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On the Energy Efficiency of WSN Communications Operating Under Non-coherent M-FSK and M-QAM Modulations

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Abstract To make Wireless Sensor Network (WSN) market growth a reality, we need to empower the network designers with a provision to optimally tailor the physical layer parameters. In this paper, we present a holistic analysis of energy related aspects of WSN communications operating under Rayleigh fading, using standardized WSN specifications. The rational expressions have been derived by taking into consideration the effects of packet size, repeated training sequences, transmission distance, path-loss, amplifier efficiency, bandwidth of the channel and active mode span for Non-coherent M-ary FSK (NC-MFSK) and M-QAM modulation schemes. The results of variation of total energy consumption along with various parameters like path-loss, amplifier efficiency, hop distance and packet size have been investigated. We found that for small transmission distances, M-QAM modulation performs better than NC-MFSK scheme, but as the distance increases the NC-MFSK outperforms the M-QAM in the terms of energy efficiency. Moreover, for communications operating with NC-MFSK modulation, the crossover point of better energy efficiency is achieved at lesser distance with increase in value of path-loss parameter. These results may enable the network designers to plan energy-efficient WSN communication architectures even in the presence of constrained environments.

Keywords Wireless sensor networks · Energy efficiency · Physical layer · Active mode span · Channel bandwidth · Communication parameters

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1 Introduction

WSNs have useful applications in many spheres of daily life, ranging from simple health care monitoring to challenging remote volcanic eruption alarming systems, but their performance is plagued by the fact that battery-operated WSNs have limited life-span. WSN lifetime maximization has been widely studied in recent past [1, 2] and is an active research topic in the present scenario also.

Communications over a wireless link are prone to short term fading caused by the arrival of multiple, randomly delayed, reflected and scattered signal components at the receiver side and long term fading because of shadowing. These impairments not only hinder performance but also degrade the energy-efficiency, hence making the study of energy related aspects an important topic for research consideration.

In the recent past, many efforts have been made in this context like: the performance analysis of coherent BPSK using compound fading model with the gamma–gamma distribution [3], study of energy consumption by analyzing optimization for popular modulation approaches using transmission time and modulation constellation order [4], performance evaluation of digital communications over Generalized-K channel in terms of outage probability [5], investigations of shadowed fading channel using the moment generating function of SNR [6] and WSN performance evaluation under impact of multi-casting and varying effects of shadowing (constant and lognormal) [7].

In other attempts, the authors used the optimal hop distance to find total energy consumed to transmit data at a certain distance in [8]. The effective energy-per-useful bit (EPUB) metric has been considered to maximize the WSN lifetime in [9]. Authors in [10] investigated the performance analysis of energy consumption under AWGN and Rayleigh fading channel using popular modulation approaches.

In a related line of research, a study with the combination of Reed–Solomon codes with popular modulation schemes has been conducted in [11]. In [12], using MQAM transmission, the optimum scheme that results in minimum energy consumption for a given hop distance was derived. Authors in [13] derived the total energy consumption for WSN communication using realistic parameters for different modulation schemes operating under the effects of Rayleigh fading considering active mode span. In [14], the authors evaluated the energy utilized per bit for WSN communications based on BPSK modulation over the Generalized-K shadowed fading channel considering the impact of channel impairments, retransmissions of packets and insertion of training sequences. In [15], the authors investigated the energy efficiency aspects of WSN using a Space time block coding communication approach for communication operating over Rayleigh channels with popular modulation techniques like BPSK and M-QAM in terms of relevant metrics such as order of transmit diversity, error rate, constellation size and data rate. This study recommended the cluster-BS distance-wise modulations and constellation sizes for a range of distances to support energy efficiency.

In [16], the authors explored physical layer attributes for energy-efficient WSN communications operating under various modulation schemes by taking symbol error rate into consideration. The advantage of choosing the optimal modulation schemes by considering optimal hop-distance, channel noise etc. was highlighted. The effects of varying packet-size, amplifier efficiency, fixed and varying hop distance, repeated training sequences etc. were also taken into consideration.

