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Published in IET Communications
Received on 12th January 2010
Revised on 26th May 2010
doi: 10.1049/iet-com.2010.0035

ISSN 1751-8628

Cooperative relaying protocol for energy-constrained *ad hoc* networks

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Abstract: Cooperative diversity is a powerful tool that can be used to improve the performance of wireless networks. The use of directional antennas has also shown to offer an effective way for efficient bandwidth utilisation. In this study, the authors investigate the effect of both the transmission power and the number of cooperative relays on the maximum achievable throughput in energy-constrained cooperative *ad hoc* networks with directional antennas. In particular, the authors develop an analytical model for the network throughput in terms of the number of cooperative relays and nodes' transmission power. Using our model, we determine the optimum number of relays for a given transmission power, and the optimum transmission power for a given number of relays. Furthermore, we propose a cooperative relaying protocol that utilises the above optimal values to maximise the achievable throughout in such energy-constrained networks. The obtained analytical results as well as the performance of the proposed protocol are validated by simulations over a Rayleigh fading channel.

1 Introduction

Throughout the literature, different diversity techniques have been proposed to mitigate the effect of channel fading [1]. Recently, multiple-input multiple-output (MIMO) technology has been introduced as a means for improving the reliability of the received signal and increasing the application data rate [2–4]. The notion of diversity has further been extended to include cooperative networks, where the concept of user cooperation is applied [5, 6]. In particular, in cooperative networks, a node at any given time can act as a sender, destination or relay depending on the network traffic and topology. Neighbouring stations to the transmitter and/or receiver can act as relay nodes to transfer the source data to the desired destination node through an independent relay channel, that is, independent from the source–destination channel [7]. In these cooperative networks, the function of the relay node can be as simple as to amplify and forward the received source data or to decode and regenerate an estimate of this data.

In order to avoid interference from other ongoing transmissions, the neighbouring nodes of any transmitter, relay or destination, must remain silent, that is, they are blocked, for the duration of transmission. In other words, as shown in Fig. 1, each of the source, relay and destination blocks a full circle with radius d_{max}, where d_{max} denotes the nodes' transmission range.

The diversity gain achieved in cooperative *ad hoc* networks is attained at the cost of losing some wireless resources (i.e. available bandwidth), because of the relaying phase. On the other hand, different from omni-directional based transmission, the use of directional antennas has shown to offer large bandwidth utilisation by allowing multiple transmissions within one radio range. To enhance the performance of cooperative networks, a new medium-access-control (MAC) protocol was proposed in [8]. The proposed protocol employs adaptive antennas at the relay stations to retransmit the received signal from the source to the destination using directional beams.

Most of the previous works on *ad hoc* networks have focused on enhancing the system performance at either the physical layer or the MAC layer. On the other hand, even with the advanced technologies that allow batteries to live longer, power is still a valuable resource that should be spent wisely. Therefore optimising the performance of such energy-constrained networks requires further interaction between different network layers. While power resource management for cooperative relay networks has been widely investigated [9–16], the majority of these works that emphasise power on allocation and rate distribution, rely on a certain topology and analyse a small part of a network.

In this paper, we consider *ad hoc* networks where the total energy of each node is limited to E_{tot}. For such energy-constrained networks, we derive an analytical model for the network throughput in terms of the number of cooperative relays and nodes' transmission power. From our model, we determine the optimum number of relays that yield to maximum network throughput under a given transmission power. Similarly, we evaluate the optimum transmission power for a fixed number of relays. Furthermore, we propose a cooperative relaying protocol, that utilises the above optimal values, to maximise the achievable throughout in such energy-constrained networks. The obtained analytical results as well as the performance of the

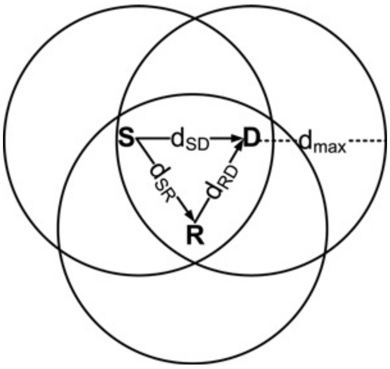

Fig. 1 *Blocked area for one transmission in CSMA/CA protocol*

proposed protocol are validated by simulations for scenarios where selective-repeat automatic repeat request (ARQ) protocol is employed between the source, relays and destination over a Rayleigh fading channel.

The rest of this paper is organised as follows. The proposed cooperative relaying protocol is described in the next section. The analytical model for the network throughput is developed in Section 3 and the optimum network performance is obtained in Section 4. Finally, the conclusions are given in Section 5.

