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On the Energy Utilization of WSN Communications Using Space-Time Block Coding Over BPSK and M-QAM Modulations

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Abstract Energy is a scarce and most vital resource in a wireless sensor network (WSN). Since space-time block coding requires less transmission energy than SISO technique for the same bit error rate (BER), therefore, it is one of the most practical diversity technique for WSN studies. In this work, we have investigated the energy utilization of a simple multiple-input single-output system using STBC for a WSN scenario constituting a number of clusters communication under Rayleigh channels with popular modulation techniques like BPSK and M-QAM. By deriving the rationale expressions for energy utilized per bit metric (E_{bit}) in terms of various quantities such as—order of transmit diversity, data rate, BER and the distance between the cluster and the base station (BS) (cluster-BS), we have investigated the suitability of transmit diversity order for varying magnitudes of distances. It has been observed that for communication involving, medium and long cluster to BS distances, the diversity order constituting two transmit antennae results in better energy efficiency and enhances reliability, but, for smaller cluster-BS distances, the contribution is not significant for the case under consideration. Further, we have explored how the energy utilization levels are affected by transmission rates and acceptable error levels. In addition, we optimized the modulation constellation order and recommended best-fit modulation approaches for the varying ranges of cluster-BS distances. Simulation results demonstrate that with increasing cluster-BS distances, the optimized constellation order of the M-QAM modulated communications decreases. BPSK based communication are found to be better in performance for long cluster-BS distances in comparison to those in M-QAM. This work may help the network designers to tailor optimal permutation and combination of various physical layer parameters to facilitate energy-efficient WSN communications.

Keywords Wireless sensor networks · Energy utilization · Space time block coding · Modulation · Constellation size

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1 Introduction

Performance of WSN is seriously challenged by energy constrained network elements and mode of hostile deployment (challenging reliability), therefore, we are persistently in search for WSN designs supporting better energy efficiency and enhanced reliability [1].

Wireless communication channels are populated with different impairments like - channel noise, interference, jamming, shadowing, fading, shadowed fading and co-channel interferences etc. These impairments contribute in deterring the performance of a network. Out of the several methods proposed in last few years for refining WSN designs from energy and performance aspects, the cooperative transmission diversity has been considered to be a good candidate for energy efficient communications even under the challenge of impairment-constrained channels [2, 3]. The space-time block coding based communications used here are specially desirable for sensor network applications as they are better in performance from energy aspect and are relatively less complex and bandwidth efficiency is more [4–6].

Recent research has witnessed several cooperative transmission diversity techniques for improved performance. In [7], authors proposed an effective transmission diversity technique for WSN in which STBC approach was used to facilitate energy savings. Another distributed space-time coding based cooperative communication protocol for reducing the effects of fading in the communicating channel was proposed in [8]. The energy-efficient modulation and transmission strategy was investigated in [9] where authors found that cooperative MIMO was more suitable from energy and delay viewpoint of the network. WSN Communications based on STBC strategy were studied in [10] for protocols supporting clustered hierarchy architecture and the results demonstrated extended sensor network lifetime.

Authors in [11], studied multiple-input single-output (MISO) approach for energy minimization in WSN. Using the optimal hop distance, the minimization of per bit energy consumption was done in [12], where the attributes like—hop distance and number of cooperative nodes were optimized together.

On the related lines of research, the investigation of energy consumption per unit transmission distance was undertaken in [13], where with optimization, the optimal transmission distance was obtained. In [14], authors explored the MISO and orthogonal frequency division multiplexing communications from energy efficiency viewpoint. In [15], cooperative communications approach when applied for long distance transmission (under the impact of channel impairments) gave energy-efficient results. In [16], the authors investigated and derived the energy utilized per bit for WSN based on BPSK communications over the Generalized-K shadowed fading channel considering the impact of packet retransmissions and training sequences.

This paper contributes by considering a WSN scenario with multiple clusters at fixed distance from BS and communications operating under Rayleigh fading channel are assumed to STBC-coded. We derived the mathematical relations for energy utilized per bit metric (E_{bit}) for the popular modulation schemes like—BPSK and M-QAM modulations, in terms of transmit diversity order, transmission data rate, bit error rate (BER) and distance between cluster and BS. Further, using numerical computations, we found optimal constellation size and the corresponding energy utilizations for varying range of distances between cluster and BS. We finally proposed best-fit of modulation schemes with constellation order for different range of cluster-BS distances so as to facilitate energy-efficient and reliable communications.