In this paper, we investigated the energy efficiencies in WSN communication operating under block fading environment for different modulation schemes. We derived rational expressions for energy utilization by considering effects of structure of data and acknowledgement packets, repeated training sequences, path-loss, channel bandwidth, amplifier efficiency and active mode span. We used M-QAM modulation for its suitability for low-cost transmitters [17] and M-FSK modulation for its faster start-up time than other modulations because of the simple circuitry design.

The paper is arranged as follows. In Sect. 2, we discuss the system and channel model. In Sect. 3, we discuss the derivation for expressions of energy utilized per bit for WSN communication by considering effects of repeated training sequences, path-loss, channel bandwidth and active mode span. Numerical results and related discussions are reported in Sect. 4. Finally, in Sect. 5 we conclude the findings of this research work.

2 System and Channel Model

We use a communication channel operating with Rayleigh fading and path-loss considerations. We consider an energy consumption model as proposed in [4] for determining power consumption of transmitter and receiver circuits. We also assume that participating nodes have similar energy levels and consume similar energy in performing similar jobs. It is further assumed that for a given SNR in a symmetric radio channel, the energy utilized to transmit data in one direction is the same as that in the reverse direction. Data and acknowledgement packets are also assumed to be of fixed size and both packet header and training sequence are assumed to be error-free. Data packets are assumed to be transmitted with repeated training sequences while acknowledgement packets are transmitted without training sequence considerations. Link quality of both forward and reverse link is also assumed to be the same.

In wireless communications, the received signal is expressed as $A = HX + N_i$, where X is the transmitted component which is modulation dependent, H is the fading channel envelop, and N_i is the channel noise.

3 Energy Modeling

Energy is a scarce resource in the battery-powered nodes of WSNs. Due to the constrained attributes of sensor nodes, tailoring energy-efficient communication parameters is an important issue in the WSN design at the physical layer. This section presents exhaustive analysis of energy efficiency of WSN communications using standardized specifications to find the optimum physical layer communication parameters by taking into consideration the effects of packet size, repeated training sequences, channel bandwidth, transmission distance, path-loss, active mode span and amplifier efficiency.

Communications under constrained scenarios often use data packet structure in which data bits are preceded by training sequences which are used for channel estimation and synchronization. Longer training sequences are used for better channel estimation and synchronization. We refer to optimal training sequence length which is sufficient to successfully remove any kind of phase offset as given in [18]. In fading environments, the prefixed training sequence at the packet-head only cannot provide an effective channel information. To overcome this difficulty, additional training sequences need to be inserted in the data packet. As acknowledgement packets are of small size, they are assumed to be transmitted without any training sequences.

Let $link_p$ and $link_a$ represent the forward and reverse link respectively between the sender S and the receiver R. Let each data packet contain b_T bits, which includes b_h bits (including training sequence and header bits) and b_i payload bits, while acknowledgement packet contains b_a bits. Let N_{tseq} represent the number of inserted training sequences (each of length b_h) and the channel coherence time be Γ ms. For attaining optimum efficiency and precise accuracy over channel bandwidth BW, we use the following mathematical relation [16]

$$\frac{b_i}{BW} + \frac{N_{tseq} \times b_h}{BW} \approx \Gamma \times N_{tseq} \tag{1}$$

Using above expression, N_{tseq} can be obtained using simple mathematical operations.

$$\begin{aligned} \frac{b_i}{BW} &\approx \Gamma \times N_{tseq} - \frac{N_{tseq} \times b_h}{BW} \\ \frac{b_i}{BW} &\approx N_{tseq} \times \left(\Gamma - \frac{b_h}{BW} \right) \\ b_i &\approx N_{tseq} \times (BW \times \Gamma - b_h) \\ N_{tseq} &= \frac{b_i}{BW \times \Gamma - b_h} \end{aligned} \tag{2}$$

We consider a proactive WSN system model employing the duty-cycling approach. We derive the expressions for energy consumption and analyze the performance metrics of the popularly used modulation schemes such as Non-coherent M-FSK and M-QAM by taking into consideration the effects of channel bandwidth, amplifier efficiency, active mode span path-loss and repeated training sequences.

