End-to-end Power Optimization in Non-Homogenous Relay Environment for Wireless Body Area Networks (WBANs)

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***Abstract*—Wireless body area networks (WBANs) is a special designed sensor network to connect various medical sensors for health which emerges as the natural byproduct of existing sensor network technology and biomedical engineering. In this paper, the tradeoff between the total power consumption and the end-to-end rate in non-homogenous relay environment for WBANs has been investigated. We consider such scenario involved two communication links, implant to body surface and body surface to off body. WCE emits RF signal from inside of human GI tract, the external AP that is designed destination to collect the transmitted bits by an on-body relay node which is placed on the belt of the human body. The energy consumption to deliver one bit and the end-to-end rate for the whole relay network is formulated. The total energy and end-to-end rate tradeoff has been studied with bandwidth, propagation distance and data rate for each link. The minimum energies over all possible data rate is obtained for different conditions.**

I. Introduction

Wireless body area networks (WBANs) is a specifically designed sensor network to connect various medical sensors for health which emerges as the natural byproduct of existing sensor network technology and biomedical engineering. WBANs comprises a series of miniature sensor each of which has its own energy supply, consisting of storage and energy scavenging devices. Each node has enough intelligence to carry out its task. These nodes can be placed inside, on the surface of, or around the body, which can provide long term health monitoring of patients without constraining their normal activities as an alternative to traditional practices of monitoring a patients physiological condition [1].

The wireless capsule endoscopy (WCE) is an important part of WBANs which provides a noninvasive way to inspect the entire Gastrointestinal (GI) tract. It is capable to provide the interior view of intestinal system and at the same time associate the view with location and motion information of the capsule [2][3]. As the capsule moves through the intestines, it takes pictures, which are transmitted to a small intermediate data recorder that the patient wears on his/her belt. The capsule is disposable and does not need to be recovered by the patient or medical personnel. So power consumption of the WCE is another core research topic [4].

Besides WCE, other nodes in WBANs are also required to operate under strict resource constraints. The most limited factor is power source, which determines maximum power consumption of the system. Specifically, power for transmitting data from WBANs node to the remote Access Point (AP) must be preserved so that battery life is extended. In addition, the total power consumption to transmit information bits at the end-to-end rate is also an important consideration. The relay nodes play an important role in reducing the transmission power of biosensors and energy consumption of networks [5]. The advantages of resorting to cooperative communications for WBANs in terms of minimized energy consumption are investigated in [6]. The dynamic resource management in higher-level protocols by investigating the trade-off between connection latency and energy consumption is addressed [7]. A protocol named Distance Aware Relaying Energy efficient (DARE) to monitor patients in multi-hop Body Area Sensor Networks (BASNs) is proposed to increase network lifetime and efficiently reduce the energy consumption [8]. Previous research has mainly focused on designing algorithm and protocol to minimize the energy for WBANs nodes and leverage the end-to-end energy-bandwidth trade-off in multi-hop wireless networks in homogenous environment [9].

In this paper, we consider the trade-off between the total power consumption and the end-to-end rate in non-homogenous relay environment for WBANs and select WCE application as a case study, for which the total power consumption for single bit transmission only includes the data forwarding cost in each individual link. In the WCE case, the relay node is placed on the belt of the human body, over which the WCE can communicate with external AP. We first derive the expression for the relationship between the overall energy per bit to noise power spectral density ratio and end-to-end rate. Then we use the WCE system to demonstrate the total energy and end-to-end rate trade-off with various bandwidth, deployment and data rate for individual link. As far as we can see, no such research on the overall energy per bit to noise power spectral density ratio and the end-to-end rate has been conducted in the perspective of non-homogenous environment for WBANs.

The rest of this paper is organized as follows. We describe the system model in Section II and the problem formulation in wireless body area networks on the total power and the end-to-end rate in section III. In section IV, we provide numerical results and conclude the paper in section V.

TABLE I: IEEE 802.15.6 radio propagation channel models.

