Energy Efficiency in the Wideband Regime

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***Abstract*—End-to-end communication is the fundamental building block of communication networks. In this paper, we discuss globally optimal energy efficient design for end-to-end communications. An end-to-end multiple-hop system with one sender, one receiver, and multiple relays is considered. We first study in detail energy-efficient designs in the wideband regime that is characterized by wide signal bandwidth and low spectral efficiency, and later briefly those in the narrowband regime. We will reveal the globally optimal link adaptation as well as relay deployment strategies such that the whole system can achieve the highest energy efficiency. The technologies proposed can be used in various communication systems, such as the deployment and communication of wired core networks and wireless relay networks, to improve their energy efficiency. While this paper focuses on a linear end-to-end network topology, the methodology can be easily extended to two-dimensional network topologies for energy-efficient designs of the whole network .**

***Index Terms*—Relay, energy efficiency, power optimization, wideband, deployment.**

I. INTRODUCTION

ENERGY efficiency is increasingly important for communication networks because of both climate and cost issues. Information and communication technology (ICT) plays an important role in global greenhouse gas emissions since the amount of energy consumed by ICT increases dramatically to meet with the explosive growing service requirements [1]. It is shown that nowadays the total energy used by the infrastructure of cellular networks, wired networks, and Internet takes up more than 3% of the worldwide electric energy consumption [2]. In addition, this amount of energy is expected to increase rapidly in the future.

The exponential relationship between rate and power in Shannon capacity indicates that energy efficiency can only be achieved with infinite bandwidth or infinitely small data rate. But this qualitative analysis considers only transmission energy and ignores practical issues such as power consumption used for operating circuit and signal processing [3]. Therefore energy-efficient network design should find tradeoff between transmission energy and energy overhead like circuit energy. This tradeoff exists in almost all aspects of wireless networks, from individual transceivers [4]–[6] to cellular network deployments[7], [8]. For example in [4], a unique globally optimal power allocation and link adaptation is revealed for multiple input and multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) transmission and this scheme automatically balances the energy consumption between the circuit power and the transmission powers on all subchannels. When there are multiple users in the network, the network resources should also be managed such that the overall network energy efficiency is maximized rather than that of single users [3], [6], [9], [10]. A thorough tutorial can be found in [3] which discusses energy-efficient resource management in time, frequency, and space domains. In addition to single cell resource management, energy efficiency should also be considered from the multi-cell aspect [11]–[13]. In [11], [12], it is observed that power optimization is important in both energy efficiency improvement and inter-cell interference control. Besides, energy-efficient power control, not only improves network energy efficiency, but also spectral efficiency because its conservative nature of power allocation automatically alleviates inter-cell interference to improve overall network throughput.

In this paper we first study energy-efficient communications in the wideband regime, where the signal bandwidth is large and the channel is flat. Examples include wired communications using copper or fiber optics where the bandwidth is almost infinite and the channel is flat and line-of-sight (LOS) wireless backhaul communications with multi-gigahertz bandwidth[14]. For instance, the wireless channels around 60 GHz do not exhibit rich multipath. The non-line-of-sight (NLOS) components suffer from tremendous attenuation and the channel is almost flat [14]. In addition, at 60 GHz, a broad spectrum, e.g. several gigahertz, can be used to achieve a high data rate for backhaul communications. Therefore a backhaul system using 60 GHz carrier frequency can have large signal bandwidth and a flat channel. The scenario we will focus on would be an end-to-end link using multiple relays. We assume that there are no interferences between different relays. This is obvious in wired communications. In wireless communications, e.g. 60 GHz backhaul communications, directive antennas are usually used and the interference is negligible. Later, we extend our study to the general case of narrowband communications and discuss the differences and similarities of optimal relay deployment and link adaptation compared to the wideband communications.

The question we will answer, is what would be the globally optimal link adaptation and relay deployment strategy such that the whole system is the most energy efficient. This strategy can be used in many applications, e.g. core network deployment or wireless relay backhaul, to improve their end-to-end energy efficiency. The paper is structured as follows. In Section II we present the system model. In Section III, we discuss energy-efficient communication without any relay. In Sections IV, V, and VI, we study the optimal link adaptation as well as relay deployment strategies, assuming an arbitrary number of relays in the wideband regime. In Section VII, we

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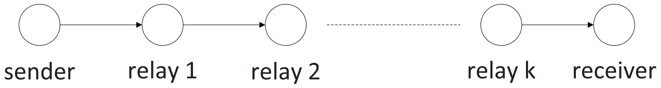

Fig. 1. System model.

present the corresponding results in the narrowband regime. In Section VIII, energy-efficient communications with quality of service (QoS) assurance are discussed. In Section IX, we present the simulation results. Finally the paper is concluded in Section X.