We consider an arrangement where a sensor node transmits constant data to sink during each time span and both the nodes tune as per duty-cycling fashion. While operating in active mode span T_A, the data is digitized and further transmitted to the sink node after applying pre-determined modulation. Then, the node switches over to the sleep mode for duration T_S. Let T_T represent transient span comprising change-over time of both sleep to active mode and also from active to sleep mode (assumed to be negligibly small). T_T is approximately equal to change-over time from sleep to active mode. The sensor/sink nodes require processing of N-bit data over a active period span.

We assume that nodes operate with Direct Current to Direct Current (DC–DC) unit which enables reduction in power consumption. The power transfer efficiency is denoted by χ_e (assumed to be <1) and battery model is also assumed to be linear, i.e., discharge of batteries in active mode can be regained in sleep mode.

Assuming short distance between nodes in a WSN, the total power consumption of the underlying circuitry, defined by $P_{circuit} = P_{tck} + P_{rck}$, where P_{tck} and P_{rck} represent the circuit power consumptions for the transmitting and receiving nodes respectively. The total energy consumption denoted as E_{TOTAL} in each span T_N corresponding to an N-bit message can be computed as in [19]

$$E_{TOTAL} \approx \frac{1}{\chi_e} [(P_{circuit} + P_t) T_A + P_{tr} T_T] \tag{3}$$

where P_t represents transmit power, T_A is a function of N and the bandwidth of the channel, $\frac{P_{tr}}{\chi_e} T_T$ is the energy consumption of the circuit during the transient mode span, where, P_{tr} is the power consumption during the transient mode period. Now, we investigate the energy efficiency of communications operating over popular modulations like NC-MFSK and M-QAM under the effects of Rayleigh fading.

3.1 Non Coherent M-FSK

An M-FSK modulator is characterized by fast start-up time, less complex circuitry and low power consumption. The non-coherent variant of M-FSK has more applicability in the energy constrained WSN applications. Assume $\Delta f = \frac{1}{\zeta T_s^{FS}}$ to be the carrier separation (least possible), where T_s^{FS} represents the symbol duration, $\zeta = 1$ for non-coherent FSK [20]. The bandwidth of the channel is obtained as the product of constellation size (M) and minimum carrier separation. The bandwidth efficiency (BW_{eff}^{FS}) is the ratio of data rate (R^{FS}) to the channel bandwidth [13].

$$BW_{eff}^{FS} \triangleq \frac{R^{FS}}{BW} = \frac{\zeta log_2 M}{M} \text{b/s/Hz} \tag{4}$$

Further, the expression for active mode span T_A^{MFSK} can be obtained by taking into consideration the effects of the repeated training sequences [13, 16]

$$T_A^{MFSK} = \frac{M}{\zeta \times BW \times log_2 M} \left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h \right) \tag{5}$$

Now, we derive transmit energy for each symbol (E_{tr}^{NCMFSK}) expressed in terms of error rate (P_{sym}^{NCMFSK}) which is given as

$$P_{sym}^{NCMFSK} = 1 - \left(1 - \frac{1}{2 + \overline{\gamma}^{MFSK}}\right)^{M-1} \quad (6)$$

