

Energy-Efficient Modulation Design for Reliable Communication in Wireless Networks

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Abstract—¹ In this paper, we have considered the optimization of the M -ary quadrature amplitude modulation (MQAM) constellation size to minimize the bit energy consumption under average bit error rate (BER) constraints. In the computation of the energy expenditure, the circuit, transmission, and retransmission energies are taken into account. A combined log-normal shadowing and Rayleigh fading model is employed to model the wireless channel. The link reliabilities and retransmission probabilities are determined through the outage probabilities under log-normal shadowing effects. Both single-hop and multi-hop transmissions are considered. Through numerical results, the optimal constellation sizes are identified. Several interesting observations with practical implications are made. It is seen that while large constellations are preferred at small transmission distances, constellation size should be decreased as the distance increases. Similar trends are observed in both fixed and variable transmit power scenarios. We have noted that variable power schemes can attain higher energy-efficiencies. The analysis of energy-efficient modulation design is also conducted in multi-hop linear networks. In this case, the modulation size and routing paths are jointly optimized, and the analysis of both the bit energy and delay experienced in the linear network is provided.

I. INTRODUCTION

In wireless communications, the analysis of energy efficiency and reliable packet transmission has attracted much interest recently, spurred by emerging wireless applications, such as in wireless sensor networks, where recharging and/or replacing the batteries of the wireless devices are difficult. In such scenarios, a wireless node can transmit and receive a finite number of bits before its battery runs out. Therefore, minimizing the bit-energy consumption will be a key factor in maximizing the node and, eventually, the network lifetime.

In wireless networks, operation at all levels of the communication protocol stack has an impact on the energy consumption and therefore, energy efficiency has to be addressed in device, physical, link, and network layers jointly. In early work in the networking literature, minimum-energy routing algorithms, which select the paths with the minimum total transmission power over all the nodes, are developed (see e.g., [1], [2]). As described in [3], if the links are assumed to be error-free and hence there is no need for retransmission, energy-efficient routing algorithms choose the minimum-hop paths in cases in which the transmitter power is fixed. On the other hand, in variable-transmission power scenarios, the sender nodes dynamically vary their transmission power P_t proportional to

d^β , where d is the link distance and β is the path loss exponent, so that the received signal power is kept fixed to achieve an acceptable signal-to-noise ratio (SNR) level at the receiver. In such cases, again when error-free links are considered, energy-efficient routing protocols tend to choose routes with a large number of small-range hops. We note that the assumption of error-free links has led to the design of algorithms which consider the energy spent only in a single transmission over each link.

However, in practical wireless channels, transmitted signals are subject to random propagation effects such as shadowing and multipath fading, leading to random fluctuations in the strength of the received signal. As a result of these random variations, reliable reception of the transmitted message signal cannot be guaranteed all the time. In cases in which the received signal power is below a certain threshold required for acceptable performance, outage is said to have occurred and retransmission of the transmitted signal is required. Due to their significant impact on the overall energy consumption, retransmissions, which are generally handled by the link layer, must be considered in the analysis of energy-efficient operation. Two types of retransmission schemes, namely end-to-end retransmission (*EER*) and hop-by-hop retransmission (*HHR*), are elaborated in [3] and [4], where the relationship between the link error probability of individual links and the overall number of retransmissions needed to ensure reliable packet delivery is established. In [3], the authors designed energy-efficient routing algorithms in the network layer by also taking into account the link layer retransmission probabilities and energies.

Clearly, design in the device and physical layers has a significant impact on the energy expenditure. For instance, transmission power depends on the selected modulation type and size, required error probability levels, and assumed channel attenuation models, all of which are mainly physical layer considerations. At the device level, besides the transmission energy, the circuit energy of the microchips performing as radio frequency transceivers, A/D and D/A converters and baseband processors or other application interfaces in the battery-driving nodes is an additional source of energy consumption. The circuit energy, together with the transmission energy, has to be considered in the overall optimization modeling, especially in short range networks in which the circuit energy is comparable to the transmission energy, and also as

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the number of retransmissions increases.

