Constellation Size Optimization of MPSK and MQAM for Short-Range Wireless Communications

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Abstract—This paper presents a technique to improve energy efficiency of a short-range ad-hoc wireless network by optimizing constellation size of MPSK and MQAM in the non-frequency selective slow Rayleigh fading channel and AWGN channel.

I. INTRODUCTION

Energy efficiency is a major challenge for the fast growing wireless ad-hoc technology. In fact, there exists a continuously growing gap between the increase in available energy, consecutive to battery-technology evolution, and the increase in energy consumed by advanced applications.

The long-range wireless systems ignore circuit energy and just consider transmission energy while computing total transmission energy. However, in short-range ad-hoc communication, the circuit energy has also significant contribution on total transmission energy and energy efficiency. Thus, circuit energy cannot be ignored. Energy efficiency of the system can be improved by considering both transmission energy and circuit energy [1] along with the appropriate modulation techniques and MAC protocols in short range communications [2].

Several publications mentioned the effect of modulation techniques on energy efficiency. Such as, [3] proposes an optimal strategy to decrease the transmission energy per bit. In [1], the binary and M-ary modulation schemes are compared. It showed that M-ary will be energy efficient than binary for a small overhead and transmit-on time. Moreover, sleep/wake-up mechanism is a common method to save energy e.g. as in wireless sensor networks. In sleep/wake-up mechanism, the transient time required to change a node from sleep state to wake-up state (or vice versa) is termed as *transmit-on time*. When the transmit-on time exceeds certain limit, the energy consumption of the M-ary modulation will be more. Furthermore [4] has presented MQAM and MFSK modulation schemes for AWGN channel. It gave detail trade-off analysis based on peak-power and delay constraints.

Apart from previous publications that just considered AWGN channel, this paper compares MPSK and MQAM for Rayleigh channel to achieve energy efficiency by optimizing constellation size. It analyzes the total transmission energy based on constellation size, transmit-on time, and distance between nodes.

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II. SYSTEM SETUP AND COMPUTATION OF PARAMETERS

A. *Transceiver model*

For theoretical analysis, we assume that the transceiver has a circular communication range of 10m with k^{th} power path loss model [5]. The transmitter part consists of digital to analog converter (DAC), filter, mixer, frequency synthesizer, and power amplifier. While the receiver consists of filter, low noise amplifier (LNA), mixer, frequency synthesizer , intermediate frequency amplifier (IFA), and analog to digital converter (ADC) [4]. Furthermore, the transceiver implements sleep/wake-up mechanism to conserve energy.

B. *Time and Power Parameters*

It is assumed that the transceiver circuit powered off completely during sleep period i.e. $(P_{sleep} = 0)$. The wake-up/sleep transmit-on time is neglected because it is quite negligible with respect to the sleep/wake-up transmit-on time, because latter has to settle its phase locked loop (PLL).

Let us consider a transceiver transmitting L bits of data to another transceiver in T seconds, then total time required for data communication will be,

$$T = T_{start} + T_{on} + T_{sleep} .$$

Where, T_{start} : Transmit-on time ; T_{on} : Wake-up time required to send L bits ; T_{sleep} : Sleep time

Let us assume, P_{on} , P_{start} , and P_{amp} are power required communicating L bits, Power consumed during T_{start} , and power consumed by the amplifier alone respectively.

Moreover, we introduce an energy saving technique during transmit-on time by switching on rest of the electronic components just after PLL are settled. Since, PLL requires longest transmit-on time as compare to other circuits.

C. *Energy Parameters*

The total energy consumed by the transceiver is given by,

$$E_{total} = P_{on}T_{on} + P_{start}T_{start} + P_{sleep}T_{sleep} = P_{on}T_{on} + P_{start}T_{start}$$

$$(P_{sleep} = 0)$$

Where, E_{total}: Total energy consumption and E_{ckt} : Total energy consumed by the electronic components of transceiver

During wake-up state, power is required for the transmission, electronic circuits (excluding power amplifier) and power amplifier. While frequency synthesizers/ PLL of the transmitter and receiver part only consume power during transmit-on time.

$$E_{total} = (P_t + P_{ckt})T_{on} + 2P_{fsyn}T_{start} \quad (1)$$

$$= (P_t + P_{amp} + P_{ckt})T_{on} + 2P_{fsyn}T_{start} \quad (2)$$

Where, P_t : Power required for transmission; P_{ckt} : Power consumed by different electronic circuits excluding amplifier; P_{fsyn} : Power consumed by PLL/freq synthesizer; P_{amp} : Power consumed by amplifier.