where $\overline{\gamma}^{MFSK} = \frac{\Omega}{\mathrm{L_d}}\frac{E_{tr}^{NCMFSK}}{N_0}$, with $\mathrm{L_d}$ is the gain factor of ηth-power path-loss channel given as ratio of transmitted to receiver signal powers and mathematically represented by $L_d \triangleq M_g d^\eta L_1$ where M_g represents gain margin, d represents transmission distance and $\mathrm{L_1}$ is the gain factor at unit distance. Further, $\Omega \triangleq \mathbb{E}[|h_i|^2]$ and h_i the fading channel coefficient corresponding to symbol i, where the amplitude $|h_i|^2$ is Rayleigh distributed and N_0 is taken as -180 dB [13]. The transmit energy per symbol is expressed as

$$E_{tr}^{NCMFSK} = \left[\left(1 - (1 - P_{sym}^{NCMFSK})^{\frac{1}{M-1}}\right)^{-1} - 2\right]\frac{\mathrm{L_d} N_0}{\Omega} \quad (7)$$

The output energy consumption for transmitting b_T bits by considering the effects of power efficiency and the repeated training sequences during T_A^{MFSK} is computed as

$$E^F = \left[\left(1 - (1 - P_{sym}^{NCMFSK})^{\frac{1}{M-1}}\right)^{-1} - 2\right]\frac{\mathrm{L_d} N_0}{\Omega \chi_e} \times \frac{1}{log_2 M} \times \left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h\right) \quad (8)$$

3.1.1 Total Circuit Energy Consumption

Now, total circuit energy consumption denoted by E_{CKT} can be treated as the sum of energies used at the sensor as well as at the sink end represented as P_{CKTT}^F and P_{CKTR}^F respectively.

$$E_{CKT} = \frac{P_{CKTT}^F + P_{CKTR}^F}{\chi_e} T_A^{MFSK} \quad (9)$$

The power consumption of sensor and sink node circuits are considered as below:

- *Sensor node circuit power consumption* It is computed as the sum of power consumptions of various subcomponents like synthesizers, filters and amplifiers represented by P_{SYN}^F, P_{FIL}^F and P_{AMP}^F respectively.
- *Sink node circuit power consumption* It is computed as the total of powers of Low-Noise Amplifier (LNA)(P_{LNA}^F), an Intermediate-Frequency Amplifier (IFA)(P_{IFA}^F), an ADC and power contribution of M filters and envelope detectors.

Now, the power consumption for transient mode span T_T^{MFSK} is dependent on the frequency synthesizers at both ends [4], so the total energy consumption during this period is given as $2\frac{P_{SYN}^F}{\chi_e} T_T^{MFSK}$ [13]. Now, total energy consumption in transmitting a data of b_T bits is computed as

$$E_{TOTAL}^F = \left[(1 + \alpha^F)\left(\frac{M-1}{P_{sym}^{NCMFSK}} - 2\right)\frac{\mathrm{L_d} N_0}{\Omega} + (P_{circuit}^F - P_{AMP}^F) \times \frac{M}{BW}\right] \times \frac{1}{\chi_e} \times \frac{1}{log_2 M}\left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h\right) + 2\frac{P_{SYN}^F}{\chi_e} T_T^{MFSK} \quad (10)$$

Further including the effects of acknowledgement packet (assumed to be smaller size and without repeated training sequences), the total energy consumption can be expressed as

$$E_{TOTAL}^F = \left[(1 + \alpha^F)\left(\frac{M-1}{P_{sym}^{NCMFSK}} - 2\right)\frac{\mathrm{L_d} N_0}{\Omega} + (P_{circuit}^F - P_{AMP}^F) \times \frac{M}{BW}\right] \times \frac{1}{\chi_e} \times \frac{1}{log_2 M}\left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h + b_a\right) + 2\frac{P_{SYN}^F}{\chi_e} T_T^{MFSK} \quad (11)$$