II. SYSTEM MODEL

Consider a multi-hop system with one sender, one receiver, and K relays, as illustrated in Fig. 1. The data is sent from the sender to the first relay, which decodes the data and forwards it to the second relay. This process repeats itself until the data reaches the receiver. We focus on the end-to-end performance and the achieved end-to-end data rate is the minimum rate of all relays. All transmissions experience additive white Gaussian noise (AWGN) channels and the data rate is given by

$$\begin{aligned} R_i &= B\log_2\left(1+\frac{P_i\xi_i h_i}{BN_o}\right), i=0,1,...,K, \\ s.t. \quad & P_i \le P_{mi}, \end{aligned} \tag{1}$$

where B denotes the signal bandwidth, P_i the transmission power consumed by the power amplifier, ξ_i the power amplifier efficiency, h_i the channel power gain, N_o the noise spectral density, and P_{mi} the power limit. The transmission of the sender is indexed with 0 while the transmission of the ith relay indexed with i. In the following we may refer to the transmitter and relays as user i according to their indices.

In the wideband regime, assume $B \to \infty$, then

$$R_i = \frac{P_i\xi_i h_i}{N_o \ln 2}. \tag{2}$$

As discussed in [15] many digital communication systems, particularly wireless, satellite, deep-space, and sensor networks, operate in the power-limited region. In this regime the spectral efficiency is relatively low. This regime is an attractive choice because of power savings, ease of multiaccess, ability of overlay with other systems, and diversity against frequency-selective fading. Assume that all relays work in the full-duplex mode, because their data reception and transmission can be easily separated by e.g. frequency-division duplexing (FDD). The above approximation (2) still holds when B is divided into half. In this paper, the theories and algorithms will be based on this linear approximation. Note that when the achieved data rate and transmission power can not be approximated linearly, e.g. when B is finite in (1), the following link adaptation strategy can be used to obtain the linearity. As shown in Fig. 2, each frame consists of M symbols. The link adaptation strategy only uses the first m symbols and each symbol will be transmitted with the highest power, P_{mi}, if used. When all symbols are used, the achieved data rate is R_{mi}, which is non-linear in P_{mi}. The average achieved data rate is

$$R_i = R_{mi}\frac{m}{M}$$

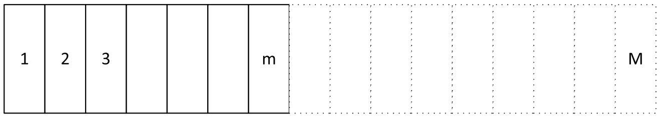

Fig. 2. A linear link adaptation scheme.

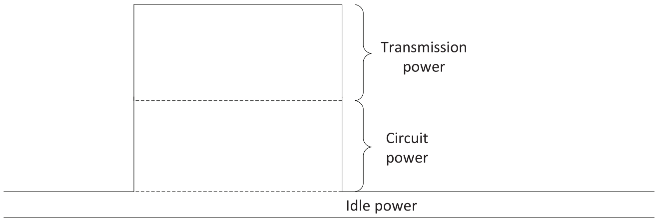

Fig. 3. Different components of power consumption.

and the average transmission power consumption is

$$P_i = P_{mi}\frac{m}{M}.$$

Therefore, we have the linear relationship

$$R_i = P_i\frac{R_{mi}}{P_{mi}} \tag{3}$$

and the following theories and algorithms can be applied by replacing $\frac{\xi_i h_i}{N_o \ln 2}$ with $\frac{R_{mi}}{P_{mi}}$.

In addition to transmission power, each device also consumes circuit power for computation purposes in the transmission state, e.g. signal processing, filtering, and coding[4]. The total power consumption is

$$\hat{P}_i = P_i + P_{ci}, \tag{4}$$

where P_{ci} denotes the circuit power in the transmission state. Note that a device may be in different operating modes, e.g. transmission or idle modes. Different circuit components would be active in different modes and different amounts of power will be consumed. In general the transmission mode consumes much more power than other modes and this paper focuses solely on the transmission mode. The circuit power, P_{ci}, in this paper denotes the additional power, excluding the transmission power, consumed in the transmission state compared to the following low-power mode, e.g. idle mode, as illustrated in Fig. 3. The circuit power consumption of the receiver is defined as P_r. The energy efficiency of the system, u, is defined as the total number of bits that can be transmitted consuming a certain amount of energy, or equivalently, the network throughput divided by the total network power consumption [4], i.e.

$$u = \frac{R}{\sum_i (P_i + P_{ci}) + P_r}, \tag{5}$$

where R denotes the achieved data rate of the whole system. In the following, we study the optimal link adaptation as well as relay deployment strategy such that the whole system is the most energy efficient.

III. DIRECT ENERGY-EFFICIENT COMMUNICATIONS

When there is no relay and the sender transmits data directly to the receiver, the transmitter wants to make link adaptation such that its energy efficiency is maximized, i.e. the power is given by

$$\begin{aligned} P_0^* &= \arg\max_{P_0} \frac{R_0}{P_0 + P_{c0} + P_r} \\ &= \arg\max_{P_0} \frac{\frac{P_0 \xi_0 h_0}{N_o \ln 2}}{P_0 + P_{c0} + P_r} \\ s.t. \quad & P_0 \leq P_{m0}. \end{aligned} \tag{6}$$

The energy efficiency,

$$\frac{\frac{P_0 \xi_0 h_0}{N_o \ln 2}}{P_0 + P_{c0} + P_r},$$

increases with the transmission power, P_0, and therefore the highest power should always be used, i.e.

$$P_0^* = P_{m0}. \tag{7}$$

This indicates that if there is any data that needs to be sent, it should be transmitted with the highest possible data rate to achieve the highest energy efficiency. The highest energy efficiency is

$$u^* = \frac{P_{m0} \xi_0 h_0}{(P_{m0} + P_{c0} + P_r) N_o \ln 2}. \tag{8}$$

Theoretically, if there is no power limit, i.e. $P_{m0} \to \infty$, the energy efficiency upper bound is

$$u^* = \frac{\xi_0 h_0}{N_o \ln 2}. \tag{9}$$

The energy efficiency in (8) indicates five ways of improving energy efficiency from an implementation perspective, that is,

- increasing the power limit (mainly the linear range of the power amplifier),
- increasing the power amplifier efficiency,
- increasing the channel gain,
- reducing the circuit power of both the transmitter and receiver,
- and reducing the thermal noise.