The rest of the paper is arranged as follows. We present the proposed multiple cluster WSN network model with derivations of the expressions of energy utilization in Sect. 2. Section 3 gives details of results obtained and discussions. The conclusions of this study are enlisted in the Sect. 4.

2 System Model

Here, we give details of proposed scenario used for derivations of expressions for different modulations.

2.1 Network Model and Assumptions

We use a WSN model as shown in the Fig. 1. The base station (BS) or the sink node is assumed to be located at the center of the network and a number of clusters surround it. Every cluster contains a cluster-head (CH) and number of sensors. Different Cluster heads are assumed to be located at fixed distance from BS. We further assume that the sensor nodes are constrained by limited energy levels and processing capabilities in contrast to the capabilities of CHs.

Wireless sensor network communications constitute—the communications within a cluster and the communications between a cluster and a base station. Because, magnitude of distance between the cluster and base station is assumed to be much more than the cluster radius, so, for convenience, we consider cluster-BS communications only for the energy per bit computations. We consider an energy

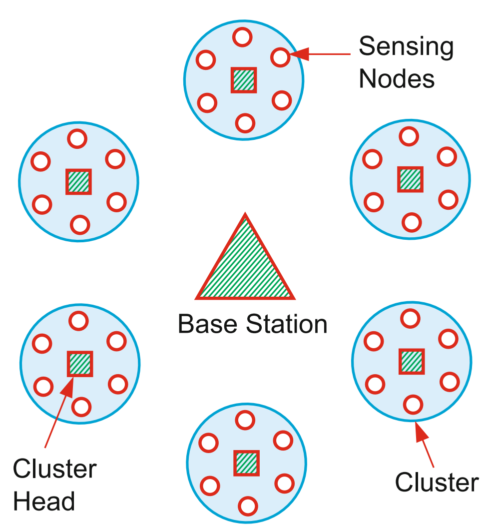

Fig. 1 Multi-cluster network layout

consumption model as proposed in [9] for determining power consumption of transmitter and receiver circuits.

Cooperative nodes participating in the communication between a cluster and BS are assumed to employ STBC for data encoding and transmit it simultaneously to the BS. The cluster head performs the accumulation of the data received from the sensors in the cluster. It chooses a pool of cooperative nodes to carry forward the required transmission. The proposed system arrangement is of MISO nature, because only the BS receives the cluster-BS data.

2.2 Energy Utilized Per Bit

Here, we proceed further to derive the relations for energy utilization per bit for different modulation schemes. The data under transmission is viewed as 2-D array, where horizontal entries represent number of the transmit antennae and vertical entries represent transmission time slots. The data at the destination are fused and then sent to the MLE (maximum likelihood detector) where the decision logics operate.

The power consumed is computed as sum of powers of amplifiers (P_{PA}) and participating circuitry (P_{CKT}). The power of amplifier is written in terms of transmit power P_T as below

$$P_{PA} = (1+\eta)P_T \tag{1}$$

where $\eta = \frac{\xi}{\zeta} - 1$ with ζ—drain efficiency and ξ—peak-to-average power ratio (PAR) [17]. Now, P_T can be expressed as [18]

$$P_T = \overline{E_b}\frac{R_b(4\Pi d)^2}{G_t G_r \lambda^2} L_{margin} \times N_{figure} \tag{2}$$

where $(\overline{E_b})$—average energy required per bit for acceptable error, R_b—data rate, d—transmission distance, G_t and G_r—gains of transmitter and receiver antennae, λ—wavelength, L_{margin}—link margin, and N_{figure} receiver noise figure represented as $N_{figure} = \frac{N_r}{N_o}$ with N_o—one-sided thermal noise power spectral density (PSD) and N_r—PSD of the total effective noise at receiver.

We first derive the exressions for M-QAM based communications for which the average BER $(\overline{P_b})$ is expressed by the following relation [18]

$$\overline{P_b} \approx E_H\left[\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)Q\left(\sqrt{\frac{3b}{M-1}SNR_i}\right)\right] \tag{3}$$

where $E_H\{.\}$ signifies the mean value, b represents constellation size, SNR_i represents instantaneous received signal-to-noise ratio (SNR) and $M = 2^b$.

