Energy Level Performance of Packet Delivery Schemes in Wireless Sensor Networks over Fading Channels

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Abstract

Energy level performance of three packet delivery schemes in a Wireless Sensor Networks (WSNs) over fading channels is evaluated. Effects of two short term fading such as Rayleigh and Rician on packet delivery schemes are evaluated. Three different information delivery mechanisms are considered using regenerative relays with or without error correction capability. In all the three schemes, message packet is sent on hop-by-hop basis. In scheme I, message is corrected for error at every hop while in the other two schemes; message is corrected at the destination. Energy consumption for successful delivery of a data packet for each mechanism is evaluated and compared under several conditions of node density, bit rate and transmit power. Energy efficiencies of different retransmission schemes are evaluated. Further an optimal packet length based on energy efficiency is derived in each transmission scheme. Effects of different level of severity of Rician fading on energy efficiency and energy consumption are also investigated. Impact of optimal packet size on total energy expenditure is analyzed.

Keywords- *Wireless Sensor Networks (WSNs); Rician Fading; Rayleigh Fading; Bit Error Rate (BER); ARQ; Energy Efficiency.*

1. Introduction

Recent advances in wireless communication technologies led to great interest in wireless sensor networks (WSNs). WSN consists of wireless interconnection of several sensor nodes which comprise of sensor devices with wireless communication facilities [1]. Most of the works on performance of WSNs assume idealized radio propagation models without considering impact of fading and shadowing effects at physical layer. However network performance may degrade due to presence of channel impairments such as shadowing and fading [2-3]. Energy conservation is one of the most important issues in WSN, where nodes are likely to rely on limited battery power. If the transmission power is not sufficiently high there may be single or multiple link failure(s). Further transmitting at high power reduces the battery life and introduces excessive amount of inter node interference. Hence there is an optimal transmit power so as to strike a balance between the two effects [4]. Previous research works in this field assume free-space radio link model and Additive White Gaussian Noise (AWGN) [4-6]. However wireless channels are often accurately modeled as Rayleigh fading or Rician fading. Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver. It is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. However if there is a dominant line of sight, Rician fading may be more applicable. Rician fading captures a wide range of fading model depending on the value of Rician factor. Rician factor, K defined as the power ratio of specular to diffused components [7]. Several approaches have been proposed in literature to prolong network lifetime. Panichpapiboon et al. evaluated Bit Error Rate (BER) performance and optimal power to preserve the network connectivity considering only path-loss and thermal noise [4]. In [5], Bettstetter derived the transmission range for which network is connected with high probability considering free-space radio link model. Tseng et al. studied the relationships between transmission range, service area and network connectivity in a free space model [6]. BER performance and optimal transmit power in WSN over Rayleigh fading channel has been derived in [8]. Narayanaswamy et al. proposed a protocol that extends battery life through providing low power routes in a medium with path loss exponent greater than 2 [9]. A minimum uniform transmission power of an ad hoc wireless network to maintain network connectivity considering only path loss has been proposed in [10].

In this paper energy level performance of three different information delivery mechanisms in a multihop WSN are considered in fading channel. In all the three schemes, message packet is sent on hop-by-hop basis. Further in scheme I message is corrected for error at every hop while in the other two schemes, message is corrected at the destination. However in case II, ACK/NACK propagates from destination to source via multiple hops through intermediate nodes while in case III it propagates directly from destination node to source node. The energy requirement for successful packet transmission also depends on routing and the Medium Access Control (MAC) protocol used [4, 11-12]. More precisely energy requirement for successful delivery of a packet is evaluated for all the three packet delivery schemes under several conditions of network such as node density, packet size etc. Impact of Rayleigh and Rician fading on energy consumption is indicated. We derive energy efficiency of the three retransmission mechanisms. Energy efficiency is an optimization metric that captures the energy and reliability constraints [15-16]. Impact of Rayleigh and Rician fading on energy efficiency is also investigated. Further an optimal packet length which corresponds to highest energy efficiency for a particular set of network conditions is evaluated for each packet delivery scheme. Impact of fading on optimal packet is also investigated. A scheme utilizing optimal size packet is analyzed and the impact of optimal size packet on energy consumption is indicated for different types of fading channel.

The rest of the paper is organized as follows: In Section II, we describe the system model that is used in the derivation of energy consumption and energy efficiency of three different information delivery mechanisms in fading channel. In Section III, we describe the simulation model developed. Section IV shows simulation results and discussions. Finally the paper is concluded in Section V.