So far, several studies have addressed different aspects of energy-efficient operation. Optimization of the one-hop transmission distance without retransmission mechanism is studied in [5] while optimal routing with retransmission mechanism considering *EER* and *HHR* models is investigated [3]. In these studies, physical and device layer considerations are not incorporated in the models in detail. Authors in [6] and [7] consider both circuit and transmission energy consumption and address the optimization of modulation size under energy constraints. However, in these studies, link layer outage events, link reliabilities, and retransmission energies are not considered in the optimization.

In this paper, we provide a holistic approach by studying the energy efficiency considering device, physical, link, and network layers jointly. In particular, we investigate the optimal size of the quadrature amplitude modulation (QAM) constellation that minimizes the energy required to send one bit of information. An accurate energy consumption model is used, in which the total energy equals to the sum of circuit energy (device layer), transmission energy (physical layer), retransmission energy (link layer). Initial results are obtained for single-hop transmissions. Subsequently, results are extended to a simple linear multi-hop network model for which energy-efficient routing paths (network layer) are studied.

The remainder of the paper is organized as follows. Section II introduces the log-normal shadowing effects and link outage probability. Section III presents the accurate energy consumption model and discusses how to compute the average receive power \bar{P}_r over the Rayleigh fading channel given an average BER constraint \bar{p}_b for uncoded square MQAM. Section IV presents the linear network model and analyzes the bit energy consumption, delay performance, the optimal routing for a specific MQAM constellation and also for the optimal MQAM constellation.

II. LOG-NORMAL SHADOWING AND LINK RELIABILITY

A combined path loss and log-normal shadowing model is considered as a model for the large-scale propagation effects. This has been confirmed empirically to accurately model the variations in the received power in indoor and outdoor radio propagation environments [9]-[11]. For this model, the ratio of the received power to transmission power in dB is given by

$$\frac{P_r}{P_t}(dB) = K_{dB} - 10\beta \log_{10} \frac{d}{d_0} - \psi_{dB} \quad (1)$$

where ψ_{dB} is a Gaussian-distributed random variable with zero mean and variance $\sigma_{\psi_{dB}}^2$, modeling random shadowing effects; d_0 is a reference distance for the antenna far-field; β is the path loss exponent; $K_{dB} = 20 \log_{10} \frac{\lambda}{4\pi d_0}$ is a constant that depends on the wavelength λ of the transmitted signal and d_0 . In [8], an approximation for the packet error probability has been presented for the log-normal shadowing model. We hereby adopt the same idea to define the outage probability under path loss and shadowing as the probability that P_r falls

below a threshold power P_{min} . This outage probability of a certain link is denoted by p_{link} and is given by

$$p_{link} = p(P_r(d) \leq P_{min}) \quad (2)$$

$$= 1 - Q\left(\frac{P_{min} - (P_t + K_{dB} - 10\beta \log_{10}(d/d_0))}{\sigma_{\psi_{dB}}}\right) \quad (3)$$

where $Q(\cdot)$ is the Gaussian Q -function [9]. We assume that if outage occurs and hence $P_r(d) \leq P_{min}$, then receiver doesn't successfully receive the packet and the sender needs to retransmit the packet until successful reception is achieved. In our analysis, we adopt the hop-by-hop retransmission (*HHR*) scheme. We employ p_{link} to calculate the average number of retransmissions in a statistical sense. If we denote E_{ij} as the energy consumption of single transmission over a link between node i and node j with link error probability $p_{link_{ij}}$, we can derive the average total energy consumption for a reliable packet delivery over this link in the *HHR* mode as

$$E_{ij}^{total} = \frac{E_{ij}}{1 - p_{link_{ij}}}. \quad (4)$$

To compute this total energy E_{ij}^{total} and the link error probability $p_{link_{ij}}$, we have to specify the parameters in (3). Generally, we assume $d_0 = 1$ and employ the empirical results from [10] for $\sigma_{\psi_{dB}}^2$ and β . In the following section, we describe how the threshold power level P_{min} is specified.

III. ACCURATE ENERGY CONSUMPTION MODEL FOR BER CONSTRAINED MQAM

Usually in energy-constrained networks, the emphasis on minimizing the transmission energy is reasonable in long-range networks ($d \geq 100m$), where the transmission energy is dominant in the total energy consumption. On the other hand, in many recently proposed densely distributed networks such as wireless sensor networks, the average distance between nodes could be within 10 to 100 meters, for which the circuit energy consumption is comparable to the transmission energy. In such cases, the circuit energy consumption should be included in the total energy consumption for more accurate analysis.