3.2 M-QAM

M-QAM is a popular modulation approach in WSN communication because of its suitability for low-cost transmitters. Following a similar derivation as done for M-FSK modulation in Sect. 3.1, we now derive the expression for M-QAM modulated communications. The average symbol error rate in fading environment for coherent M-QAM is upper-bounded by the expression given as [21]

$$P_{sym}^Q = \frac{4(M-1)}{3\overline{\gamma}^Q + 2(M-1)}\left[1 - \frac{1}{\sqrt{M}}\right] \quad (12)$$

where $\overline{\gamma}^Q = \frac{\Omega}{\mathrm{L_d}}\frac{E_{tr}^Q}{N_0}$ represents the average SNR. Therefore, the transmit energy for each symbol is expressed as below [13]

$$E_{tr}^Q = \frac{2(M-1)}{3}\left[2\left(1 - \frac{1}{\sqrt{M}}\right)\frac{1}{P_{sym}^Q} - 1\right]\frac{\mathrm{L_d N_0}}{\Omega} \quad (13)$$

Also, the total energy used in transmitting b_T bits during active mode span is

$$E^Q = \frac{2(M-1)}{3}\left[2\left(1-\frac{1}{\sqrt{M}}\right)\frac{1}{P^Q_{sym}}-1\right]\frac{\mathrm{L_d N_0}}{\Omega\chi_e} \times \frac{1}{log_2 M} \times \left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h\right) \quad (14)$$

3.2.1 Total Circuit Energy Consumption

Now, total circuit energy consumption, E_{CKT} can be treated as the sum of energies used at the sensor end as well as the sink end represented as P^Q_{CKTT} and P^Q_{CKTR} respectively. The power consumptions of sensor and sink nodes are computed as below

- *Sensor node circuit power consumption* It can be computed as the sum of power consumptions of various sub-components like DAC, synthesizers, mixers, filters and amplifiers represented by $P^Q_{DAC}, P^Q_{SYN}, P^Q_{MIX}, P^Q_{FLT}$ and P^Q_{AMP} respectively.
- *Sink node circuit power consumption* Power consumption of sink node circuit can be computed as the sum of power consumptions of various subcomponents like Low-Noise Amplifier (LNA), an Intermediate-Frequency Amplifier (IFA), an ADC, synthesizers, filters and mixer represented by $P^Q_{LNA}, P^Q_{IFA}, P^Q_{ADC}, P^Q_{SYN}, P^Q_{FIL}$ and P^Q_{MIX} respectively.

The power consumption for the transient period span T^Q_T is dependent on the frequency synthesizers at both ends, so the total energy consumption during this period is given as $2\frac{P^Q_{SYN}}{\chi_e}T^Q_T$ [13]. Now, total energy consumption in transmitting a data of b_T bits is computed as below:

$$E^Q_{TOTAL} = \left[(1+\alpha^Q)\frac{2(M-1)}{3}\left[2\left(1-\frac{1}{\sqrt{M}}\right)\frac{1}{P^Q_{sym}}-1\right] \times \frac{\mathrm{L_d N_0}}{\Omega} + \frac{P^Q_{circuit}-P^Q_{AMP}}{2 \times BW}\right] \times \left[\frac{1}{\chi_e \times log_2 M}\left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h\right)\right] + \frac{2P^Q_{SYN}T^Q_T}{\chi_e} \quad (15)$$