IV. ENERGY-EFFICIENT RELAY LINK ADAPTATION

In this section, we assume an arbitrary number of relays with given channels and discuss the optimal energy-efficient transmission strategy.

The overall achieved data rate of the system must be

$$R = \min_i R_i. \tag{10}$$

This also indicates that all transmissions by the sender and relays should be at the same rate R, since otherwise any link with a higher rate will waste its energy consumption. Therefore, the power of user i is

$$P_i = \frac{R N_o \ln 2}{\xi_i h_i}. \tag{11}$$

The overall system energy efficiency is

$$\begin{aligned} u &= \frac{R}{\sum_i (P_i + P_{ci}) + P_r} \\ &= \frac{R}{\sum_i (\frac{R N_o \ln 2}{\xi_i h_i} + P_{ci}) + P_r}. \end{aligned} \tag{12}$$

The energy efficiency u increases with R. Therefore the highest data rate should be used and

$$R^* = \min_i \frac{P_{mi} \xi_i h_i}{N_o \ln 2}. \tag{13}$$

This also indicates that if there is any data that needs to be sent, it should be transmitted with the highest possible data rate to achieve the highest energy efficiency.

User i will use just enough power to achieve R^* and the transmission power should be

$$P_i^* = \frac{R^* N_o \ln 2}{\xi_i h_i}. \tag{14}$$

The maximum system energy efficiency is

$$u^* = \frac{R^*}{\sum_i (\frac{R^* N_o \ln 2}{\xi_i h_i} + P_{ci}) + P_r}. \tag{15}$$

If there is no power limit, the energy efficiency upper bound is given by

$$u^{**} = \frac{1}{\sum_i (\frac{1}{\xi_i h_i})} \frac{1}{N_o \ln 2}. \tag{16}$$

To implement this optimal link adaptation approach, all relays should report their link capacity $\frac{P_{mi} \xi_i h_i}{N_o \ln 2}$ to the sender, which determines R^* and will transmit with this rate. All relays will then use just enough power to achieve R^*.

V. ENERGY-EFFICIENT RELAY DEPLOYMENT

In this section, we study how to deploy relays such that the whole system is the most energy efficient, when assuming that all users transmit with a fixed power. Define the distance between the sender and receiver as d. We need to find the optimal deployment positions of all relays.

Consider only path loss in wideband wireless communications and the channel power gain is given by

$$h_i = \frac{h_o}{d_i^\alpha}, \tag{17}$$

where d_i is the link distance of user i, α the path loss exponent, and h_o the gain at the unit distance. For wired communications, the signal attenuation usually grows exponentially with the distance[16], [17], i.e.

$$h_i = \frac{h_o}{e^{\alpha d_i}}. \tag{18}$$

In the following, we will discuss energy-efficient relay deployment strategies for both channel models.

A. For Wireless Communications

The overall achieved data rate of the system is

$$R = \min_i R_i = \min_i \frac{P_i \xi_i h_o}{d_i^\alpha N_o \ln 2}. \tag{19}$$

Since the transmission power is fixed for all users, maximizing the energy efficiency u is the same as maximizing the rate R and the objective would be

$$\begin{aligned} \max_{\{d_i\}} R &= \max_{\{d_i\}} \min_i \frac{P_i \xi_i h_o}{d_i^\alpha N_o \ln 2}, \\ s.t. \quad & \sum_i d_i = d. \end{aligned} \tag{20}$$

There is a unique optimal solution to problem (20) and for the optimal solution, different users should achieve the same data rate, i.e.

$$\frac{P_i\xi_i h_o}{d_i^{*\alpha} N_o \ln 2} = \frac{P_j\xi_j h_o}{d_j^{*\alpha} N_o \ln 2}, \forall i \neq j, \tag{21}$$

as otherwise, the user with a higher data rate than the minimum rate should extend its link distance such that the distance for the user with the lowest rate can reduce its link distance to achieve a higher data rate. Therefore we have

$$\frac{d_i^*}{\sqrt[\alpha]{P_i\xi_i}} = \frac{d_j^*}{\sqrt[\alpha]{P_j\xi_j}}, \tag{22}$$

and the optimal deployment strategy is

$$d_i^* = \frac{\sqrt[\alpha]{P_i\xi_i}}{\sum_j \sqrt[\alpha]{P_j\xi_j}} d. \tag{23}$$

Correspondingly, the highest energy efficiency of the system is

$$u^* = \frac{h_o \left[\sum_i (P_i\xi_i)^{\frac{1}{\alpha}}\right]^\alpha}{d^\alpha (\sum_i (P_i + P_{ci}) + P_r) N_o \ln 2}. \tag{24}$$

Using the optimal deployment strategy, the link distance of each user will be adjusted such that its data rate is the same as all others.