The signal strength is also attenuated by the impact of fading. Let G represent scalar fading matrix modeled such that each entry is a circularly symmetric complex random variable with mean zero and variance unity. The instantaneous received SNR is expressed by the Alamouti scheme [19].

$$SNR_i = \frac{\|G\|_F^2}{M_t}\frac{\overline{E_b}}{N_o} \tag{4}$$

where $\|G\|_F^2$—squared Frobenius matrix norm representation of G and M_t represents the proportionality of transmit power between the antennae.

Now by using chernoff bound in the high SNR domain, the average BER is expressed as [18]

$$\overline{P_b} \le \frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)\left(\frac{1.5b}{M_t(2^b-1)}\frac{\overline{E_b}}{N_o}\right)^{-M_t} \tag{5}$$

Rearranging Eq. 5, we get $\overline{E_b}$ as

$$\overline{E_b} \le \frac{2}{3}\left(\frac{2^b-1}{b}\right)\left(\frac{\overline{P_b}}{\frac{4}{b}\left(1-\frac{1}{2^{\frac{b}{2}}}\right)}\right)^{-\frac{1}{M_t}} N_o M_t \tag{6}$$

Further, using the relation $\left(1-\frac{1}{2^{\frac{b}{2}}}\right) \le 1$, we obtain

$$\overline{E_b} \le \frac{2}{3}\left(\frac{2^b-1}{b^{\frac{1}{M_t}+1}}\right)\left(\frac{\overline{P_b}}{4}\right)^{-\frac{1}{M_t}} N_o M_t \tag{7}$$

Putting the upper bound of $\overline{E_b}$ from Eq. 7 into Eq. 2, we obtain

$$P_T = \frac{2}{3}\left(\frac{2^b-1}{b^{\frac{1}{M_t}+1}}\right)\left(\frac{\overline{P_b}}{4}\right)^{-\frac{1}{M_t}} N_o M_t \times \frac{R_b(4\Pi d)^2}{G_t G_r \lambda^2} L_{margin} \times N_{figure} \tag{8}$$

Further, using Eq. 1, we get P_{PA} as

$$P_{PA} = \frac{\xi}{\zeta}\frac{2}{3}\left(\frac{2^b-1}{b^{\frac{1}{M_t}+1}}\right)\left(\frac{\overline{P_b}}{4}\right)^{-\frac{1}{M_t}} N_o M_t \times \frac{R_b(4\Pi d)^2}{G_t G_r \lambda^2} L_{margin} \times N_{figure} \tag{9}$$

Now, P_{CKT} is expressed as sum of P_{CT} and P_{CR}, where P_{CT} represents the power consumed by circuitry excluding the power amplifier at the transmitter side. Considering M_t transmit antennae P_{CT} is expressed as

$$P_{CT} = M_t \times (P_{DAC} + P_{MIXT} + P_{FLT}) + 2P_{SYN} \tag{10}$$

where, P_{DAC}, P_{MIXT}, P_{FLT}, and P_{SYN} represent the power consumptions of the digital-to-analog (DAC) component, mixer, filter, and frequency synthesizer respectively at the transmitted end.

Further, P_{CR} represents power consumption of receiver circuitry. Considering M_r as number of receiver antennae (taken as 1 for MISO scenario under consideration), P_{CR} is expressed as

$$P_{CR} = M_r \times (P_{LNA} + P_{MIXR} + P_{IFA} + P_{FLR} + P_{ADC}) \quad (11)$$

where, P_{LNA}, P_{MIXR}, P_{IFA}, P_{FLR} and P_{ADC} represent the power consumptions of Low Noise amplifier, mixer, intermediate frequency amplifier, filter and analog-to-digital (ADC) component respectively at the receiver end.

The total energy utilized per bit for the WSN arrangement under consideration can be expressed as

$$E_{bit} = \frac{P_{PA} + (P_{CT} + P_{CR})}{R_b} \quad (12)$$

Further, substituting Eq. 9 in Eq. 12, we derive an expression of energy utilized per bit for M-QAM communications expressed as

$$E_{bit}^{MQAM} = \frac{\xi}{\zeta}\frac{2}{3}\left(\frac{2^b - 1}{b^{\frac{1}{M_t}+1}}\right)\left(\frac{\overline{P_b}}{4}\right)^{-\frac{1}{M_t}} N_o M_t \times \frac{(4\Pi d)^2}{G_t G_r \lambda^2} L_{margin} \times N_{figure} + \frac{P_{CT}}{R_b} + \frac{P_{CR}}{R_b} \quad (13)$$

Now, we apply similar derivation steps for communication operating over BPSK modulation.