2. System Model

We consider a simple scenario with square grid network topology as presented in [4]. Nodes are deployed in square grid fashion and sensor nodes remain stationary at their respective location. Distance between two nearest neighbor is d_{link}. It is assumed that 'N' number of nodes are distributed over a region of area A following a square grid topology. The node spatial density ρ_{sq} is defined as number of nodes per unit area i.e., $\rho_{sq} = N/A$. The minimum distance between two consecutive neighbors is given by

$$d_{link} = \frac{\sqrt{N}}{\sqrt{N}-1} \times \frac{1}{\sqrt{\rho_{sq}}} \tag{1}$$

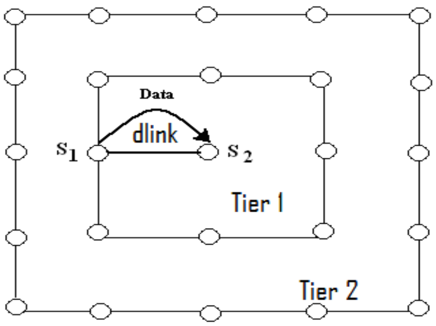

Fig. 1: Sensor Nodes in Square Grid Topology; a Link Interconnecting Node S_1 and S_2 in One Hop is Shown.

Here we assume a simple routing strategy such that a packet is relayed hop-by-hop, through a sequence of nearest neighboring nodes, until it reaches the destination [11]. Further we consider a simple reservation based MAC protocol, called reserve and go (RESGO) following [12].

The major perturbations in wireless transmission are large scale fading and small scale fading [2-3]. Large scale fading represents the average signal power attenuation or path loss due to motion over large areas. This phenomenon is affected by prominent terrain contours (hills, forests, billboards, clumps of buildings, etc.) between the transmitter and receiver. However small-scale fading exhibits rapid changes in signal amplitude and phase as a result of small changes (as small as a half-wavelength) in the spatial separation between a receiver and transmitter. If the multiple reflective paths are large in number and there is a dominant non fading signal component, the envelope of the received signal is statistically described by a Rician pdf given as [2]

$$p_z(z) = z/b^2 \exp\left[\frac{-\left(z^2+s^2\right)}{2b^2}\right] I_0\left(\frac{zs}{b^2}\right),\ z \geq 0 \tag{2}$$

where z is the envelope amplitude of the received signal, $2b^2$ is the average power in the non LOS multipath components, s^2 is the power in the LOS component and I_0 is the modified Bessel function of the first kind and zeroth order. In case of Rayleigh fading power in the LOS component (s^2) is equal to 0. In the present work we separately consider the two cases of multipath Rician fading and Rayleigh fading in addition to path loss and thermal noise.

Assuming that each destination is equally likely, the average number of hops on a route can be written as [4]

$$\bar{n}_{hop} \cong \sqrt{N}/2 \tag{3}$$

The received signal at the receiver is the sum of three components (i) the intended signal from the transmitter, (ii) interfering signals from other active nodes and (iii) thermal noise. Since the interfering signals come from other nodes, we assume that total interfering signal can be treated as an additive noise process independent of thermal noise process. The received signal, Y at the receiving node during each bit period can be expressed as [4]

$$Y = hS_{rcv} + \sum_{j=1}^{N-2} S_j + n_{thermal} \tag{4}$$

where h is the fading channel coefficient with respect to the receiving antenna, S_{rcv} is the desired signal in the receiving antenna considering only path loss, S_j is the interference from the other nodes and $n_{thermal}$ is the thermal noise signal. It is assumed that interference signal undergoes similar kind of fading as intended signal.

Assuming Binary Phase Shift Keying (BPSK) modulation, there can be two cases for the amplitude of the S_{rcv}

$$\begin{aligned} S_{rcv} &= \sqrt{\frac{P_{rcv}}{R_{bit}}} = \sqrt{E_{bit}} \text{ for a } +1 \text{ transmission} \\ &= -\sqrt{\frac{P_{rcv}}{R_{bit}}} = -\sqrt{E_{bit}} \text{ for a } -1 \text{ transmission} \end{aligned} \tag{5}$$

where P_{rcv} is the power received at the receiving end, R_{bit} is the bit rate and E_{bit} is the bit energy of the received signal considering only path loss [8]. P_{rcv} is given by frii's transmission formula [2]

$$P_{rcv} = \frac{P_t G_t G_r c^2}{(4\pi)^2 f_c^2 d_{link}^{\alpha}} \tag{6}$$

where P_t is the transmit power, G_t is the transmitting antenna gain, G_r is the receiving antenna gain, f_c is the carrier frequency, α is the path-loss exponent and c is the velocity of light. Here we considered omni directional (G_t=G_r=1) antennas at the transmitter and receiver. The carrier frequency is in the unlicensed ISM (2.4 GHz) band.