A. Circuit and Transmission Energies

We adopt the accurate energy consumption formulation from [7], [12] and [13]. We assume that the source node has L bits in one packet to transmit. One single transmission is composed of three distinct periods: transmission period T_{on} , transient period T_{tr} , and sleeping period T_{sp} . Accordingly, the total energy required to send L bits is represented by

$$E = P_{on}T_{on} + P_{sp}T_{sp} + P_{tr}T_{tr} \quad (5)$$

where

$$P_{on} = P_t + \alpha P_t + P_{ct} + P_{cr}. \quad (6)$$

Above P_{on} , P_{sp} and P_{tr} are power consumptions for the active mode, sleep mode and transient mode, respectively. Specifically, P_{on} comprises the transmission power P_t , the amplifier power αP_t , the circuit power at the transmitter P_{ct}

and the circuit power at the receiver P_{cr} . We assume that the power of the sleep mode is very small and we approximate it as $P_{sp} \approx 0$. Now, the bit energy is

$$E_a = (((1 + \alpha)P_t + P_{ct} + P_{cr})T_{on} + P_{tr}T_{tr})/L. \quad (7)$$

When we consider uncoded MQAM as our modulation scheme, we can write

$$T_{on} = \frac{LT_s}{b} = \frac{L}{bB} \quad (8)$$

where b is the constellation size defined as $b = \log_2 M$ in MQAM, and T_s is the symbol duration. Note that in the second equality in (8), the approximation $T_s \approx 1/B$ is used. Therefore, in a specific MQAM, if the number of bits L and channel bandwidth B are given, the active period T_{on} is consequently derived. Finally, we note that the amplifier efficiency for MQAM can be obtained from $\alpha = \frac{\xi}{\eta} - 1$ where $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M+1}}$ is a function of the MQAM constellation size.

B. Average BER Constraint for MQAM

We consider a wireless channel model in which, in addition to the large-scale log-normal shadowing effects discussed in Section II, small-scale Rayleigh fading is experienced. First, we note that for square-constellation MQAM, the symbol error probability P_s as a function of the instantaneous received SNR γ_s is given by [9]:

$$P_s = \frac{4(\sqrt{M}-1)}{\sqrt{M}}Q\left(\sqrt{\frac{3\gamma_s}{M-1}}\right) - \frac{4(M-2\sqrt{M}+1)}{M}Q^2\left(\sqrt{\frac{3\gamma_s}{M-1}}\right) \quad (9)$$

where the Gaussian Q -function and its square can be expressed, respectively, as

$$Q(z) = \frac{1}{\pi} \int_0^{\pi/2} \exp\left[\frac{-z^2}{2\sin^2\phi}\right] d\phi \quad (10)$$

$$Q^2(z) = \frac{1}{\pi} \int_0^{\pi/4} \exp\left[\frac{-z^2}{2\sin^2\phi}\right] d\phi. \quad (11)$$

The average symbol error probability is computed by averaging the instantaneous error probability over the specific fading distribution $p_{\gamma_s}(\gamma)$ as follows

$$\bar{P}_s = \int_0^\infty P_s(\gamma)p_{\gamma_s}(\gamma)d\gamma. \quad (12)$$

Substituting (9)-(11) into (12), we can express the average BER for Rayleigh fading approximately as

$$\begin{aligned} \bar{p}_b &= \frac{4}{\pi \log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\pi/2} M_{\gamma_s} \left(-\frac{g}{\sin^2\phi}\right) d\phi \\ &\quad - \frac{4}{\pi \log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\pi/4} M_{\gamma_s} \left(-\frac{g}{\sin^2\phi}\right) d\phi \\ &= \frac{4}{\pi \log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right) \int_0^{\pi/2} \left(1 + \frac{3\bar{\gamma}_b \log_2 M}{2(M-1)\sin^2\phi}\right)^{-1} d\phi \\ &\quad - \frac{4}{\pi \log_2 M} \left(1 - \frac{1}{\sqrt{M}}\right)^2 \int_0^{\pi/4} \left(1 + \frac{3\bar{\gamma}_b \log_2 M}{2(M-1)\sin^2\phi}\right)^{-1} d\phi. \end{aligned} \quad (13)$$