The average BER is expressed as [18]

$$P_b = Q(\sqrt{2 \times SNR_i}) \quad (14)$$

Applying the chernoff bound (in the high SNR regime)

$$\overline{P_b} = E_H\left\{Q(\sqrt{2 \times SNR_i})\right\} \le \left(\frac{\overline{E_b}}{M_t N_o}\right)^{-M_t} \quad (15)$$

Rearranging Eq. 15, we get

$$\overline{E_b} \le \left(\frac{M_t N_o}{\overline{P_b}^{\frac{1}{M_t}}}\right) \quad (16)$$

We obtain the final mathematical relation for the energy utilized per bit for WSN communication under BPSK modulation scheme as

$$E_{bit}^{BPSK} = \frac{\xi}{\zeta}\frac{M_t N_o}{\overline{P_b}^{\frac{1}{M_t}}}\frac{(4\Pi d)^2}{G_t G_r \lambda^2} \times L_{margin} \times N_{figure} + \frac{P_{CT}}{R_b} + \frac{P_{CR}}{R_b} \quad (17)$$

3 Results and Discussions

Here, we present the results of the simulation performed for the scenario under consideration in context of (1) Variation of energy utilization with transmit diversity order for different ranges of cluster-BS distances, (2) Variation of energy utilization with cluster-BS distance for different data rates, (3) Optimization of constellation size. Table 1 enlists the values of the some of the parameters used in numerical computations.

Table 1 System parameters

Parameter	Value	Parameter	Value
P_{FLT}	2.5 mW	*Freq.*	2.5 GHz
$P_{DAC} = P_{ADC}$	15.5 mW	n	0.47
P_{SYN}	50.0 mW	N_{figure}	10 dB
$P_{MIXT} = P_{MIXR}$	30.3 mW	$G_t G_r$	5 dBi
P_{IFA}	3.0 mW	P_{LNA}	20.0 mW
P_{FLR}	2.5 mW	L_{margin}	40 dB
$\sigma^2 = N_0/2$	−174 dBm/Hz	d	20/50/80 m

3.1 Variation of Energy Utilization with Transmit Diversity Order for Different Ranges of Cluster-BS Distances

Figure 2a–c show the variation of energy utilization with transmit diversity order for different ranges of cluster-BS distances. The simulation are performed by maintaining a BER of 10^{-2} and and a data rate of 15 kbps for communication operating under BPSK and square constellation M-QAM modulation schemes. Our results highlight that for the WSN scenario under consideration, when the distance between the cluster and the BS is small ($\sim$20 m), transmit diversity order doesn't contribute in enhancing energy-efficiency, whereas, when the distances are medium ($\sim$50 m) and long ($\sim$80 m), the transmit diversity order with two antennae contributes to facilitate energy-efficient and reliable operations. With the increasing constellation order and also with increasing distance magnitude between the cluster and the BS, the energy utilization level increases.

3.2 Variation of Energy Utilization with Cluster-BS Distance for Different Data Rates

Figure 3 presents the variation of energy utilization with cluster-BS distance for different data rates and transmit diversity orders. The simulation are performed for BPSK and M-QAM modulation based communications operating under the impact of Rayleigh fading. With increase in data rate, better energy-efficient results are obtained. Simulations show an improvement in performance with increase in transmit diversity order from single antenna to dual antennae as presented in Fig. 3a, b. With increase in transmit diversity order beyond two antennae, the results