Scenario	Description	Frequency Band	Channel Model
S1	Implant to implant	402-405MHz	CM1
S2	Implant to body surface	402-405MHz	CM2
S3	Implant to external	402-405MHz	CM2
S4	Body surface to body surface (LOS)	13.5,50,400,600,900MHz, 2.4, 3.1-10.6GHz	CM3
S5	Body surface to body surface (NLOS)	13.5,50,400,600,900MHz, 2.4, 3.1-10.6GHz	CM3
S6	Body surface to external (LOS)	900MHz, 2.4, 3.1-10.6GHz	CM4
S7	Body surface to external (NLOS)	900MHz, 2.4, 3.1-10.6GHz	CM4

II. System Model

Consider a wireless relay network where a source node communicates with a destination node over a distance d, through a multihop route of N relay nodes. For the ith hop ($i \in [1, N+1]$), only direct connectivity between the $(i-1)$th and ith nodes is allowed and any cooperative scheme exploiting diversity is prohibited. Assume the wireless relay network works in non-homogeneous environment, where the propagation loss of each hop can be independently modeled and calculated but at least two out of the N hops have different physical channel characteristics. With such communication system and non-homogeneous medium, the ultimate goal of this work is to investigate the end-to-end energy consumption variation in various conditions, which supports the relay network power optimization.

A. WBANs Communication System Model

The WBANs communication system employed in this study is the typical clinical wireless capsule endoscopy system, which can be abstracted into a 2-hop relay network with three critical components, namely, source node, the capsule pill that emits RF signal from inside of human GI tract; Relay node, the information forwarding device weared on the specific belt of patients; Destination node, the external AP that is designed to collect the transmitted information of interior intestinal environment. The clinical system has been plotted in Fig. 1, in which the specific belt is assumed to be at the average height of small and large intestine.

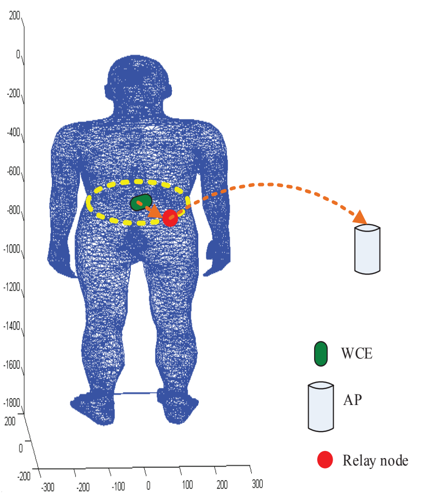

Fig. 1: A typical relay network configuration for WBANs.

The uniqueness of such wireless relay network is the non-homogeneity, that is, the 2 hops operate in different propagation mediums. MICS band technologies have been used for the first hop inside the lossy human body, while the second hop works on regular environment with modern indoor wireless access technologies. Note that even though the 2-hop special case has been employed for numerical analysis, the derivation included in following sections works in general multihop cases. Also, relay node is located on the border line of two different propagation mediums for the WBANs application in this work but such situation is not required as long as the propagation loss of each hop can be properly expressed in the form of eq. (1). The abstracted wireless relay network has been plotted in Fig. 2, where the distance of hop 1 and hop 2 is given as d_1 and d_2 respectively. The in-body region has been marked with light blue and the distance-power gradient α_1 and α_2 are also different.

B. Radio Propagation Channel Models

Considering the WBANs communication system described in the previous subsection, it is necessary to understand the physical radio propagation medium. We bring about this subsection to provide literatures of WBANs channel modeling. The statistical RF channel model has been first proposed by National Institute of Standards Technology (NIST) in 2007 and then finalized as the IEEE 802.16.5 standard in 2012 after multiple revisions [10]. The BAN channel model applies to multiple frequency bands varying throughout MICS, ISM and even UWB. It has been also partitioned into seven scenarios from S1 to S7, and four categories from CM1 to CM4. Detailed channel models has been shown in Table I [10].

The in-body communication link for WCE is a typical implementation of the implant to body surface scenario (S2), for which the standard focuses on the narrow band CM2 channel from 402 to 405MHz. Apart from that, for the off-body communication from relay node to external AP, the CM4 wideband channel for (S6) scenario can be employed. The propagation loss for both channels can be expressed as

$$L_p(d) = P_t - P_r(d) = L_p(d_0) + 10\alpha \log_{10} \frac{d}{d_0} + \zeta \qquad (1)$$

where $L_p(d)$ denotes to the pathloss between two neighboring nodes separated at distance d, P_t and $P_r(d)$ are the transmit power and receive power respectively, $L_p(d_0)$ is the pathloss at reference distance d_0, α is the distance-power gradient, and ζ denotes to the shadow fading effect.