Since, the total circuit power includes power consumed by electronic components of both side. For simplicity, it is assumed that power consumed by transmitter filter and receiver filter are equal. Similarly, power consumed by ADC and DAC are same. Therefore, the total circuit power can be expressed as:

$$P_{ckt} = P_{ckttx} + P_{cktrx} = 2P_{mix} + 2P_{fsyn} + 2P_{filt} + P_{IFA} + P_{LNA} + 2P_{ADC} \quad (3)$$

Where, P_{ckttx} and P_{cktrx} represent power consumed by the transmitter circuitry and receiver circuitry respectively ; Power consumed by mixer, filter, IFA, LNA, and ADC/DAC are represented by P_{mix}, P_{filt}, P_{IFA}, P_{LNA}, and P_{ADC} respectively. Here we consider that the mixer, frequency synthesizer, filter, and DAC are the major power consumers in the transmitter side and mixer, frequency synthesizer, filter ADC, intermediate frequency amplifier (IFA), low noise amplifier (LNA) are the major power consumers in the receiver side.

Now, expressing P_{amp} in terms of P_t [4],

$$P_{amp} = \alpha.P_t = ((\xi/\eta) - 1).P_t \quad (4)$$

Where, ξ and η are the peak to average ratio and drain efficiency of the power amplifier. ξ depends on the modulation scheme and related to the constellation size as $\xi = 3\left((\sqrt{m}-1)/(\sqrt{m}+1)\right)$ for MQAM and $\xi = 1$ for both MPSK. Here, m represents the constellation size.

Using (2-4), we can derive the total energy consumption for MQAM and MPSK.

$$E_{T-MQAM} = E_t(1+\alpha) + (2(P_{mix} + P_{fsyn} + P_{filt} + P_{ADC}) + P_{IFA} + P_{LNA})T_{on} + 2P_{fsyn}T_{start} \quad (5)$$

$$E_{T-MPSK} = E_t(1+\alpha) + (2(P_{mix} + P_{fsyn} + P_{filt} + P_{ADC}) + P_{IFA} + P_{LNA})T_{on} + 2P_{fsyn}T_{start} \quad (6)$$

$$E_t = P_t.T_{on} \quad (7)$$

III. COMPARATIVE ANALYSIS OF MQAM AND MPSK

The comparative analysis for MQAM and MPSK is done in this section by using total energy consumption equations derived in (5-7). Equations (5-7) are further elaborated based on error probability and Rayleigh distribution. Finally, we derive the relationship between energy consumption and constellation size.

A. *Theory*

The bit error probability for the above-mentioned channel can be calculated as follows. [8] [9]

$$P_e = \int_0^\infty p_{be}(g).p(g)dg \quad (8)$$

And for Rayleigh distribution, $p(g) = \frac{1}{y} \cdot e^{-\frac{g}{y}}$ (9)

Where, P_e and $p_{be}(g)$ are bit error probability in the fading and AWGN channel respectively. g : Instantaneous SNR per bit and y : Average SNR

For MQAM,[4] [6]

$$p_{be}(g) = \frac{4}{b}\left(1 - \frac{1}{\sqrt{m}}\right)Q\left(\sqrt{\frac{3bg}{m-1}}\right)$$

$$\approx \frac{4}{b}\left(1 - \frac{1}{\sqrt{m}}\right)e^{-\left(\frac{3bg}{2(m-1)}\right)} \quad (10)$$

$$\text{Or,}\quad g \approx \frac{2\left(2^b - 1\right)}{3b}\ln\left(\frac{4(1 - 2^{-b/2})}{bp_{be}(g)}\right) \quad (11)$$

Where, b and m are bits per symbol and constellation size respectively. [Note: $m = 2^b$].

Solving y from (8-10), we get an explicit formula for average SNR per bit for MQAM as follows.

$$y = \frac{4(2m-2)\left[0.25 - \frac{P_e \cdot b\sqrt{m}}{4\left(\sqrt{m}-1\right)} + \left(\frac{P_e \cdot b\sqrt{m}}{4\left(\sqrt{m}-1\right)}\right)^2\right]}{3b - 12b\left[0.25 - \frac{P_e \cdot b\sqrt{m}}{4\left(\sqrt{m}-1\right)} + \left(\frac{P_e \cdot b\sqrt{m}}{4\left(\sqrt{m}-1\right)}\right)^2\right]} \quad (12)$$

Similarly, *for MPSK, [7]*

$$p_{be}(g) = \frac{2}{b}Q\left(\sqrt{2gb}.\sin(\pi/m)\right) \approx \frac{2}{b}e^{-gb(\sin(\pi/m))^2} \quad (13)$$

$$\text{Or,}\quad g \approx \frac{1}{b(\sin(\pi/m))^2}\ln\left(\frac{2}{bp_{be}(g)}\right) \quad (14)$$

$$y = \left[\frac{1-(\frac{2bP_e}{2.5} - \frac{(bP_e)^2}{6.25})}{\frac{2bP_e}{2.5} - \frac{(bP_e)^2}{6.25}} \right] \frac{1}{b(\sin(\pi/m)^2)} \tag{15}$$

Above equality is considered for approximation. Again,

$$y = \frac{SNR.per.symbol}{b} = \frac{P_r}{2B\sigma^2 N_f b} \tag{16}$$

Using k^{th} power path loss model, we get,

$$P_t = P_r.G_d = G_1 d^k M_l \tag{17}$$

Where P_r and G_d represents the received power and power gain factor respectively and G_1, d^k and M_l are the gain factor at 1m, distance and link margin respectively.