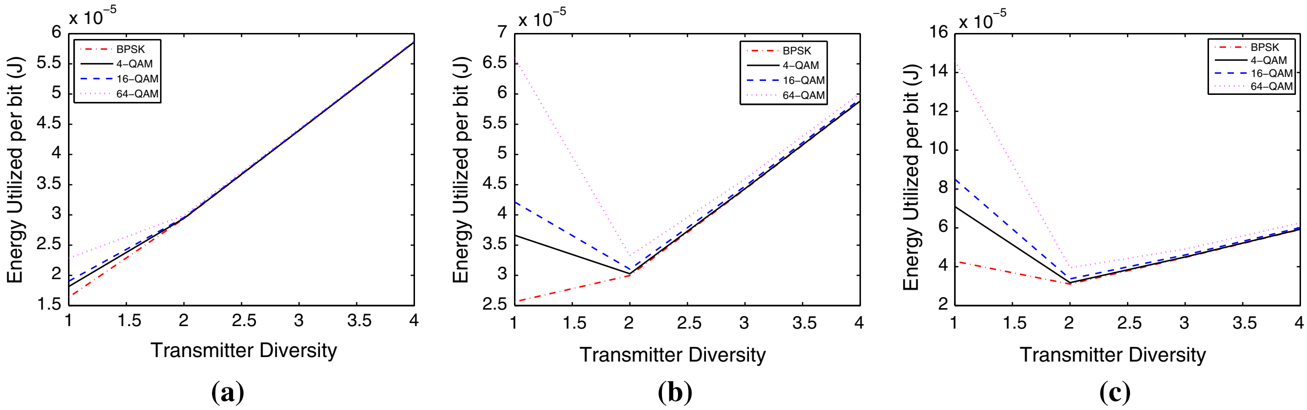

Fig. 2 Variation of energy utilization with transmit diversity orders for various modulation approaches for **a** small cluster-BS distance (~ 20 m), **b** medium cluster-BS distance (~ 50 m) and **c** long cluster-BS distance (~ 80 m)