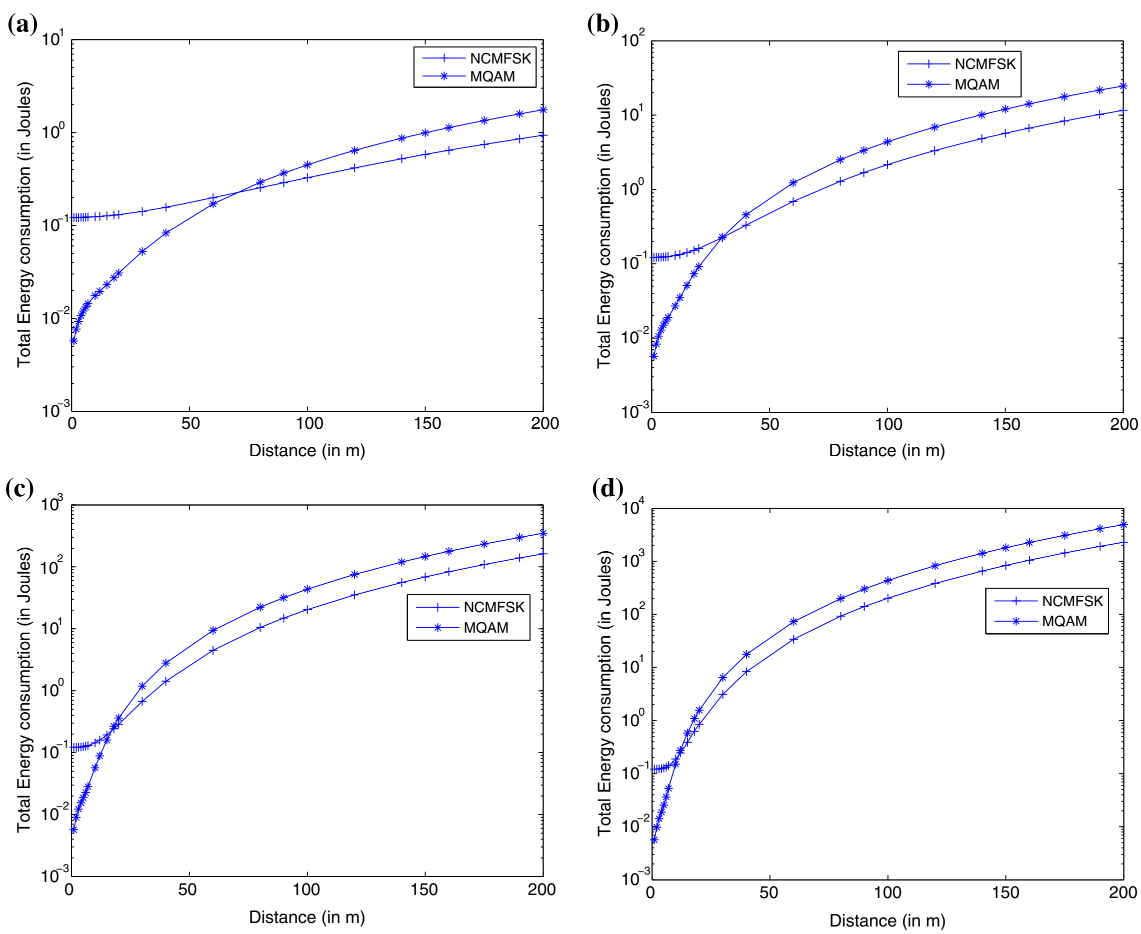

Fig. 1 Total energy consumption versus distance for different values of path-loss. **a** Value = 2, **b** Value = 2.5. **c** Value = 3. **d** Value = 3.5

Further including the effects of acknowledgement packets (assumed to be smaller size and without repeated training sequences), the total energy consumption can be expressed as

$$E^{Q}_{TOTAL} = \left[(1+\alpha^{Q}) \frac{2(M-1)}{3} \left[2\left(1-\frac{1}{\sqrt{M}}\right) \frac{1}{P^{Q}_{sym}} - 1 \right] \times \frac{L_d N_0}{\Omega} + \frac{P^{Q}_{circuit} - P^{Q}_{AMP}}{2 \times BW} \right] \times \left[\frac{1}{\chi_e \times log_2 M} \left(b_i + \frac{b_i}{BW \times \Gamma - b_h} \times b_h + b_a \right) \right] + \frac{2P^{Q}_{SYN} T^{Q}_{T}}{\chi_e} \quad (16)$$

Using derived Eqs. (11) and (16), we perform numerical computations to evaluate the desired performance metrics for WSN communications operating under NC-MFSK and M-QAM modulations respectively.