Necessary parameters for CM2 and CM4 channel can be found from [10] where we select deep tissue case for the

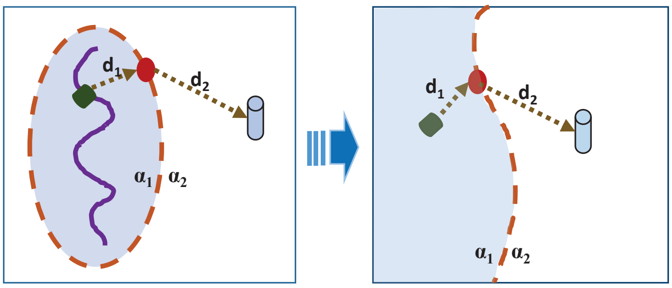

Fig. 2: Equivalent Illustration of 2-D network model for relay WBANs in non-homogenous environment.

in-body propagation. Note that for the off-body wideband channel, only the parameters for LOS scenario (S6) have been considered in this work for the purpose of clarity and simplicity. In the human body caused NLOS scenario, creeping wave has been observed and the parameters need proper modification [11].

III. Formulation of Total Energy Consumption

In this section, we provide the definition and formulation of the total energy consumption for our non-homogeneous relay network. Theoretically, the total energy consumption includes the transmission energy against the lossy propagation medium and the processing energy against the circuitry cost. In this work, we only take the transmission energy into consideration due to the fact that processing energy is a hardware related extra linear term in the formulation and is trivial in terms of magnitude.

A. End-to-End Rate

The end-to-end rate is defined as the effective datarate to transfer certain amount of information bits across the entire network within a constant time T. It can be regarded as a general performance metric of the relay network. The definition of end-to-end rate can be derived from the following equations

$$\begin{cases} TR_e = T_1R_1 = T_2R_2 = ... = T_NR_N \\ T = T_1 + T_2 + ... + T_N \end{cases} \tag{2}$$

By induction, R_e can be proved to be

$$R_e = \frac{1}{\sum_{i=1}^{N} R_i^{-1}} \tag{3}$$

With such definition of effective end-to-end rate, it is reasonable to evaluate the energy-end-to-end rate trade-off of the relay network and therefore propose power optimization mechanisms.

B. End-to-End Energy Consumption

Consider the ith link which is communicating at bit rate R_i^b with a per bit transmission energy consumption of $E_{tx,i}^b$, the total energy consumption per bit can be modeled as

$$E_{tot}^b = \sum_{i=1}^{N} E_{tx,i}^b \tag{4}$$

where N is the total number of links. Obviously, it is difficult to directly compute the transmission energy consumption but we know that the transmission power consumption is positively related to the radio propagation channel. From the pathloss model in eq. (1), the deterministic portion of transmission power for the ith link, $P_{tx,i}$, can be expressed as

$$P_{tx,i} = P_{rx,i} + L_{0,i} + 10\alpha_i \log_{10}(d_i) \tag{5}$$

where $P_{rx,i}$ is the signal strength at the receiver side; $L_{0,i}$ is the pathloss at reference distance for the ith link; α_i and d_i are distance-power gradient and TX-RX distance, respectively. Performing a linearization on the decibal power readings in eq. (5), we obtain the linear transmission power of ith link as

$$10^{\frac{P_{tx,i}}{10}} = 10^{\frac{P_{rx,i}}{10}} \times 10^{\frac{L_{0,i}}{10}} \times 10^{\alpha_i \log_{10}(d_i)} \tag{6}$$

Using a superscript to label the linear transmission power, eq. (6) can be re-written as

$$P_{tx,i}^l = P_{rx,i}^l L_{0,i}^l 10^{\alpha_i \log_{10}(d_i)} \tag{7}$$

From the energy power relationship, we express the energy consumption per symbol transmission as

$$E_{tx,i}^s = P_{tx,i}^l \times T_i^s = \frac{P_{tx,i}^l}{R_i^s} \tag{8}$$

$$E_{rx,i}^s = P_{rx,i}^l \times T_i^s = \frac{P_{rx,i}^l}{R_i^s} \tag{9}$$

where $E_{tx,i}^s$ is the energy consumption to transmit a symbol on the ith link, $E_{rx,i}^s$ is the energy consumption to receive a symbol, T_i is the symbol duration and R_i^s is the symbol rate of ith link.