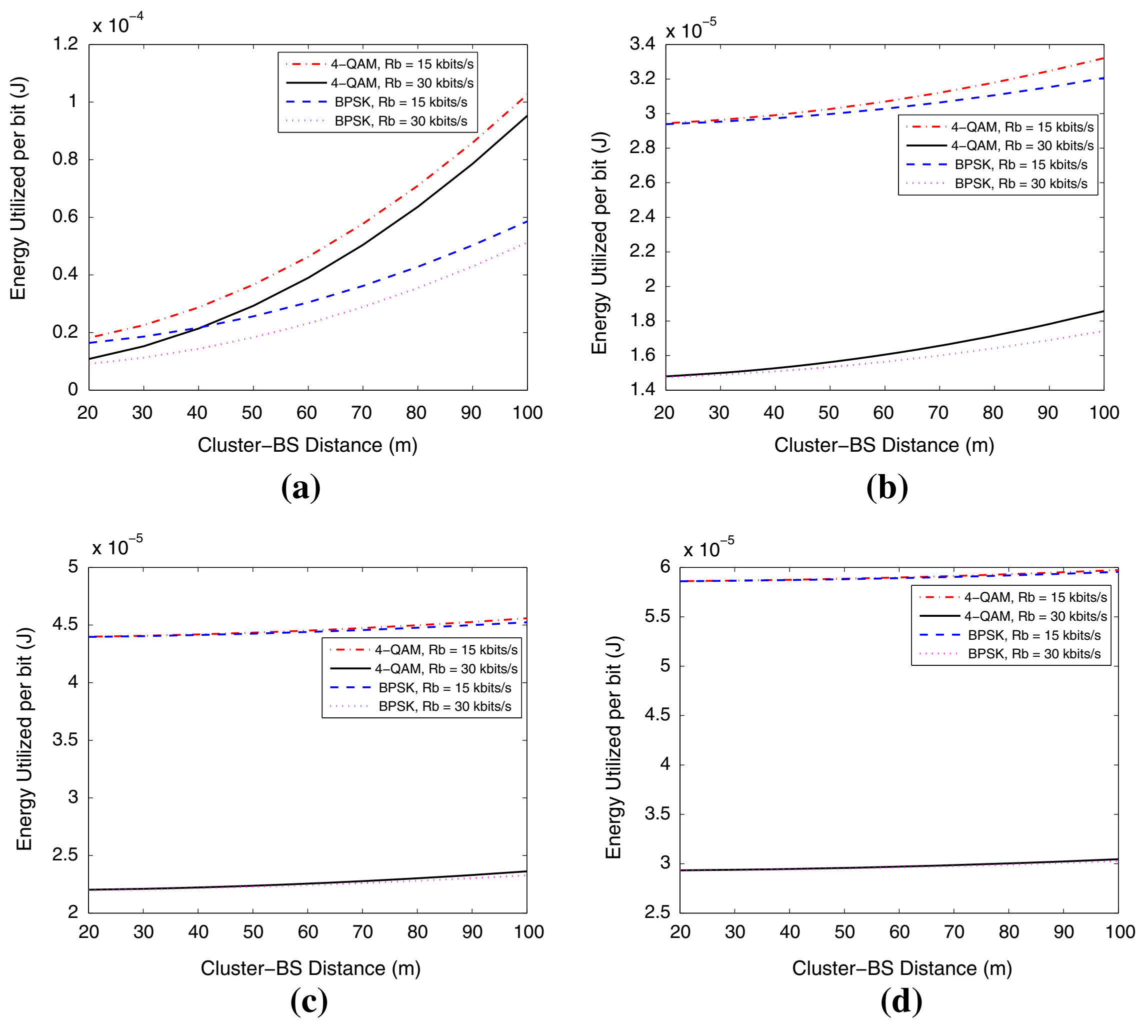

Fig. 3 Variation of energy utilization with cluster-BS distance for different data rates and transmit diversity orders **a** $M_t = 1$, **b** $M_t = 2$, **c** $M_t = 3$, **d** $M_t = 4$

obtained are not that promising from energy viewpoint as seen in Fig. 3c, d. We conclude that the transmit diversity order of two is more suitable from energy-efficiency viewpoint.

3.3 Optimizing Constellation Sizes

For the range of distances between the cluster and the BS, we evaluated the energy expressions and optimized the results to get optimal constellation and corresponding energy utilization levels. Simulation were performed with two transmit antennae and at a fixed data rate. Figure 4 presents the results of energy utilization for various modulation schemes along with varying range of distances between the cluster and the BS. It was found that the energy utilization increases with increase in the distance between the cluster and the BS keeping error rate to acceptable value and using two transmit antennae. Furthermore, results are found to be less energy-efficient for communication using higher order M-QAM constellation size, whereas BPSK based communications proved to be more promising from energy saving viewpoint for long cluster-BS distances. Results conclude that the higher constellation sizes modulations should be used for small communication distances, while with increasing cluster-BS distances, the preferred constellation order should be low.

Furthermore, Fig. 5 shows the optimal constellation order for communication based on the M-QAM modulations for varying range of distances between cluster and the BS. Table 2 enlists the cluster-BS distance-wise optimal modulation, constellation size and corresponding energy utilization levels. It can be easily seen that for the same acceptable error rates, with increase in distance between the cluster and the BS, the optimal modulation constellation order decreases to facilitate energy-efficient operations. Higher-order constellations can pack more bits in a given symbol, which in turn results in enhanced spectral efficiency.

We observe from simulation results that communication based on M-QAM modulation with higher constellation, takes place at a faster rate which results in reduction in transmit energy. However, when the constellation size is higher, the transmission leads to a more outage probability which results in more retransmissions attempts. On the contrary, a small constellation size requires less retransmissions attempts, but increases the transmit energy. Hence, the use of optimal modulation constellation order for energy-efficient communications may help to synchronize these tradeoffs.

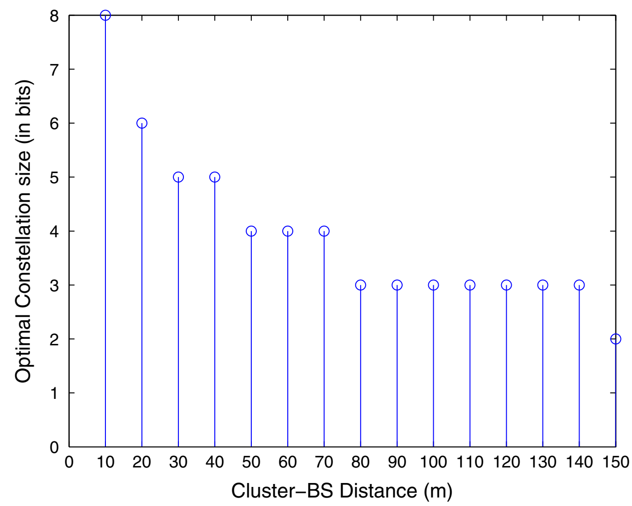

Fig. 5 Optimal constellation size for varying range of cluster-BS distances with two transmit antennae