Above, $M_\gamma(s)$ denotes the moment generating function

$$M_\gamma(s) = \int_0^\infty p_{\gamma_s}(\gamma)e^{s\gamma}d\gamma \quad (14)$$

of the fading distribution $p_{\gamma_s}(\gamma)$ in the Rayleigh fading channel where

$$p_{\gamma_s}(\gamma) = \frac{1}{\bar{\gamma}_s} e^{-\gamma/\bar{\gamma}_s}. \quad (15)$$

For a given BER constraint \bar{p}_b , we can use (13) to compute the required bit SNR $\bar{\gamma}_b$ numerically. Then, the minimum average received power that guarantees an average BER of \bar{p}_b is computed by [9]:

$$P_{min} = \bar{\gamma}_b N_0 B \log_2 M \quad (16)$$

where $\frac{N_0}{2}$ is the noise power spectrum density. Below this power level, the received information packets might undergo unacceptable distortion and the transmission is considered unreliable, which is quantitatively modeled by the outage probability in the log-normal shadowing model in Section II.

IV. OPTIMAL MODULATION FOR SINGLE-HOP AND MULTI-HOP TRANSMISSIONS

In this section, we numerically evaluate the optimal QAM constellation size that minimizes the bit energy consumption under different BER constraints, and establish the tradeoffs associated with this analysis. The bit energy is computed by taking into account circuit, transmission, and retransmission energies. Initially, we consider single-hop transmissions and then investigate multi-hop links.

A. Optimal MQAM Constellation Size in Single-Hop Transmissions

In this section, we study the bit energy consumption in single-hop transmissions where retransmission, circuit energy, uncoded square MQAM and \bar{p}_b constraint are considered based on equations (3), (4), (7), (13), and (16). We consider two transmit power policies: fixed P_t and variable P_t .

The values of the set of parameters used in numerical results are provided in Table 1. For instance, the maximum allowable average BER is $\bar{p}_b = 0.0001$. In fixed transmit power scheme, we assume $P_t=100\text{mW}$ and vary the constellation size $b \in [2, 4, 6, 8, 10]$ at link distance $d \in$

TABLE I
NETWORK AND CIRCUIT PARAMETERS

$\bar{p}_b = 0.0001$	$\eta=0.35$
$N_0 = 4 * 10^{-21} W/Hz$	$\beta=3.12$
$L=20000$ bits	$freq = 2.5 * 10^9 Hz$
$P_{tr}=100mW$	$P_{ct}=98.2mW$
$\sigma_{\psi_{dB}}=3.8dB$	$P_{cr}=112.5mW$
$B=10KHz$	$T_{tr}=5\mu s$

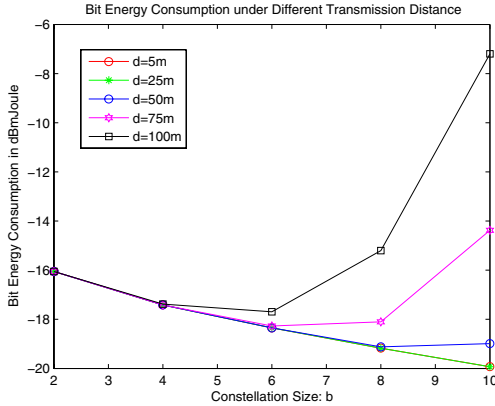


Fig. 1. Bit-energy consumption vs. constellation size b when P_t is fixed

[5m, 25m, 50m, 75m, 100m]. The bit energy consumption vs. constellation size curves for different transmission distances are given in Figure 1. We immediately observe that the bit energy increases as the constellation size gets either large or very small, and there exists an optimal b value at which the bit energy is minimized. This tradeoff is due to the following. We note that an MQAM with large constellation sends the information at a faster rate decreasing T_{on} and hence the transmit energy. However, a large constellation requires a larger P_{min} , leading to a higher outage probability and consequently more retransmissions. On the other hand, a small constellation size requires less retransmissions but increases T_{on} and hence the transmit energy. Hence, the optimal constellation size should provide a balance between these effects. In Fig. 1, we observe that the optimal b is 8 at $d = 50m$ and the optimal b is 6 at $d = 75m$. We note that the energy-minimizing constellation size gets smaller with increasing distance. In Fig. 2., the bit energy is plotted as a function of transmission distance for different constellation sizes. We see that while large constellation sizes are performing well at small distances, small constellations should be preferred when the distance gets large.