B. For Wired Communications

The objective is

$$\begin{aligned} \max_{\{d_i\}} R = \max_{\{d_i\}} \min_i \frac{P_i\xi_i h_o}{e^{\alpha d_i} N_o \ln 2}, \\ s.t. \qquad \sum_i d_i = d. \end{aligned} \tag{25}$$

Similar to the wireless case, there is a unique optimal solution and different users should achieve the same data rate, i.e.

$$\frac{P_i\xi_i h_o}{e^{\alpha d_i^*} N_o \ln 2} = \frac{P_j\xi_j h_o}{e^{\alpha d_j^*} N_o \ln 2}, \forall i \neq j. \tag{26}$$

The optimal deployment strategy is

$$d_i^* = \frac{d}{K+1} - \frac{1}{\alpha(K+1)} \ln \left[\frac{\prod_{j\neq i} P_j\xi_j}{(P_i\xi_i)^K}\right]. \tag{27}$$

Correspondingly, the highest system energy efficiency is

$$u^* = \frac{h_o \left[\prod P_i\xi_i\right]^{\frac{1}{K+1}}}{e^{\frac{\alpha d}{K+1}} (\sum_i (P_i + P_{ci}) + P_r) N_o \ln 2}. \tag{28}$$

The link distance of each user is adjusted such that its data rate is the same as all others.

VI. ENERGY-EFFICIENT RELAY DEPLOYMENT AND LINK ADAPTATION

In this section we discuss the optimal energy-efficient relay deployment with link adaptation.

The optimal deployment in this case should still satisfy the condition in Section V because the deployment strategies in (23) and (27) are optimal for all transmission power settings. Given the transmission power values, the highest system energy efficiency has been found in (24) and (28). The remaining question is what would be the optimal transmission powers of all users that would result in the highest energy efficiency (24) and (28).

A. For Wireless Communications

The problem is to find the optimal transmission powers to maximize (24). Let u denote the expression in (24). We have the following objective

$$\begin{aligned} \max_{\mathbf{P}} u = \frac{h_o \left[\sum_i (P_i\xi_i)^{\frac{1}{\alpha}}\right]^\alpha}{d^\alpha (\sum_i (P_i + P_{ci}) + P_r) N_o \ln 2} \\ s.t. \qquad P_i \leq P_{mi}, \forall i. \end{aligned} \tag{29}$$

where the vector $\mathbf{P} = [P_0, P_1, ..., P_K]$. Similar to the proof in [4], it can be easily proven that the objective function is strictly quasi-concave in $\mathbf{P}$ and there is a unique globally optimal power setting. Furthermore, u first strictly increases in P_i and then decreases in it. Therefore user i will use either the peak power P_{mi} or the power value at which the first-order derivative of u is zero. Summarizing the above, we have the following necessary and sufficient condition for the globally optimal relay deployment and link adaptation and the maximum energy efficiency.

Theorem 1. *There exists a unique globally optimal relay deployment* $\mathbf{d}^* = [d_0^*, ..., d_K^*]$ *and link adaptation,* $\mathbf{P}^*$*, where*

$$d_i^* = \frac{\sqrt[\alpha]{P_i^*\xi_i}}{\sum_j \sqrt[\alpha]{P_j^*\xi_j}} d \tag{30}$$

and

$$P_i^* = \min\left(\widehat{P}\xi_i^{\frac{1}{\alpha-1}}, P_{mi}\right), \tag{31}$$

where $\widehat{P} = \left[\frac{P_{idle} + \sum_j P_j^*}{\sum_j (P_j^*\xi_j^*)^{\frac{1}{\alpha}}}\right]^{\frac{\alpha}{\alpha-1}}$ *and* $P_{idle} = \sum_i P_{ci} + P_r$*, the total power except transmission power. The maximum energy efficiency of the system is*

$$u^* = \frac{\left[h_o \sum_i (P_i^*\xi_i)^{\frac{1}{\alpha}}\right]^\alpha}{d^\alpha (\sum_i (P_i^* + P_{ci}) + P_r) N_o \ln 2}. \tag{32}$$

Assume no power limit and the same power amplifier efficiency $\xi_i = \xi_j, \forall i \neq j$. Then $P_i^* = P_j^* = P_0^*$ according to (31). The maximum energy efficiency is

$$u^* = \frac{h_o P_0^* (K+1)^\alpha}{d^\alpha ((K+1)P_0^* + P_{idle}) N_o \ln 2}. \tag{33}$$

u^* increases in P_0^* and the highest power should be used. Therefore we have the upper bound of u^* when $P_0^* \to \infty$, i.e.

$$u^{**} = \frac{h_o (K+1)^{\alpha-1}}{d^\alpha N_o \ln 2}. \tag{34}$$

This indicates that without a power limit, the energy efficiency of the system can always be improved with more relays. An intuitive explanation is that with an infinitely high data rate, the time sending each bit can be infinitely small and the circuit energy consumption is then negligible. The system energy efficiency is therefore almost solely determined by the transmission energy. As the energy consumption increases exponentially with the distance, more relays will always help to reduce the communication distances and therefore improve the energy efficiency exponentially. However, this conclusion may no longer be valid when there are power limits. With power limits, the data rate will be limited and circuit energy consumption is not negligible. Whether an additional relay can improve system energy efficiency will depend on how much additional circuit power the relay consumes. However we can always use Theorem 1 to compare the energy efficiency when the system has different sets of relays and decide how many relays would be the most energy efficient.