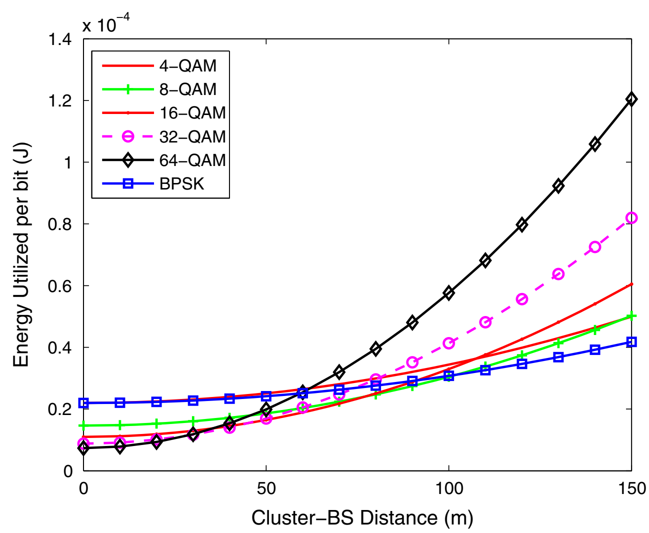

Fig. 4 Energy utilized per bit for varying cluster-BS distances at BER of 10^{-3} for varying modulation constellation sizes and with transmit diversity order 2

Table 2 Cluster-BS distance-wise optimal modulation, constellation size and corresponding energy utilization levels

Cluster-BS distance (m)	Optimal constellation size	Energy utilized per bit (J)	Proposed M-QAM modulation
10	8	$6.81E-06$	$256-MQAM$
20	6	$9.28E-06$	$64-MQAM$
30	5	$1.16E-05$	$32-MQAM$
40	5	$1.39E-05$	$32-MQAM$
50	4	$1.64E-05$	$16-MQAM$
60	4	$1.89E-05$	$16-MQAM$
70	4	$2.16E-05$	$16-MQAM$
80	3	$2.44E-05$	$8-MQAM$
90	3	$2.73E-05$	$8-MQAM$
100	3	$3.04E-05$	$8-MQAM$
110	3	$3.37E-05$	$8-MQAM$
120	3	$3.72E-05$	$8-MQAM$
130	3	$4.08E-05$	$8-MQAM$
140	3	$4.47E-05$	$8-MQAM$
150	2	$4.87E-05$	$4-MQAM$

4 Conclusions

In this work, we holistically explored the energy aspects of WSN scenario based on MISO approach constituting multiple cluster located at fixed distance from the base station. We used space-time block coding for the underlying communication operating with BPSK and M-QAM modulations under the effects of Rayleigh fading. We derived the mathematical relations for the energy utilizations for both the modulation schemes in terms relevant attributes like—order of transmit diversity, error rate, constellation size and data rate. We also recommended the cluster-BS distance-wise modulations and constellation sizes for a range of distances to support energy efficiency. Following are the some of the main conclusions of our study:

- Communication involving, medium and long cluster to BS distances, with the diversity order constituting two transmit antennae, results in better energy efficiency and enhances reliability, but, for smaller cluster-BS distances, the contribution is not significant for the case under consideration.
- At higher data rates for acceptable error rates and transmission diversity levels, the results are better energy-efficient.
- The M-QAM modulation with low order constellation order are more suitable for long cluster-BS distances. The optimal modulation constellation order decreases with increase in the distance between cluster and BS. Furthermore, our results demonstrate that for distance ranges of (in m) 10–19, 20–29, 30–49, 50–79, 80–149 and 150 the proposed modulation constellation orders 8, 6, 5, 4, 3 and 2 respectively and subsequently the recommended modulation approaches are 256 QAM, 64 QAM, 32 QAM, 16 QAM, 8 QAM and 4 QAM respectively.
- For long distances between the cluster and BS, the BPSK modulation based communications are found to be better-fit in comparison to M-QAM modulation.

We infer that while evaluating the WSN energy utilization to facilitate energy-efficient and reliable communications one needs to tailor optimal permutation and combination of various communication parameters like - distance wise modulation approach opted, transmission data rate, transmission diversity, acceptable error rates. These results may enable network designers to develop energy-efficient WSN communication architectures.

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