For each interfering node j, the amplitude of the interfering signal can be of three types with different probability [4, 8, 12]

$$\begin{aligned} S_j &= \sqrt{\frac{P_{\text{int}\,j}}{R_{bit}}} \text{ with probability } \frac{1}{2}P_{trans} \\ &= -\sqrt{\frac{P_{\text{int}\,j}}{R_{bit}}} \text{ with probability } \frac{1}{2}P_{trans} \\ &= 0 \text{ with probability } (1 - P_{trans}) \end{aligned} \tag{7}$$

where P_{trans} and P_{intj} are the transmission probability of interfering nodes and the interference power received from node j respectively. The probability that an interfering node will transmit and cause interference depends on the MAC protocol used. Considering the RESGO MAC protocol and assuming that each node transmits packets with length L_{pkt}, the interference probability is equal to the probability that an interfering node transmits during the vulnerable interval of duration L_{pkt}/R_{bit}, where R_{bit} is the bit rate. This probability can be written as [10]

$$p_{trans} = 1 - e^{-\frac{\lambda_t L_{packet}}{R_{bit}}} \tag{8}$$

The interference vector $\vec{S}_j$ is defined as: $\vec{S}_j = \{s_j\}_{j=1,2,\ldots,(N-2)} = \{s_1, s_2, \ldots, s_{N-2}\}$, where s_j (as given in eqn. (7)) is the amplitude of the signal of an interfering node j received at the receiver. Size of the interference vector $\vec{S}_j$ increases as the number of nodes increases in the network.

The thermal noise signal can be written as [2, 4]

$$n_{thermal} = \sqrt{FkT_0B} \tag{9}$$

where F is the noise figure, $k = 1.38 \times 10^{-23} J/K$ is the Boltzmann's constant, T_0 is the room temperature and B is the transmission bandwidth.

Next we derive the energy spent in successfully transmitting a data packet considering three different retransmission schemes between a pair of source and destination nodes. Fig. 2 shows three different packet delivery mechanisms.

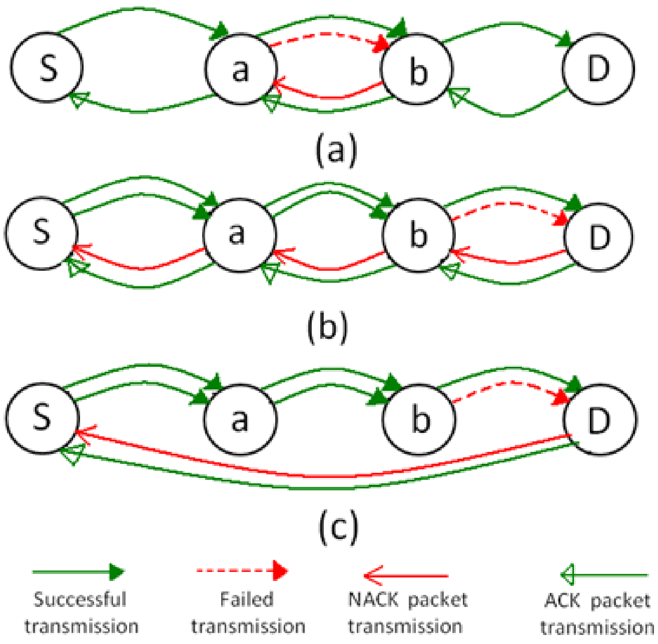

Fig. 2: Different Information Delivery Mechanisms

Scheme I is based on hop-by-hop retransmission, as shown in Fig.2a following [13], where at every hop the receiver checks the correctness of the packet and requests for a retransmission with a NACK packet to previous node until a correct packet is received. ACK packet is sent to the transmitter indicating a successful transmission. Thus every data packet is corrected in each hop.