B. Relationship between T_{on} and b

The bits per symbol of each modulation scheme can be related to the transmit-on time as follows.

$$b = L/(BT_{on}) \tag{18}$$

Where, B represents the bandwidth.

Since, y and g are the SNR per bit for AWGN and Rayleigh channel. Using above defined parameters, equations (5-6) can be expressed in terms of b or transmit-on time.

For AWGN channel, $P_r = 2gB\sigma^2 N_f b$ (19)

We can derive an expression for total energy consumption per bit for MQAM in AWGN channel from above equations. From equation (11), (17), and (19), we get,

$$P_t = \frac{4}{3} N_f \sigma^2 \left(2^b - 1\right) \ln\left(\frac{4\left(1-2^{-b/2}\right)}{bp_{be}(g)} \right) G_d B \tag{20}$$

Then, from equation (5), (7), and (20), we get

$$E_{T-MQAM} = \frac{\left[\begin{array}{l} ((1+\alpha)\frac{4}{3} N_f \sigma^2 (2^b - 1) \ln\left(4(1-2^{-b}) / bP_e \right) G_d BT_{on} \\ +2(P_{mix} + P_{fsyn} + P_{filt} + P_{ADC} + P_{IFA} + P_{LNA})T_{on} \\ +2P_{fsyn}T_{start} \end{array} \right]}{L}$$

Similarly, from equation (6), (7), (14), (17), and (19), we can get similar expression for MPSK in AWGN channel

$$E_{T-MPSK} = \frac{\left[\begin{array}{l} ((1+\alpha)2N_f\sigma^2 \left[\ln\left(2/bP_e \right) / (\sin(\pi/m))^2 \right] G_d BT_{on} \\ +2(P_{mix} + P_{fsyn} + P_{filt} + P_{ADC} + P_{IFA} + P_{LNA})T_{on} + 2P_{fsyn}T_{start} \end{array} \right]}{L}$$

For Rayleigh channel, total energy consumption per bit equations can be derived in similar way. Using equation (5), (7), (12), (16), and (17), we get an expression for MQAM as

$$E_{Tf-MQAM} = \frac{\left[\begin{array}{l} (2(1+\alpha)yN_f\sigma^2 G_d BT_{on} + 2(P_{mix} \\ +P_{fsyn} + P_{filt} + P_{ADC} + P_{IFA} + P_{LNA})T_{on} + 2P_{fsyn}T_{start} \end{array} \right]}{L}$$

Similarly, using equation (6), (7), (15), (16), and (17), we get an expression for MPSK as

$$E_{Tf-MPSK} = \frac{\left[\begin{array}{l} (2b(1+\alpha)yN_f\sigma^2 G_d BT_{on} \\ +2(P_{mix} + P_{fsyn} + P_{filt} + P_{ADC} + P_{IFA} + P_{LNA})T_{on} + 2P_{fsyn}T_{start} \end{array} \right]}{L}$$

Above equations give a relationship between total transmission energy and T_{on}. We can deduce an optimum T_{on} time or constellation size by using these equations. Since, equation (18) gives the relationship between T_{on} and b.

IV. SIMULATION AND RESULTS

Above derived relationships between energy and constellation size are simulated under MATLAB. The data's considered in simulation are tabulated in Table I.

TABLE I :DATA'S FOR SIMULATION

Carrier frequency: 2.45 GHz (ISM band) ; B : 10 KHz k : 2-4 (3 is selected) η: 0.35 σ^2 : - 170dBm/Hz L : 2 kb P_{mix} =30.3mW P_{fsyn} =50mW $P_{filtx} = P_{filrx}$ =2.5mW P_{LNA} =20mW	$P_{DAC} = P_{ADC}$ =2.5mW T_{start} = 5 μs M_l (link margin)=40dB T = 100ms P_b =10-3 $N_f = \frac{N_{total}}{2B\sigma^2}$ = 10dB (receiver noise figure.) G_1 =30dB P_{IFA} =3mW

Table II shows the simulation result for the optimum constellation size (b) for fixed L and B for MQAM and MPSK. The optimum constellation size is defined as the value of constellation size for which the value of total transmission energy is minimal. It depicts that there exists an optimum constellation size that varies with fading for both modulations. Although optimum constellation size decreases slightly when the scenario changes to Rayleigh, there is significant energy saving at optimum constellation point as compared to the non-optimized case for each modulation. Thus, the circuit energy should not be ignored for short-range communications. Moreover, the MQAM consumes less energy and conserves 2dB total energy consumption than MPSK in both scenarios but has huge constellation size.