To solve the energy consumption per symbol transmission, it is intuitive to go with Shannon's theorem as

$$\frac{C_i}{W_i} = \frac{R_i^b}{W_i} = \log_2(1 + \frac{E_{rx,i}^s}{N_0}) \tag{10}$$

where C_i is the capacity of the physical channel of ith link, W_i is the bandwidth of that channel, N_0 is the background noise level. Note that we assume that maximum information transfer rate is achievable so that $C_i = R_i^b$. The derivation does not lose generality with that assumption due to the fact a scale factor on R_i^b can be easily added as a compensation. Solving $E_{rx,i}^s$, we have

$$E_{rx,i}^s = N_0(2^{\frac{R_i^b}{W_i}} - 1) \tag{11}$$

Substituting eq. (11) into (9) we know that

$$P_{rx,i}^l = W_i N_0 (2^{\frac{R_i^b}{W_i}} - 1) \tag{12}$$

With the $P_{tx,i}^l$, $P_{rx,i}^l$ relationship in eq. (7), we have

$$P_{tx,i}^l = W_i N_0 L_{0,i}^l 10^{\alpha_i \log_{10}(d_i)} (2^{\frac{R_i^b}{W_i}} - 1) \tag{13}$$

Finally, substitute eq. (13) into (8), the energy consumption to transmit a symbol on the ith link, $E_{tx,i}^s$, can be given as

$$E_{tx,i}^s = N_0 L_{0,i}^l 10^{\alpha_i \log_{10}(d_i)} (2^{\frac{R_i^b}{W_i}} - 1) \tag{14}$$

With our previous assumption of maximum bandwidth efficiency $C_i = R_i^b$, we have $E_{tx,i}^s = R_i^b \times E_{tx,i}^b / W_i$ and the energy consumption per bit transmission can be given as

$$E_{tx,i}^b = N_0 L_{0,i}^l 10^{\alpha_i \log_{10}(d_i)} (2^{\frac{R_i^b}{W_i}} - 1) \frac{W_i}{R_i^b} \tag{15}$$

and the overall energy per bit to noise power spectral density ratio E_{tot}^b / N_0 can be given as

$$\frac{E_{tx,i}^b}{N_0} = L_{0,i}^l 10^{\alpha_i \log_{10}(d_i)} (2^{\frac{R_i^b}{W_i}} - 1) \frac{W_i}{R_i^b} \tag{16}$$

Considering eq. (15) and (16), the overall energy per bit to noise power spectral density ratio E_{tot}^b / N_0 in a non-homogeneous relay network will be affected by four different aspects. (1) The bandwidth allocation of each link, $\bar{W} = \{W_1, W_2, ..., W_N\}$; (2) The channel characteristics of each link, $\bar{\alpha} = \{\alpha_1, \alpha_2, ..., \alpha_N\}$; (3) The actual propagation distance of each link, $\bar{d} = \{d_1, d_2, ..., d_N\}$; (4) The actual bit rate of each link, $\bar{R} = \{R_1, R_2, ..., R_N\}$.

Aspects (1), (2) and (4) depends on the communication technologies selected for each link, take the WCE case as an example, the in-body propagation link works on 402-405MHz MICS channel while the off-body link may works in 2.4GHz ISM band or even UWB band. Aspect (3) depends on the deployment of relay networks and the distance between source and destination.

IV. Numerical Results for Power Optimization

It is explained in the previous section that the overall energy per bit to noise power spectral density ratio E_{tot}^b / N_0 depends on for different aspects, namely, bandwidth $\bar{W}$, channel characteristics $\bar{\alpha}$, actual propagation distance $\bar{d}$ and bit rate of each link $\bar{R}$. In this section, we provide numerical simulation results to investigate the influence of these aspects. Since the bandwidth $\bar{W}$ and the channel characteristics $\bar{\alpha}$ are highly correlated with each other, we do not isolate them from each other.