Scheme II is based on multi-hop delivery with intermediate nodes, performing as digital repeaters [14] as shown in Fig.2b. The packet is checked only at destination for correctness; retransmissions are requested to source, with a NACK coming back from destination to source via intermediate nodes through multi-hop path.

Scheme III is based on multi-hop delivery with intermediate nodes, performing as digital repeaters [14] as shown in Fig.2c. The packet is checked at the destination for correctness. However retransmissions are requested to source, with a NACK coming back to source directly from destination (without multi-hop).

It is assumed that each packet consists of header, message and trailer as shown in Fig. 3. So, transmitted packet length can be expressed as [15],

$$L_{pkt} = l_h + l_m + l_t \tag{10}$$

Fig. 3. Simple Structure of a Packet

where l_h, l_m and l_t are the header length, message length and trailer length respectively. So, the energy required to transmit a single packet is

$$E_t = \frac{P_t L_{pkt}}{R_{bit}} \tag{11}$$

We assume that 75% of the transmit energy is required to receive a packet [16]. So, energy required to communicate, i.e. transmit and receive a single packet is given by [16]

$$E_{packet} = \frac{P_t (L_{pkt} + l_{ack})}{R_{bit}} \times 1.75 + E_d \tag{12}$$

where E_d is the decoding energy to decode a single packet and l_{ack} is the acknowledge frame length. Since Forward Error Correction (FEC) technique is not used here, decoding energy and trailer length both are assumed zero [15]. Thus the energy to communicate a single packet is:

$$E_{packet} = \frac{P_t (l_h + l_m + l_{ack})}{R_{bit}} \times 1.75 \tag{13}$$

The minimum energy required to communicate a packet is the energy required to transmit and receive the message bits (l_m) only. Thus minimum energy is given by the following expression:

$$E_{\min} = \frac{P_t l_m}{R_{bit}} \times 1.75 \tag{14}$$

With the above energy model, we evaluate the energy requirement for three different information delivery mechanisms as mentioned above to communicate a data packet from source to destination node until it is received successfully.

Scheme I:

Average probability of error at packet level at each hop is expressed as [16]

$$PER_{link} = 1 - (1 - BER_{link})^{L_{pkt}} \tag{15}$$

where, BER_{link} is the link BER. The effect of fading is incorporated in BER. The probability of 'n' retransmissions is the product of failure in the (n-1) transmissions and the probability of success at the n^{th} transmission:

$$P_I[n] = (1 - PER_{link})(PER_{link})^{n-1} \tag{16}$$

Average number of retransmissions for scheme I, assuming an infinite ARQ

$$R_I = \sum_{n=1}^{\infty} P_I[n].n = \frac{PER_{link}}{(1 - PER_{link})} \tag{17}$$

We consider only path loss in reverse link. Further we assume that ACK/NACK from receiving node is instantaneous and error free. Considering receiver sensitivity S_i, the required transmit power for reverse link is given by [2]

$$P_{tI} = \frac{S_i (4\pi f)^2 d_{link}^2}{G_t G_r c^2} \tag{18}$$

The energy consumed per packet at the end of $\bar{n}_{hop}$ number of hops is considered as the energy spent in forward transmission of information and reverse transmission for NACK/ACK as in [16]

$$E_I = \frac{1.75 \times (1 + R_I) \times \bar{n}_{hop}}{R_{bit}} \left[P_t \, (l_h + l_m) + P_{tI} \, l_{ack} \right] \tag{19}$$

Scheme II:

Average probability of error at packet level at the end of multihop route is given as

$$PER_{route} = 1 - (1 - PER_{link})^{\bar{n}_{hop}} \tag{20}$$

Average number of retransmissions for scheme II is given by

$$R_{II} = \sum_{n=1}^{\infty} P_{II}[n].n = \frac{PER_{route}}{(1 - PER_{route})} \tag{21}$$

where $P_{II}[n]$ is the probability of 'n' retransmissions considering Scheme II. The energy consumed per packet at the end of $\bar{n}_{hop}$ number of hops is given by

$$E_{II} = \frac{1.75 \times (1 + R_{II}) \times \bar{n}_{hop}}{R_{bit}} \left[P_t (l_h + l_m) + P_{tII} l_{ack} \right] \tag{22}$$

where P_{tII} is the transmit power of reverse link and same as P_{tI}.

