rate lookup table is only 25.1KB on disk, therefore, the storage cost is too less. At last, network cost is the extra packets to send to make sure the data can be directly transmitted. Thus, network cost of the system is the transmission of polling messages and ACK messages. In BSN, a data packet delivery to the aggregator needs $\frac{l_p}{r_m} \times \frac{1}{p_{r_m}^2}$ -byte extra data transmission. In WiFi network, since ACK message is tiny and communication is stable and efficient, we do not count the cost of ACK message. Therefore, the cost of computation, storage and networks in BSN-WiFi network system is much less.

5.5 Comparison with Optimal Packet Size Solution

A prior work [31,53] presents an optimal packet size solution to optimize the energy consumption in BSN-WiFi networks, which transmits data packets with optimal packet size according to current PDR, but with fixed data rate. We compare our solution with the packet size solution on energy consumption. As illustrated in Fig.6, obviously, our solution consumes less energy than optimal

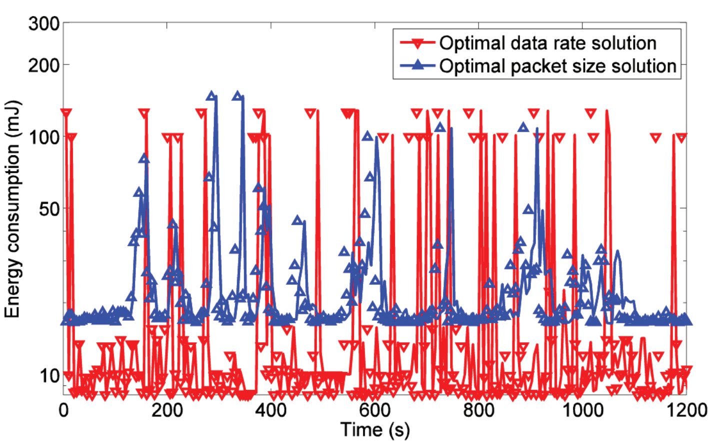

FIGURE 6
Comparison of two solutions in energy consumption.

packet size solution. On the other hand, our solution can save 10% energy than the other solution. In addition, the mean energy consumption of our solution is 22.6*mJ*, while it is 23.2*mJ* for optimal packet size solution. Therefore, our solution consumes less energy than the optimal packet size solution.

6 CONCLUSIONS

In this work, we consider the communication energy consumption optimization for BSN- WiFi networks by using joint data rate adaptation. More concretely, we first detail the BSN-WiFi network system in four consecutive phases. Then, we analyze the communication energy consumption, illustrate throughput and time delay, and derive SNR-PDR mappings for BSN and WiFi networks, respectively. Next, we build an energy optimization model with constraints of SNR-PDR mappings, throughput, and time delay thereby minimizing the energy consumption in BSN-WiFi networks, which is then demonstrated to be a GP problem. With a software *cvx*, we solve the model with inputs of SNRs, and outputs of optimal data rates, which are tabulated for online data rate adaptation. For performance evaluation, we collect 20-minute traces from a specific BSN-WiFi network system, and our results demonstrate that the solution achieves up to 86% energy savings compared with the solutions using fixed data rates, and saves 10% energy than the optimal packet size solution.

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