A. Energy-Bandwidth Tradeoff

The numerical result presented in this subsection shows the energy-bandwidth trade-off for the 2-hop relay network in non-homogeneous environment. According to the practical WCE applications, we fix the in-body propagation to MICS band with bandwidth $W_1 = 3$MHz and employ $\alpha_1 = 4.26$ for deep tissue propagation [10]. After that we vary the bandwidth of off-body propagation W_2 from 1MHz to 1GHz to investigate the change of E_{tot}^b / N_0. The value of power gradient α_2 is selected according to the frequency dependent channel model in [12]. In-body propagation distance has been fixed as 0.25m and off-body propagation distance d_2 is 1m (we denote 2-hop distance as d_1:d_2=0.25:1.0 in the following section for simplicity). Finally the data rates for these 2 links satisfy eq. (3) with R_1:R_2=1:1.

The overall energy per bit to noise power spectral density ratio E_{tot}^b / N_0 has been plotted in Fig. (3) against effective end-to-end rate R_e. Three regions can be observed in Fig. (3).

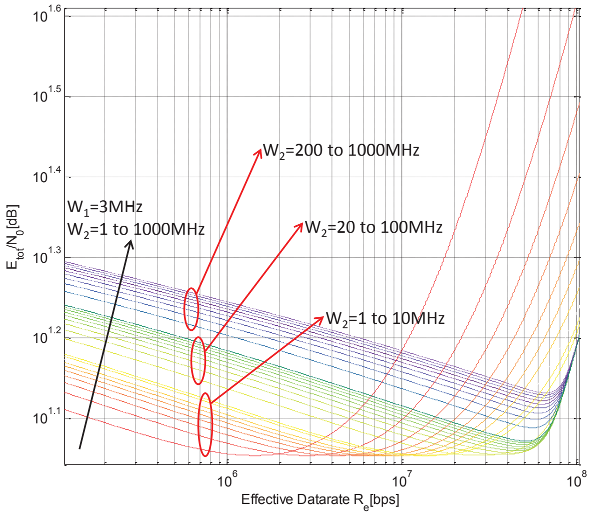

Fig. 3: Energy-bandwidth trade-off for the relay network.

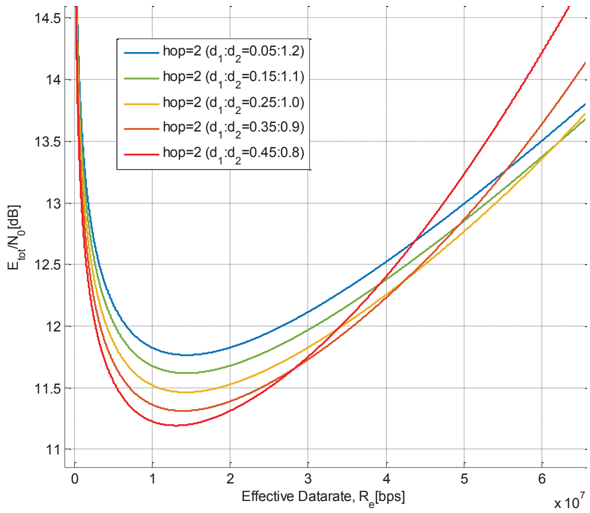

Fig. 4: Energy-deployment trade-off for the relay network.

The first region is for narrow band off-body propagation where W_2 ranges from 1 to 10MHz. For each curve with specific W_2, a minimum E_{tot}^b / N_0 can be observed at certain effective data rate R_e. With the increment of W_2, R_e with minimum E_{tot}^b / N_0 increases, indicating that for greater $W_1 : W_2$ ratio, higher optimal end-to-end data rate can be achieved with minimized energy per bit to noise power spectral density ratio. In addition, it is worth mentioning, for narrow band off-body propagation region, the value of minimum E_{tot}^b / N_0 has very little variation.

The second region is for wide band off-body propagation where W_2 ranges from 20 to 100MHz. In that region, similar trend as the first region can be still observed but the value of minimum E_{tot}^b / N_0 slightly increases with the increment of W_2. Also, the R_e with minimum E_{tot}^b / N_0 increases slower with the increment of W_2. Finally, UWB off-body propagation with W_2 from 200 to 1000MHz has been plotted in the third region. Still the same trend can be observed as both E_{tot}^b / N_0 and R_e for minimum E_{tot}^b / N_0 increases with the increment of W_2.