Scheme III:

The energy consumed per packet at the end of $\bar{n}_{hop}$ number of hops using Scheme III is given by

$$E_{III} = \frac{1.75 \times (1 + R_{III}) \times \bar{n}_{hop}}{R_{bit}} \left[P_t (l_h + l_m) + P_{tIII} l_{ack} \right] \tag{23}$$

where average number of retransmissions, R_{III} is same as R_{II}. Reverse link transmit power P_{tIII} is given as

$$P_{tIII} = \frac{S_i (4\pi f)^2 d_{avg}^2}{G_t G_r c^2} \tag{24}$$

where d_{avg} is the average distance between source and destination. It is obvious that value P_{tIII} is quite large compared to P_{tI}.

Now the energy efficiency (η) of each scheme can be expressed as [16]:

$$\eta = \frac{E_{\min}}{\text{Energy Required for that Scheme}} \tag{25}$$

where E_{min} is defined as in eqn. (13).

3. Simulation Model

We now present our simulation model developed in MATLAB to evaluate the performance of three different information delivery mechanisms in fading channel:

- Digital data 1 and 0 with equal probability is generated at base band. Our transmitted signal is +1 or -1 corresponding to data 1 or 0.
- Fading channel coefficients are generated following Rayleigh or Rician distribution depending on the case of investigation.
- Active interfering nodes are identified using Binomial distributed random variables for node activity.
- Interference from such active interfering nodes are generated assuming interference undergoes similar kind of fading as signal.
- The desired message signal is affected by multipath fading, thermal noise and interference from other nodes. The signal received by the receiving antenna in destination node is generated following eqn. (4).
- The received signal Y as given in eqn. (4) is then detected considering the threshold level at 0. If the received signal is greater than the threshold level 0 then it is detected as 1. Otherwise it is detected as 0.
- Each received bit is then compared with the transmitted bits. If there is mismatch an error counter is incremented. Now dividing the error count by the total number of transmitted bits, link BERs is obtained.
- The energy efficiency for three information delivery mechanisms is evaluated following eqn. (25).
- The energy consumption of the three retransmission schemes is evaluated using eqn. (19), (22) and (23).

4. Results and Discussion

Table 1 shows the important network parameters used in the simulation study.

Table 1. Network Parameters Used in the Simulation

Parameter	Values
Path loss exponent (γ)	2
Number of nodes in the network (N)	289
Node spatial Density (ρ_{sq})	$10^{-9} – 10^{-1}$
Packet arrival rate at each node (λ_t)	0.5 pck/s
Career frequency (f_c)	2.4 GHz
Noise figure (F)	6 dB
Room Temperature (T_0)	300k
Transmission Power (P_t)	10 mW, 100 mW
Receiver Sensitivity (S_i)	-60 dBm
Rician Factor (K)	0, 3 and 10

Table 2 shows the symbols used in the literature

Table 2. List of Symbols

Symbol	Details
K	Rician factor
PER_{link}	Link PER
BER_{link}	Link BER
PER_{link}	Route PER
R_I, R_{II} and R_{III}	Average number of retransmissions for scheme I, II and III respectively
PtI, P_{tII} and P_{tIII}	Reverse link transmit power to send ACK/NACK packet for scheme I, II and III respectively
E_I, E_{II} and E_{III}	Energy consumption of scheme I, II and III respectively
η	Energy efficiency
d_{avg}	Average distance between source and destination
E_{min}	Minimum energy required to communicate a packet

Fig. 4 shows the link BER, denoted as BER_{link} for different values of node spatial density considering different bit rate, transmit power and fading. It is observed that BER_{link} performance improves with the increase in node spatial density. However it is seen that beyond a certain node density the BER_{link} does not change with further increase in node spatial density and a floor in BER_{link}, as denoted by BER_{floor} appears. The desired signal power as well as the inter-node interference increases with increase in node density. As a result we obtain the BER_{floor}. This is expected because, increasing node spatial density beyond a certain limit no longer improves the signal to noise ratio (SNR), as the interfering nodes also become close enough to the receiver. It is seen that link BER performance degrades in presence of fading [curve (v, vi)]. It is also seen that link BER degrades with increase in severity Rician fading [curve (ii, v)]. Further BER_{link} performance degrades as bit rate decreases [curve (ii, ii)]. This is due to increase in vulnerable interval with decrease in bit rate [4]. As a result, transmission probability of the interfering nodes increases. Further it is observed that BER floor appears earlier with increase in transmit power for a fixed bit rate [curve (ii, iv)].