Now, we consider a variable transmit power scheme, where P_t is dynamically adjusted so that the average received power is

$$P_{min} = P_t + K_{dB} - 10\beta \log_{10}(d/d_0). \quad (17)$$

In this case, it can be easily seen that the link error probability p_{link} in (3) is always equal to 0.5 independent of the transmission distance. We apply the same configuration to compute the bit energy for different MQAM constellation

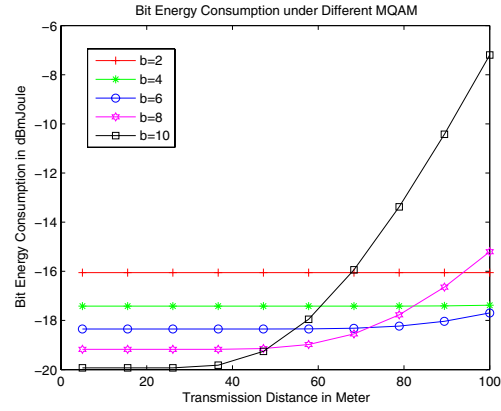


Fig. 2. Bit-energy consumption vs. transmission distance when P_t is fixed

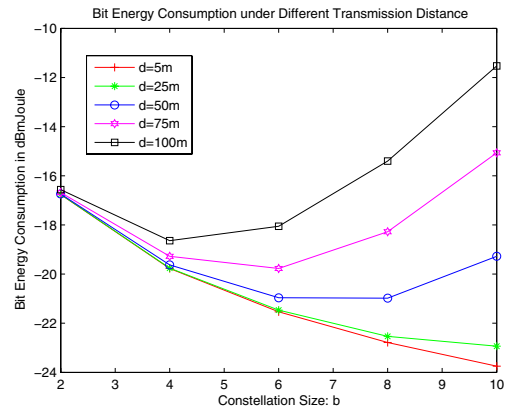


Fig. 3. Bit-energy consumption vs. constellation size b when P_t is variable

sizes and transmission distance. Figures 3 and 4 provide the numerical results. Conclusions similar to those for the fixed-transmit power case can be drawn in the variable-power case as well. However, we note that smaller bit energies and hence higher energy efficiency can be attained in the variable-power case as evidenced in the numerical results.

B. Linear Network Model

In this section, we study multi-hop scenarios and consider a simple linear network with $N + 2$ nodes: source, destination and N intermediate nodes equally distributed in between. Each intermediate node can behave as either an active relay or just a sleeping node. The working condition of N intermediate nodes could be visualized by a binary code, where the active nodes are denoted as 1 and the sleeping nodes as 0. In this model, totally 2^N routing paths are available in the HHR relay transmission scenario. Accordingly, we can either choose a routing path with less intermediate relay nodes and longer hops, or a routing path with more intermediate relay nodes and shorter hops. Note that longer hops tend to have higher p_{link} , resulting in more retransmissions while more intermediate relay nodes imply a potentially higher circuit energy consumption. Therefore, the selection of the optimal

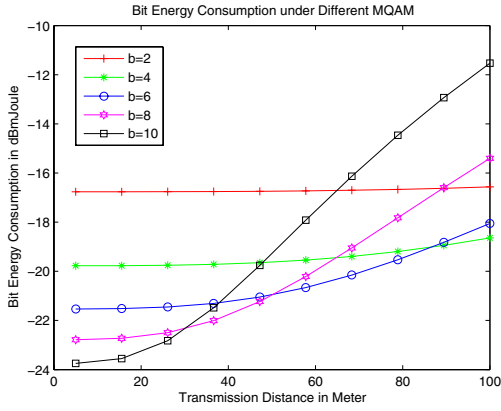


Fig. 4. Bit-energy consumption vs. transmission distance when P_t is variable

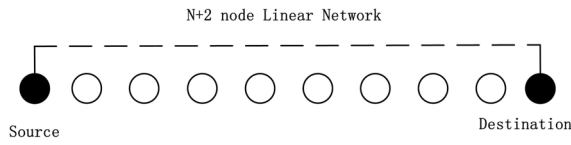


Fig. 5. Topology of Linear Network

route should strike a balance between these tradeoffs.