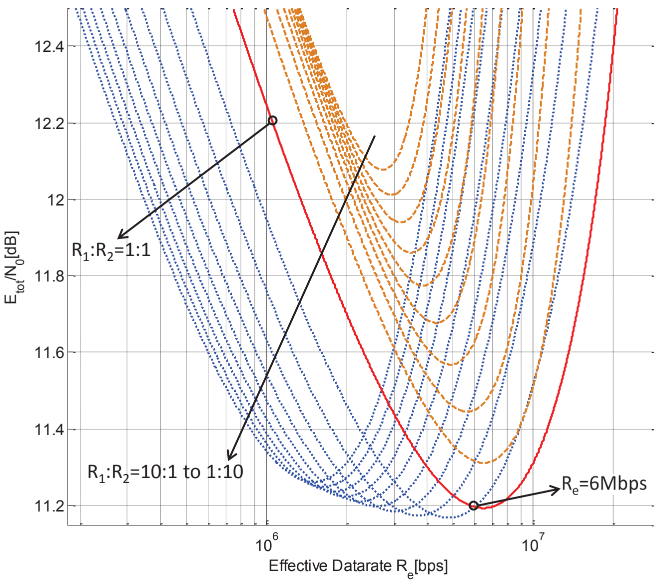

Fig. 5: Energy-datarate trade-off for the relay network.

B. Energy-Deployment Tradeoff

This subsection reports the energy-deployment trade-off for the 2-hop relay network in non-homogeneous environment. To analyze the effect of deployment, we first fix W_1:W_2=3:7 with properly selected $\bar{\alpha}$ values; R_1:R_2=1:1 and R_1, R_1 satisfy eq. (3). Then we setup d_1:d_2 ratio to represent various system deployment. For the abdomen of a adult male individual, the in-body propagation distance usually ranges in [0.05m, 0.45m]. Also, we set the distance between on-body relay node and external AP to be within [0.8m, 1.2m]. Given the propagation distances, the d_1:d_2 ratio goes from 0.05:1.2 to 0.45:0.8. With these setup, the overall energy per bit to noise power spectral density ratio E^b_{tot}/N_0 has been plotted in Fig. (4) against effective end-to-end rate R_e.

As can be seen from Fig. (4), with a greater d_1:d_2 ratio, the R_e for minimal E^b_{tot}/N_0 decreases and the minimal E^b_{tot}/N_0 also decreases. Such trend indicate that when d_1 and d_2 get imbalanced, the minimal energy consumption can be higher. It is worth mentioning that this observation can be only applied to the WCE case. In the general sense, it is possible to have reversed trends for d_1:d_2 smaller than specific constant c or d_1:d_2 larger than the constant c (c=1:1 for homogeneous case). We leave this problem open for future works.

C. Energy-Datarate Tradeoff

This subsection reports the energy-datarate trade-off for the 2-hop relay network in non-homogeneous environment. To investigate the effect of data rate, we first fix W_1:W_2=3:3 with properly selected $\bar{\alpha}$ values; d_1:d_2=0.25:1.0. The R_1:R_2 ratio varies from R_1:R_2=1:10 to R_1:R_2=10:1. Note that R_1 and R_2 always satisfy eq. (3). The overall energy per bit to noise power spectral density ratio E^b_{tot}/N_0 has been plotted in Fig. (5) against effective end-to-end rate R_e. Observation of energy-datarate trade-off is that the balance between R_1 and R_2 is important. When R_1:R_2=1:1, maximized efficiency can be achieved as the minimal E^b_{tot}/N_0 of 11.2dB provides the maximum R_e of over 6MHz. If R_1:R_2 <1:1, as the blue curves in Fig. (5), lower energy consumption can be achieved with the sacrifice of end-to-end data rate R_e. However, when R_1:R_2 >1:1, more energy is required and R_e still goes lower than R_1:R_2=1:1, which is not recommended in the implementation of relay networks.

V. Conclusion

In this paper, we considered the trade-off between the total power consumption and the end-to-end rate in non-homogenous relay environment for WBANs where the relay node is placed on the belt of the human body by which the WCE can communicate with external AP. We formulated the energy consumption to deliver one bit and the end-to-end rate for the whole relay network. The overall energy per bit to noise power spectral density ratio and end-to-end rate trade-off had been studied for different aspects such as bandwidth, channel characteristics, actual propagation distance and data rate of each link. Also we investigate the influence on the total power consumption optimization of these aspects.

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