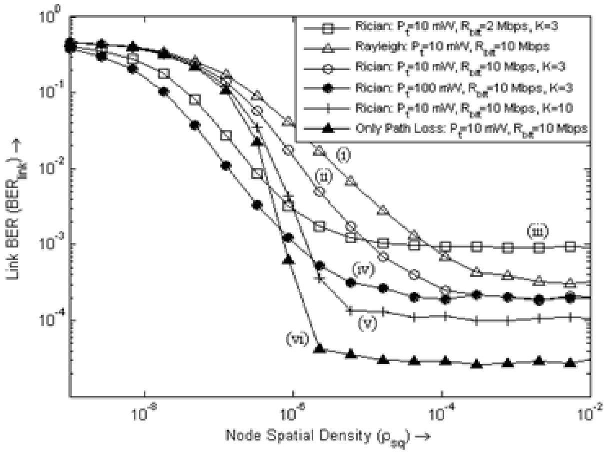

Fig. 4. Link BER as a Function of Node Spatial Density for Different Bit Rate and Transmit Power.

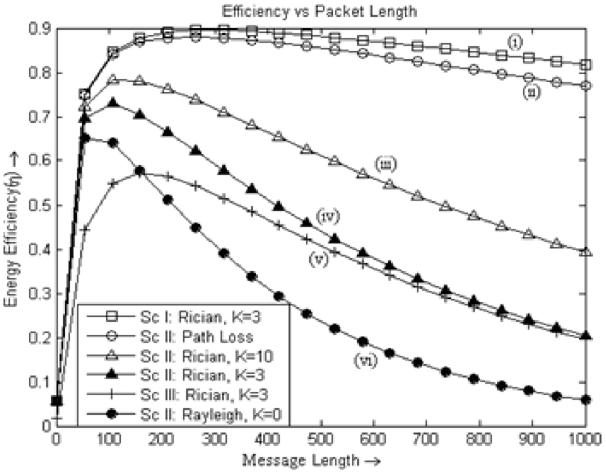

Fig. 5. Energy Efficiency as a Function of Packet Length for Different Retransmission Schemes; Pt=10 mW, ρsq= 2×10^{-3}.

Fig. 5 shows the energy efficiency as a function of packet length in bits for different information delivery mechanisms. It is seen that there exists a peak value of efficiency for a given packet size. The message length corresponding to maximum efficiency is the optimum packet size from energy efficiency perspective [15]. Thus there exists an optimal packet size for a particular network condition. It is seen that optimal packet length decreases in presence of fading. Further optimal packet length decreases with increase in severity of multipath Rician fading. For example, in case of scheme II at a node density of 2×10^{-3} and K=10, optimal packet size is 128 bit but it decreases to 96 bit when K factor decreases to 3 [curve (iii, iv)]. Energy efficiency shows a steep drop for message lengths smaller than the optimal length. This behavior can be attributed to the higher overhead and start-up energy consumption of smaller packets [15]. On the other hand, for message length larger than the optimal length, the drop in energy efficiency is much slower due to increase in average retransmission. With the increase of packet length the vulnerable interval increases and the probability of transmission of an interfering node becomes high. It is observed that energy efficiency degrades in fading channel [curve (ii, iii)]. Further energy efficiency degrades with increase in severity of Rician fading [curve (iii, iv)]. It is seen that Scheme I is the most energy efficient information delivery system [curve (i)]. This is because in case of Scheme I, additional energy is spent for a single hop for erroneous packets. But in case of Scheme II and Scheme III, additional energy is spent for the entire multi hop route for erroneous packets. Further among the three retransmission schemes, Scheme I has the highest optimal packet length [curve (i)].

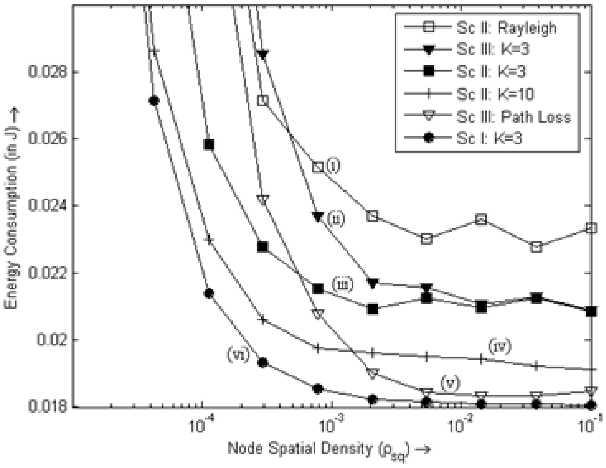

Fig. 6. Energy Consumption to Transfer a File (size of 106 bit) Using Fixed Packet of Size 100 Bit in Different Retransmission Schemes; Rbit=10 Mbps , Pt=10 mW.