B. For Wired Communications

Similar to the wireless case, we need to find the optimal transmission powers to maximize (28) and the objective is

$$\begin{aligned}\max_{\mathbf{P}} u &= \frac{h_o\left[\prod P_i\xi_i\right]^{\frac{1}{K+1}}}{e^{\frac{\alpha d}{K+1}}(\sum_i(P_i+P_{ci})+P_r)N_o\ln 2} \\ s.t. \quad & P_i \le P_{mi}, \forall i.\end{aligned} \tag{35}$$

The objective function is also strictly quasi-concave in $\mathbf{P}$ and there is a unique globally optimal power setting, which is summarized in the following theorem.

Theorem 2. *There exists a unique globally optimal relay deployment* $\mathbf{d}^* = [d_0^*, ..., d_K^*]$ *and link adaptation,* $\mathbf{P}^*$*, where*

$$d_i^* = \frac{d}{K+1} - \frac{1}{\alpha(K+1)}\ln\left[\frac{\prod_{j\neq i}P_j^*\xi_j}{(P_i^*\xi_i)^K}\right] \tag{36}$$

and

$$P_i^* = \min\left(\widehat{P}, P_{mi}\right), \tag{37}$$

where $\widehat{P} = \frac{\sum_j P_j^* + P_{idle}}{K+1}$*. The maximum energy efficiency of the system is*

$$u^* = \frac{h_o\left[\prod P_i^*\xi_i\right]^{\frac{1}{K+1}}}{e^{\frac{\alpha d}{K+1}}(\sum_i(P_i^*+P_{ci})+P_r)N_o\ln 2}. \tag{38}$$

Assume no power limit and $P_i^* = P_j^* = P_0^*$ according to (37) and the maximum energy efficiency is

$$u^* = \frac{h_oP_0^*\left[\prod \xi_i\right]^{\frac{1}{K+1}}}{e^{\frac{\alpha d}{K+1}}(P_0^*(K+1)+\sum_i(P_{ci})+P_r)N_o\ln 2}, \tag{39}$$

which increases in P_0^*. Letting $P_0^* \to \infty$, we have the upper bound of the system energy efficiency,

$$u^{**} = \frac{h_o\left[\prod \xi_i\right]^{\frac{1}{K+1}}}{e^{\frac{\alpha d}{K+1}}(K+1)N_o\ln 2}. \tag{40}$$

C. Algorithm Design

Theorems 1 and 2 do not give the explicit $\mathbf{P}^*$ and numerical algorithms are needed to search for it. A similar issue has been thoroughly studied in [4] to find the optimal energy-efficient link adaptation for MIMO and OFDM communications. The difference in this paper is the per-element power limits, $\{P_{mi}\}$. If the power limits are sufficiently large, the binary search assisted ascent (BSAA) algorithm in [4] can be used here too. Otherwise, we can modify BSAA slightly to reflect the consideration of per-element power limits. The improved BSAA for finding the optimal power setting is summarized in Table I.

```
Algorithm IBSAA($\hat{\mathbf{P}}$)
Input: initial guess $\hat{\mathbf{P}}$
Output: the optimal $\mathbf{P}^*$
$\mathbf{P} = \hat{\mathbf{P}}$ and $\mathbf{P}_m = [P_{m0}, ..., P_{mK}]$.
while no convergence
    do use GABS [4] to find the optimal step size $\mu^*$;
        $\mathbf{P} = \min\left[[\mathbf{P} + \mu^*\nabla u(\mathbf{P})]^+, \mathbf{P}_m\right]$
return P
```

Table I: Improved binary search assisted ascent

VII. ENERGY-EFFICIENT COMMUNICATIONS IN THE NARROWBAND REGIME

In the above sections we have realistically assumed the system bandwidth is sufficiently large such that the data rate can be linearly approximated as a function of the transmission power. With this approximation the analysis is greatly simplified and closed-form solutions are obtained. In this section, we discuss energy-efficient relay deployment and link adaptation when the bandwidth is limited, i.e. when the data rate and transmission power have a logarithm relationship as in (1). Note that the conclusions in this section are mainly due to the strictly concave relationship between the achieved data rate of each user and the corresponding transmission power. In fact, the developed methodology and approaches in this section can be used as long as the overall achieved data rate of each user is strictly concave in the total transmission power. Therefore the channels between users are not necessarily AWGN ones and can be of other types, e.g. frequency-selective channels [4].

A. Energy-efficient Link Adaptation

With the same assumptions in Section IV, the achievable data rate is still given in (10) and the power of user i is

$$P_i = \left(2^{\frac{R}{B}} - 1\right)\frac{BN_o}{\xi_ih_i}. \tag{41}$$

The overall system energy efficiency is

$$u = \frac{R}{\sum_i\left(\left(2^{\frac{R}{B}}-1\right)\frac{BN_o}{\xi_ih_i} + P_{ci}\right) + P_r}. \tag{42}$$

As shown in [4], u is strictly quasi-concave in R and there is a unique finite positive optimal rate R^*, which optimally balances the power consumption between transmission and circuit operations. R^* has no closed-form expression and needs to be searched iteratively using the BSAA algorithm in [4].