4 Results and Discussion

In the sub-sections to follow, we discuss the results in the terms of various performance metrics considering the impact of repeated training sequences for communications operating under M-QAM and Non-Coherent M-FSK modulations. The impact of channel bandwidth, active mode span have also been considered. Following results are discussed:

- Variation of energy consumption along with different path-loss values
- Variation of energy consumption along with amplifier efficiency
- Variation of energy consumption along with hop distance and packet size

4.1 Variation of Energy Consumption Along with Different Path-Loss Values

Path-loss is a critical parameter and must be incorporated into the energy computations for more realistic result evaluation. The results depicted in Fig. 1 show the changes in the total energy consumption along with distance for different values of path-loss for communications operating under NC-MFSK and M-QAM modulation schemes. It is observed that for small distances, communications with M-QAM modulation performs better than NC-MFSK scheme, but as the distance increases NC-MFSK based communications outperform M-QAM in the terms of energy efficiency. Furthermore, the crossover point of better energy efficiency using NC-MFSK modulation is achieved at lesser distance with increase in value of path-loss parameter, as with increase in path loss values, more energy is required to meet distance demands, therefore, the total energy consumption increases. Moreover, MFSK based transmission requires lower SNR for meeting target rate, but since the bandwidth efficiency in MFSK modulation is lower, the underlying transmission is more time consuming and hence circuit energy consumption is higher. It is also very clear from the graphs that MFSK is less suitable for shorter distances, as the circuit energy consumption contributes a significant share, but becomes energy efficient for longer distances, as signal energy consumption becomes more significant.

4.2 Variation of Energy Consumption Along with Amplifier Efficiency

The results depicted in Fig. 2 shows the variation of total energy consumption along with distance for values of amplifier efficiency for non-coherent MFSK modulation scheme considering the effects of repeated training sequences in the packet. It shows that with increase in distance the energy consumption level increases and it is also seen that use of higher amplifier efficiency results in higher energy consumption values. The range and degree of the nonlinearity in amplifier efficiency as a function of transmit power, determines the shape of curve and level of distortion. Our results demonstrate minimal variation in the shape of the curve for varying amplification efficiency.

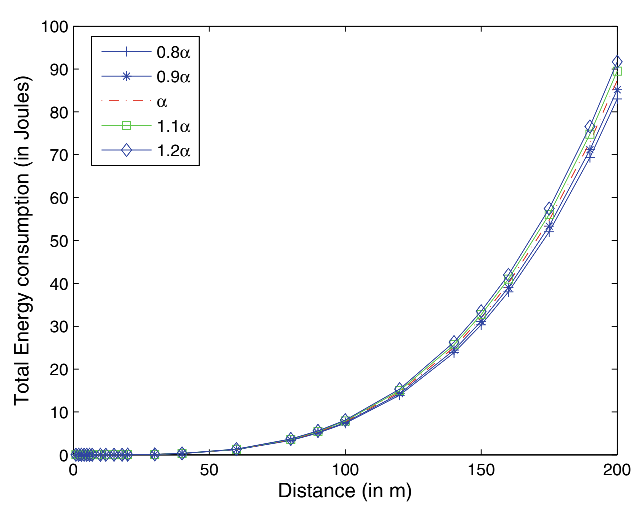

Fig. 2 Total energy consumption versus distance for different values of amplifier efficiency

4.3 Variation of Energy Consumption Along with Hop Distance and Packet Size

Packet size plays a dominant role in determining the efficiency of the underlying communication system. The probability of a successfully received packet decreases with increase in packet size, and therefore, use of small packets will facilitate lower energy consumption levels. The results depicted in Fig. 3a, b shows the variation of total energy consumption with distance for varying values of packet sizes for NC-MFSK and M-QAM modulation schemes respectively. It is observed that with increase in distance the total energy consumption increases and also use of larger packet size results in higher energy consumption values. The effects of repeated training sequences in the packet have been taken into consideration.