TABLE II: OPTIMUM CONSTELLATION SIZE AT $d = 5m$

Channel	MQAM	MPSK
AWGN	9.5	6.7
Rayleigh	8.3	5.5

The variation of optimum transmit-on time under assumed operating range (1-10m) for both scenarios is shown in Fig. 1. When channel scenario changes, there is only slight variation of transmit-on time for short distance. While there is a large change of transmit-on time at maximum operating distance as compared to short distance. This result agrees with the result of [4]. Here we observe that up to 10m, the total energy consumption is not monotonically decreasing function of transmit-on time. Moreover, at $d = 1m$, approximately 8 dB and 6 dB energy saving are achieved for MQAM and MPSK under optimized than non-optimized case $(T_{on} = T)$ for both scenarios.

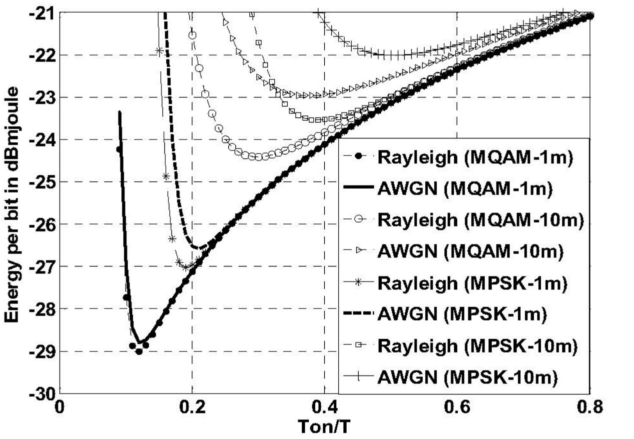

Fig. 1: Total energy consumption for different modulation scheme within an operating range (1-10m)

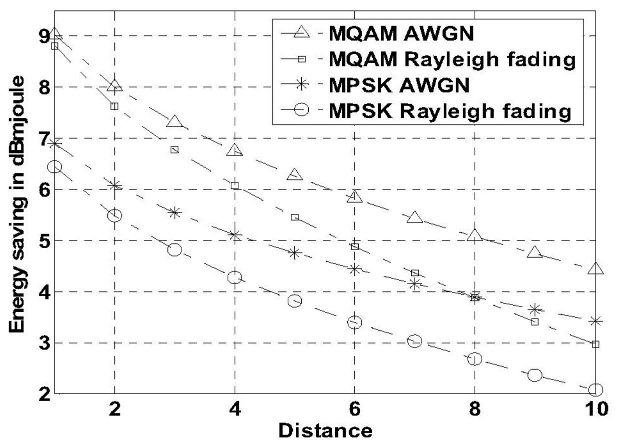

Fig. 2: Energy saving at optimum constellation with respect to $T = T_{on}$ point.

However, as the distance increases, the energy consumption changes due to fading and even not same in both scenarios. It is observed that about 1 dB more energy is consumed when scenario changes from AWGN to Rayleigh for both modulations. There is only 3dB and 1dB energy saving under Rayleigh fading for MQAM and MPSK respectively. Thus the energy saving can be achieved by optimizing T_{on} but it decreases with increase in distance. Therefore, energy efficiency can be achieved by the transmit-on time optimization for both scenarios at short range. Fig. 2 depicts energy saving in both channels. Under both channels, MQAM seems more energy efficient although the energy efficiency declines with distance because of fading. The optimum constellation size is not consistent and decreases with increase in distance. Distance and channel scenario introduce inconsistency on optimum constellation size, which is one of the challenging tradeoff.

V. Conclusion

This circuit energy based comparative analysis presented in this paper concludes that the energy efficiency can be achieved by optimizing transmit-on time or constellation size. However, the optimized constellation size is not consistent in whole operating range. Techniques like adaptive modulation scheme have to be deployed to obtain an optimum constellation size over completely operating range. Furthermore, MQAM modulation seems more efficient than MPSK in both AWGN and Rayleigh channel. Therefore, energy saving can be achieved by implementing correct modulation technique with an optimum constellation size or transmit-on time, which is quite dissimilar from long range wireless systems that ignores circuit energy consumption. The hardware complexity arises due to the consideration of modulation techniques inhibits above implementation in low data rate wireless personnel area networks (LR-WPAN) and wireless sensor networks (WSN). However, it may be a good consideration for HR-WPAN (high data rate wireless personnel area networks) and wireless Ad-hoc networks. Thus, short range (less than 10m) and ultra-short range communication systems may conserve energy by considering the effect of circuit energy, hence constellation size on energy efficiency.

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