In the linear network, we set the distance between the source and destination to 100m, consider 9 intermediate nodes, and choose \bar{p}_b from the following set: $\{0.0001, 0.0003, 0.0005, 0.0008, 0.001\}$. We apply the parameters in Table 1 and employ the method used in Section IV.A for each possible relay link. Given the constellation size $b = \log_2 M$ and a specific \bar{p}_b , we search the 2^N routing paths to find the optimal route that requires the minimum bit energy consumption defined as:

$$\text{minimize}(E_{a_{total}}^{HHR}) = \min \sum_{i,j} \frac{Ea_{ij}}{1 - plink_{ij}}. \quad (18)$$

At fixed $P_t=100\text{mW}$ scheme, among all possible routings, the optimal routing is found in terms of the minimum bit energy consumption when the packet containing 20000 bits is relayed in HHR mode successfully from the source to the destination via intermediate nodes. Fig. 6 shows the minimum bit energy consumption corresponding to the optimal routing for each square uncoded MQAM under different BER constraints when P_t is fixed. Hence, in the figure, the bit energies for different constellation sizes are the ones required by the optimal route. Again, there exists a certain constellation size that minimizes the bit energy consumption. Moreover, we observe that lower error probabilities expectedly require more energy. Fig. 7 shows the corresponding delay experienced in optimal routing. The delay is formulated as the sum of time intervals consumed over the relay links, whose individual delay is computed as:

$$\text{Delay}_{link_{ij}} = \frac{T_{on} + T_{tr}}{1 - plink_{ij}} \quad (19)$$

Fig. 7 is showing that on points which achieve optimal bit

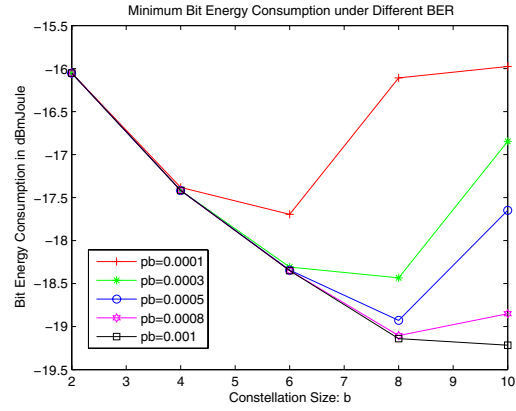


Fig. 6. Optimal bit energy consumption vs. constellation size b when P_t is fixed

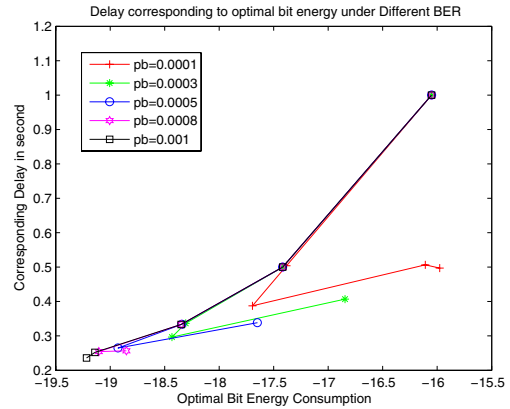


Fig. 7. Delay vs. optimal bit energy consumption when P_t is fixed

energy consumption, the corresponding delay is also minimal. This is due to the fact that the optimal route and modulation size that minimize the energy requirements are favorable in terms of delay as well, because they try to diminish both T_{on} and the number of retransmissions by finding a balance between competing factors in the fixed-transmit-power case.