B. Energy-efficient Relay Deployment

With the same assumptions in Section V, the objective is also to maximize the minimum data rate of all users and different users should achieve the same rate. It can be easily seen that the deployment strategies in (23) and (27) are also optimal when $R_i = B\log_2\left(1+\frac{P_i\xi_ih_i}{BN_o}\right)$. Given the optimal deployment strategies, the highest system energy efficiency for wireless communications is

$$u^* = \frac{B\log_2\left[1 + \frac{h_o\left[\sum_i(P_i\xi_i)^{\frac{1}{\alpha}}\right]^{\alpha}}{BN_od^{\alpha}}\right]}{\sum_i(P_i+P_{ci})+P_r}. \tag{43}$$

and for wired communications is

$$u^* = \frac{B \log_2 \left[1 + \frac{h_o [\prod P_i \xi_i]^{\frac{1}{K+1}}}{B N_o e^{\frac{\alpha d}{K+1}}} \right]}{\sum_i (P_i + P_{ci}) + P_r}. \tag{44}$$

C. Energy-efficient Relay Deployment and Link Adaptation

Similar to the discussion in Section VI, for wireless communications, the problem is

$$\max_{\mathbf{P}} u = \frac{B \log_2 \left[1 + \frac{h_o \left[\sum_i (P_i \xi_i)^{\frac{1}{\alpha}} \right]^{\alpha}}{B N_o d^{\alpha}} \right]}{\sum_i (P_i + P_{ci}) + P_r} \tag{45}$$
$$s.t. \qquad P_i \leq P_{mi}, \forall i.$$

Similar to (29), the objective function is also strictly quasi-concave in $\mathbf{P}$ and there is a unique globally optimal power setting. Besides u also first strictly increases in P_i and then decreases in it. Therefore user i will use either the peak power P_{mi} or the power value at which the first-order derivative of u is zero. The following theorem summarizes the properties of energy-efficient relay deployment and link adaptation.

Theorem 3. *For wireless communications, there exists a unique globally optimal relay deployment* $\mathbf{d}^* = [d_0^*, ..., d_K^*]$ *and link adaptation,* $\mathbf{P}^*$*, where*

$$d_i^* = \frac{\sqrt[\alpha]{P_i^* \xi_i}}{\sum_j \sqrt[\alpha]{P_j^* \xi_j}} d \tag{46}$$

and

$$P_i^* = \min \left(\widehat{P} \xi_i^{\frac{1}{\alpha - 1}}, P_{mi} \right), \tag{47}$$

where $\widehat{P} = \left[\frac{A (P_{idle} + \sum_j P_j^*) \left[\sum_j (P_j^* \xi_j^*)^{\frac{1}{\alpha}} \right]^{\alpha - 1}}{(1 + A \left[\sum_j (P_j^* \xi_j^*)^{\frac{1}{\alpha}} \right]^{\alpha}) R^* \ln 2} \right]^{\frac{\alpha}{\alpha - 1}}$ *and* $A = \frac{h_o}{B N_o d^{\alpha}}$*. The maximum energy efficiency of the system is*

$$u^* = \frac{B \log_2 \left[1 + \frac{h_o \left[\sum_i (P_i^* \xi_i)^{\frac{1}{\alpha}} \right]^{\alpha}}{B N_o d^{\alpha}} \right]}{\sum_i (P_i^* + P_{ci}) + P_r}. \tag{48}$$

The same approach can be used to analyse wired communications and the optimal relay deployment and link adaptation is summarized in the following theorem.

Theorem 4. *For wired communications, there exists a unique globally optimal relay deployment* $\mathbf{d}^* = [d_0^*, ..., d_K^*]$ *and link adaptation,* $\mathbf{P}^*$*, where*

$$d_i^* = \frac{d}{K+1} - \frac{1}{\alpha (K+1)} \ln \left[\frac{\prod_{j \neq i} P_j^* \xi_j}{(P_i^* \xi_i)^K} \right] \tag{49}$$

and

$$P_i^* = \min \left(\widehat{P}, P_{mi} \right), \tag{50}$$

where $\widehat{P} = \frac{A (\sum_j P_j^* + P_{idle}) [\prod P_i^* \xi_i]^{\frac{1}{K+1}}}{(K+1) R^* (1 + A \left[\prod P_i^* \xi_i \right]^{\frac{1}{K+1}}) \ln 2}$*. The maximum energy efficiency of the system is*

$$u^* = \frac{B \log_2 \left[1 + \frac{h_o [\prod P_i^* \xi_i]^{\frac{1}{K+1}}}{B N_o e^{\frac{\alpha d}{K+1}}} \right]}{\sum_i (P_i^* + P_{ci}) + P_r}. \tag{51}$$

Because of the similarities, the IBSAA algorithm in Section VI-C can also be used here to search for the optimal power settings.