Fig. 6 shows the energy required to successfully deliver a file of size 10^6 bit using packet of fixed size 100 bit in three different information delivery schemes. Energy consumption in multipath Rician fading is compared with that of path loss and Rayleigh fading case. It is seen that in presence of fading energy requirement increases [curve (ii, v)]. It is also observed that scheme I is the best retransmission scheme from energy consumption perspective [curve (ii, iii, vi)]. Further Scheme II and Scheme III consume nearly same amount of energy in high node density region [curve (ii, iii)]. However Scheme II performs better in low node spatial density region. For example, in Rician fading channel using fixed size packet of 100 bit, K=3 and $\rho_{\text{sq}} = 2.9\times10^{-4}$, required energy to transfer a file of size 10^6 bit is 22.7 mJ for Scheme II while it increases to 28.5 mJ for Scheme III. Further energy spent to successfully deliver a file increases with increase in severity of multipath Rician fading [curve (iii, iv)]. This is because with increase in severity of fading the SNR degrades. This results in more number of retransmissions for successful delivery of a packet. Thus the energy spent to successfully transfer data increases.

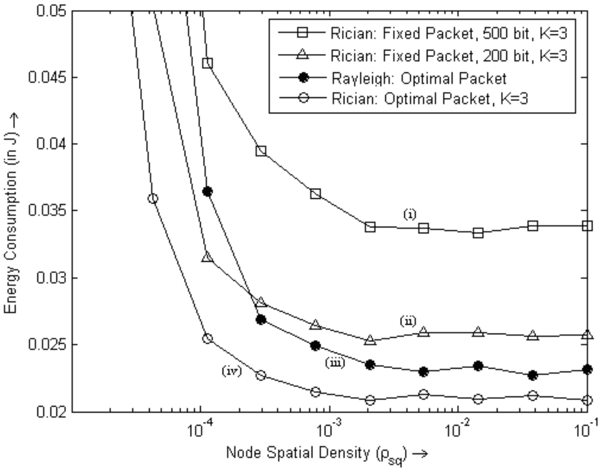

Fig. 7. Energy Consumption to Transfer a File (size of 106 bit) in Scheme II Using Fixed and Optimal Packet Size; Rbit=10 Mbps and Pt=10 mW, K=3.

Fig. 7 shows the energy required to successfully deliver a file of size 10^6 bit with different packet sizes using Scheme II. Energy consumption for optimal packet based transmission scheme is compared with fixed packet size based transmission. Two different fixed packet sizes of 200 bit and 500 bit are used. In case of optimal packet based transmission, optimal packet size corresponding to the node density and other network condition has been used. It is seen that energy requirement increases with increase in packet size [curve (i, ii)]. Further use of optimal size packets reduces energy requirement significantly [curve (ii, iv)]. For a node density of 1.1×10^{-4}, required energy to transfer the file is 25.4 mJ using optimal size packet, while it increases to 46 mJ for fixed packet of size 500 bit.

5. Conclusion

In this paper we evaluated the energy level performance of three information delivery schemes in fading channel. A simulation test bed has been developed to assess the performance of such network in terms of energy consumption, energy efficiency and bit error rate. Energy consumption using three different information delivery schemes are studied and compared. It is seen that Scheme I performs better than the other two schemes. Scheme II consumes less energy than Scheme III in low node density region. Energy consumption increases in presence of fading. It is also seen that Scheme I provides highest energy efficiency as compared to other schemes. An optimum packet length, which maximizes energy efficiency, is also derived. It is observed that scheme I yields highest size of optimum packet compared to other two schemes. It is also seen that optimal packet length decreases with increase in severity of fading. Decoding and retransmission for error correction at every node in multi-hop path seems to be more energy efficient compared to other mechanisms. The analysis is useful in designing energy efficient Wireless Sensor Networks. Further use of optimal size packets shows a significant reduction in energy consumption. Thus Scheme I and use of optimal size packets enhance network lifetime significantly.

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