Finally we consider the variable P_t scheme, and adopt all previous parameters to repeat the bit energy as well as delay analysis. Figure 8 shows the minimum bit energy consumption corresponding to the optimal routing for each square uncoded MQAM when P_t is variable. Compared to Fig. 6, the variable P_t scheme shows better performance, requiring about 1-1.5 dBmJoule less than that of the fixed P_t scheme at optimal MQAM points. Fig. 9 plots the optimal bit energy-delay curves. Here, we note that it no longer holds that optimal bit energy and optimal delay are achieved at the same point for all BER constraints \bar{p}_b .

Intuitively, in the fixed P_t scheme, the transmit power P_t would strongly affect $plink_{ij}$. Accordingly, we can also vary P_t as well as constellation size b to find the global minimum point under a given \bar{p}_b constraint. Fig. 10 illustrates optimal bit energy consumption corresponding to the optimal routing as

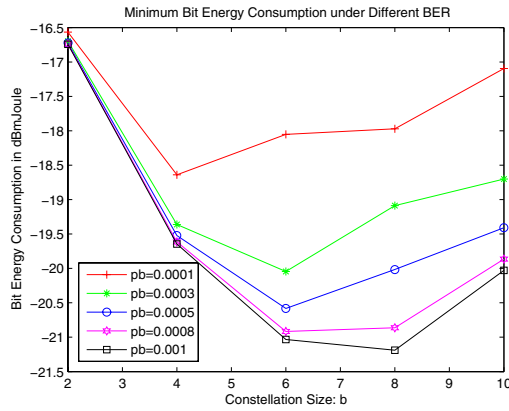


Fig. 8. Optimal bit energy consumption vs. constellation size b when P_t is variable

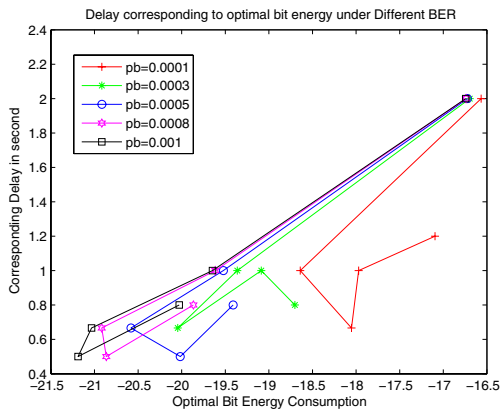


Fig. 9. Optimal bit energy consumption vs. constellation b when P_t is variable

a function of b and P_t . The numerical result shows the global minimum is -19.71 dBmJoule for the error rate constraint $\bar{p}_b=0.0001$, found when $b=4$ and $P_t=25\text{mW}$.

V. CONCLUSION

In this paper, we have considered the optimization of the MQAM constellation size to minimize the bit energy consumption under average BER constraints. In the computation of the energy expenditure, the circuit, transmission, and retransmission energies are taken into account. A combined log-normal shadowing and Rayleigh fading model is employed to model the wireless channel. The link reliabilities and retransmission probabilities are determined through the outage probabilities under log-normal shadowing effects. Both single-hop and multi-hop transmissions are considered. Through numerical results, the optimal constellation sizes are identified. Several interesting observations with practical implications are made. It is seen that while large constellations are preferred at small transmission distances, constellation size should be decreased as the distance increases. Similar trends are observed in both fixed and variable transmit power scenarios. We have noted that variable power schemes can attain higher

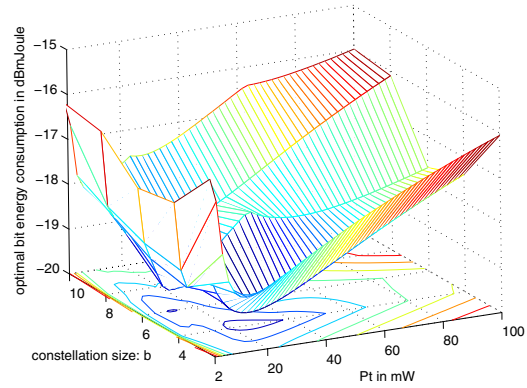


Fig. 10. Optimal bit energy consumption vs. constellation size b and transmit power P_t .

energy-efficiencies. The analysis of energy-efficient modulation design is also conducted in multi-hop linear networks. In this case, the modulation size and routing paths are jointly optimized, and the analysis of both the bit energy and delay experienced in the linear network is provided.

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