VIII. ENERGY-EFFICIENT COMMUNICATIONS WITH QOS ASSURANCE

In this section, we discuss energy-efficient link adaptation and relay deployment when the system has QoS requirements. There are many QoS performance metrics like delay, jitter, utility, and so on. Depending on the service type, there are different QoS requirements that would impact the network energy efficiency. In this paper, we have focused on best effort data services. In the following, we will consider a feasible data rate requirement Γ, i.e. $R \geq \Gamma$. The discussions related to other metrics are beyond the scope of this paper because of page limit but will be our future work. We focus our discussions now on the wideband regime and similar conclusions can be easily obtained for the narrowband regime.

Given the relay deployment, according to the discussions in Sections III and IV, if there is any data that needs to be sent, it should be transmitted with the highest possible data rate, R^*, to achieve the highest energy efficiency. When there is a feasible data rate requirement, $\Gamma \leq R^*$, the same strategy should be used, i.e. the system should send data at the rate R^* to achieve the highest energy efficiency. Similarly, when only deployment is considered, the optimal deployment strategy in Section V maximizes both energy efficiency and the data rate that the system can support. Since the rate requirement is feasible, the system should send data at the highest rate R^* to achieve the highest energy efficiency.

Assume both link adaptation and relay deployment are used, as in Section IV. If the solution in Section IV achieves a data rate that is higher than Γ, then it is also the solution which fulfills the data rate requirement. Otherwise, the system should be designed such that the achieved data rate is Γ and for all users,

$$\Gamma = \frac{P_i h_i \xi_i}{N_o \ln 2}, \tag{52}$$

where $h_i = \frac{h_o}{d_i^{\alpha}}$ for wireless communications and $h_i = \frac{h_o}{e^{\alpha d_i}}$ for wired ones. Maximizing system energy efficiency u in this case is the same as minimizing the total power consumption. The problem can be described as

$$\begin{aligned} & \min_{\mathbf{P}} \sum_i P_i \\ s.t. \qquad & P_i \leq P_{mi}, \forall i, \\ & \sum_i d_i = d, \\ & P_i = \frac{\Gamma N_o \ln 2}{h_i \xi_i}, \forall i. \end{aligned} \tag{53}$$

This is a strictly convex problem and there is a unique globally optimal solution, which can be found using iterative numerical algorithms like interior-point methods [18].

IX. SIMULATIONS

In the simulations, we focus on wireless communications, but wired communications can be run in a similar way. 60 GHz wireless channels have very high bandwidth and

TABLE I
SIMULATION PARAMETERS

Maximum Tx power, P_m	20 mW
Path loss at 1 m, PL_0	57.5 dB
Path loss exponent, α	2.5
Noise figure, NF	6 dB
Noise spectral density, N_o	-204 dB/Hz
Implementation Loss, IL	6 dB
Antenna Gain, G_t, G_r	30 dB
Bandwidth, B	1.5 GHz
Circuit power for the transmitter, P_c	0.2 W
Circuit power for the receiver, P_r	0.2 W
Power Amplifier efficiency, ξ	0.1

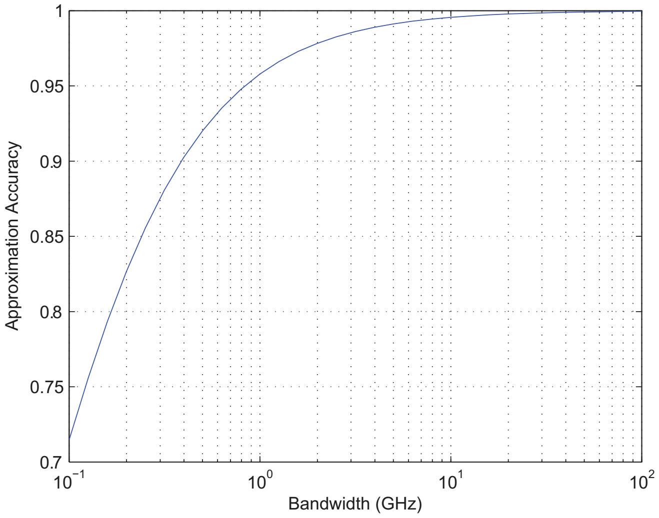

Fig. 4. Approximation accuracy of the linear power-rate relationship.

limited transmission power, which means that the wideband approximation is valid. We have looked at short distance 60 GHz radio links and used the system model in Fig. 1. The simulation parameters are summarized in Table I, most of which are based on the parameters in [19]. The circuit power and power amplifier efficiency are estimated from comparisons to similar low power transmitters. The antenna gain, noise figure, and implementation loss are included in the constant h_o in equation (17) and the channel power gain is expressed as follows

$$h(d) = \frac{G_t G_r}{PL_0 \cdot IL \cdot NF \cdot d^{\alpha}}. \tag{54}$$

Fig. 4 shows the accuracy of using the linear power-rate relationship in (2) to approximate the data rate for this system when the system has different system bandwidth from 0.1 GHz to 100 GHz. The approximation accuracy is the ratio between the Shannon rate in (1) and the linear approximation in (2). As we can see, the accuracy is already above 90% when the bandwidth is higher than 0.4 GHz. In the following simulation, the system bandwidth is 1.5 GHz and the approximation accuracy is higher than 95%.