5 Conclusions

In this work, we investigated the energy aspects for WSN communications operating under block Rayleigh fading channel for data and acknowledgement packets. We derived expressions for energy consumption considering statistical performance characteristics like symbol error probability, path-loss, hop distance, transmit energy levels, amplifier efficiency and repeated training sequences. Effects of bandwidth of the channel and active mode span were also taken into consideration. We performed holistic analysis of energy efficiency of WSN communications using standardized WSN models to find the optimal WSN physical layer communication parameters. Some of the main conclusions of this work are as follows:

- Path-loss is an important parameter in physical layer and must be incorporated into energy computations for more realistic result evaluation. Results conclude that for small distances M-QAM modulation performs better than NC-MFSK scheme, but as the distance increases the NC-MFSK outperforms the M-QAM in the terms of energy efficiency. Moreover, the crossover point of better energy efficiency using NC-MFSK modulation is achieved at lesser distance with increase in value of path-loss parameter.
- The energy consumption levels increase with increase in transmission distance as well as amplifier efficiency for non-coherent MFSK modulation scheme considering the effects of repeated training sequences in the packet. The range and degree of the nonlinearity in amplifier efficiency as a function of transmit power, determines the shape of curve and level of distortion. Our results conclude a minimal variation in the shape of the curve for varying amplification efficiency.
- Packet size plays a dominant role in determining the efficiency of the system. Our investigations conclude that with increase in distance the total energy consumption increases and also use of larger packet size results in higher energy consumption values. The effects of repeated training sequences in the packet have been taken into consideration for NC-MFSK and M-QAM modulations.

We infer that to facilitate energy-efficient and reliable communications one needs to employ effective techniques to ameliorate the disastrous effects of fading impairment and tailor optimal permutation and combination of various communication parameters like—optimal transmit power, optimal EUB, optimal hop distance etc. This work can be extended by considering random distances between nodes as nodes will not always be equally spaced in realty. Work can also be extended to evaluate results on actual hardware and various types of motes.

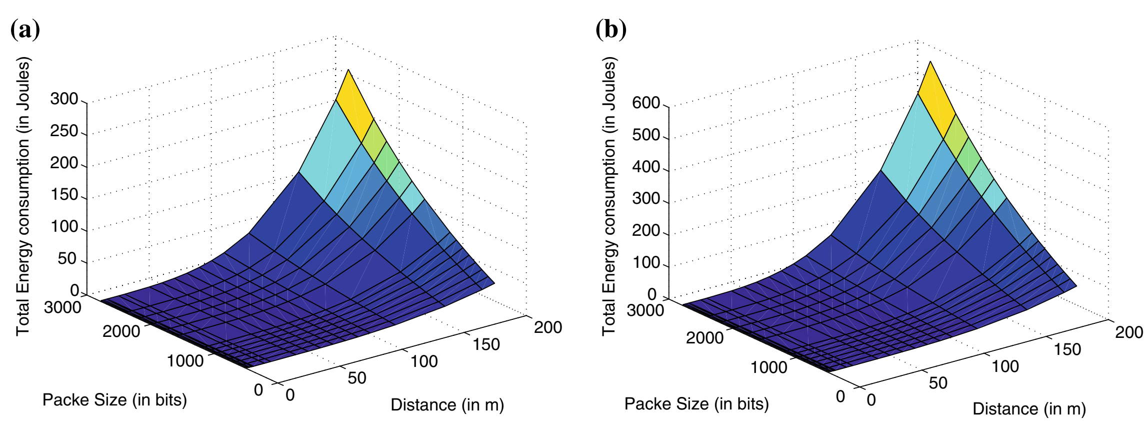

Fig. 3 Variation of total energy consumption with distance for different values packet size using **a** NC-MFSK modulation, **b** MQAM modulation

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