In Fig. 5, we show the energy efficiency as a function of distance for a direct link and for a link with one relay. The upper bound is for the link with one relay and no power limit. Using relays improves the energy efficiency as the decreased path loss leads to increased maximum data rate. This effect is much larger compared to the increased power consumption due to the relay transmission and circuit power. Fig. 6 shows that the energy efficiency increases with the number of relays, but the gain diminishes with higher numbers of relays, in which case more relays are needed for the same effect. This diminishing return is shown more clearly in Fig. 7. In Fig. 8 it is shown that increased circuit power of relays reduces the benefit of the energy efficiency of using multiple relays. In Fig. 9, we further compare the performance of energy-efficient link adaptation (LA), relay deployment (RD), and link adaptation together with relay deployment (RD+LA). The relays are randomly placed in the LA simulation and the transmission power values are randomly determined in the RD simulation.

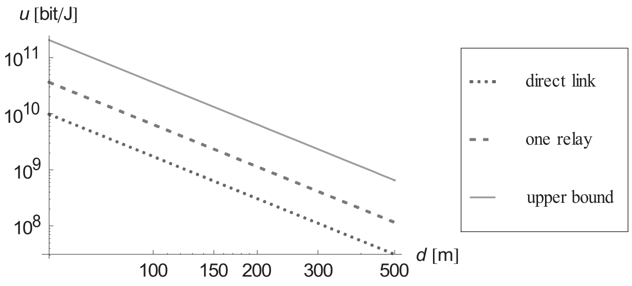

Fig. 5. Energy efficiency and distance with one relay.

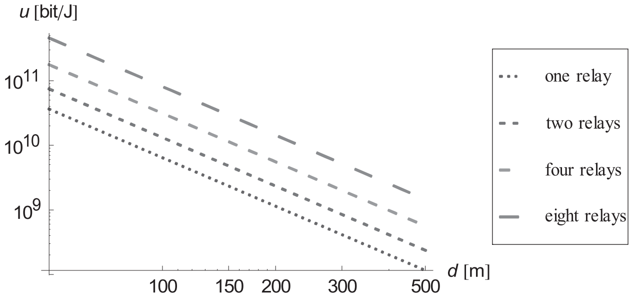

Fig. 6. Energy efficiency and distance.

X. CONCLUSION

In this paper we have discussed optimal energy-efficient communications for end-to-end communications. Specifically we have discovered the globally optimal link adaptation as well as relay deployment strategies such that a multi-hop

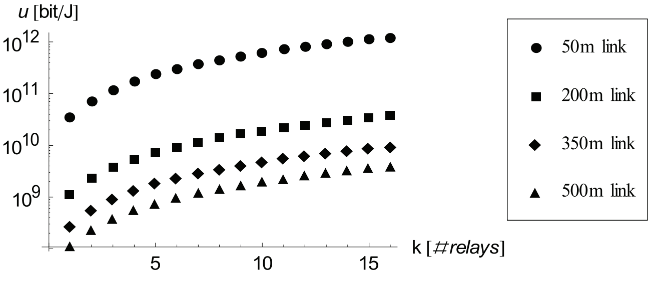

Fig. 7. Energy efficiency and number of relays.

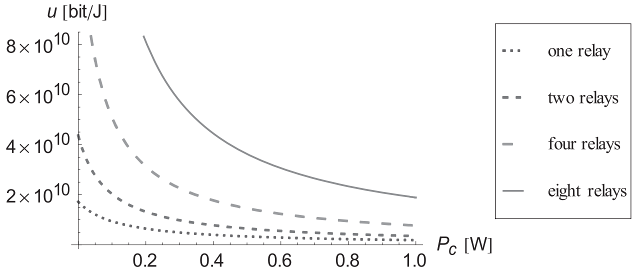

Fig. 8. Energy efficiency and circuit power.

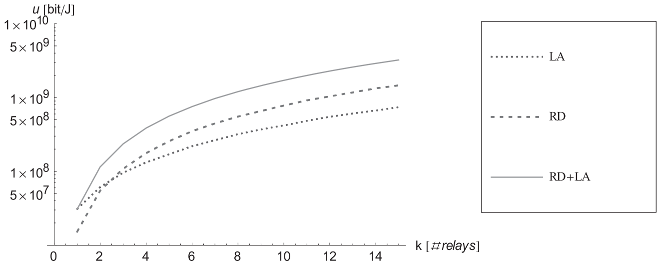

Fig. 9. Energy efficiency of different schemes.

system can run with the highest energy efficiency. We have first investigated the designs in the wideband regime. In this regime, if only link adaptation is used, all users should transmit with the highest necessary data rate so that the circuit energy consumption can be minimized. When all users transmit with fixed power, the relays should be deployed such that each link achieves the same data rate. If both the deployment and power can be adapted, we have revealed the unique and globally optimal strategy that automatically balances the contribution to power consumption from transmission, circuit operation, distance, and power amplifiers. Later we have also studied energy-efficient designs in the normal regime. The technologies proposed can be used in various communication systems, such as the deployment and communication of wired core networks and wireless broadband relay backhauls, to improve their end-to-end energy efficiency. This paper has been focused on a simple linear end-to-end network topology. The methodology can be easily extended to two-dimensional network topologies for energy-efficient designs of a whole network.

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