2 Proposed protocol

In the considered cooperative system, each time frame is divided into two slots. In the first slot, the source broadcasts its data to both the destination and selected relays. In the second slot, the relays decode and forward the received packets to the destination. We assume that all nodes are equipped with directional antennas with beamwidth θ. To prevent collisions between ongoing transmissions and newly initiated ones, a narrow band channel is dedicated for channel reservation protocol and the remaining spectrum is dedicated to data transmission. The channel reservation protocol employs two types of network allocation vectors (NAVs). The first NAV counts the period during which a node cannot use the channel to transmit packets in any direction (similar to the function of the NAV table in IEEE 802.11). The second one is a directional NAV (DNAV) that keeps track of the blocked directions and the corresponding durations towards which a node must not initiate a transmission in theses specified directions.

The channel reservation protocol works as follows. A request-to-send (RTS) is broadcasted by the source, including the file size and its available energy. Using orthogonal channels, all the potential relays (i.e. nodes within the source's directional coverage) replay with a relay acknowledgement packet (RACK) that includes their available energy. Both the source and the potential relays use their omni-directional antennas to send the RTS and RACK packets. Based on the estimated bit-error-rate (BER), the size of the file to be transmitted, the available number of relays, and the available energy at the source and relays, the destination checks the possibility of the current transmission. Using the optimum value for the signal-to-noise ratio, $E_b/N_{0_{\rm opt}}$, (determined in Section 4), the destination determines the number of cooperative relays and E_b/N_0 to be used. A clear-to-send (CTS) is then broadcasted by the destination using its omni-directional antenna. The sent CTS packet contains the E_b/N_0 to be used and the node IDs of the selected relays.

The RTS and RACK packets inform all nodes, within their transmission range, with the source, relays and destination coordinates. Consequently, all the neighbouring nodes would be able to determine the direction of transmission between the source and destination, as well as between the selected relays and destination. The nodes laying within the directional beam of the source or relay will be blocked and set their NAV to the period of the required transmission. Other nodes within their transmission range can act as a relay or source with their directional antennas facing other directions, but are blocked from being destinations. These nodes will set their DNAV for the period of the required transmission. Note that the destination node blocks a full circle with radius of $d_{\max}$ and all nodes within this circle set their NAV to the period of the required transmission. A timing diagram for the above protocol is shown in Fig. 2.

Since the destination employs an omni-directional antenna, and hence it always blocks a full circle of radius $d_{\max}$, in the ideal case, the areas blocked by both the source and relay transmissions should coincide within this circle as shown in Fig. 3. Assume that the fixed beamwidth of the deployed directional antenna is θ. In [17], it was shown that restricting the maximum beamwidth to less than or equal to

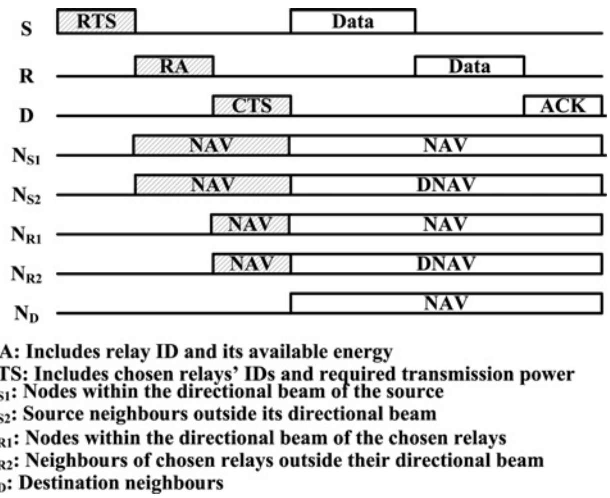

Fig. 2 *Timing diagram of the proposed protocol*

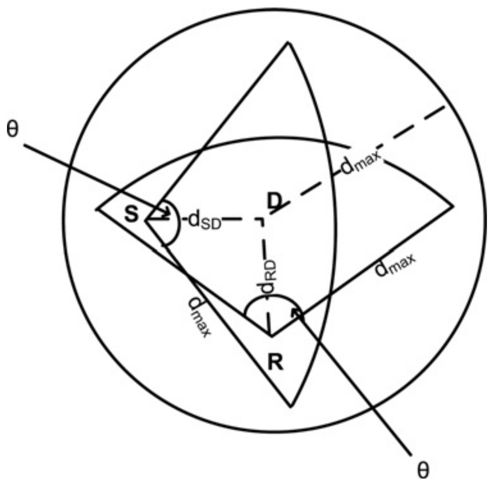

Fig. 3 *Blocked area for one transmission when using directional antennas*

120° optimises the blocking area by ensuring that it is reduced to one circle with radius d_{max} around the destination.

3 Network model

In this section, we derive a mathematical model for the underlaying network. This model will then enable us to analyse the performance of the proposed cooperative protocol and find the optimum system parameters. Throughout our analysis, we assume that all M nodes are uniformly distributed over a square area (z^2) and they always have data files available for transmission. The channel is modelled as Rayleigh fading and all packets are modulated using binary-phase shift-keying (BPSK) modulation. Furthermore, we assume that all relays are chosen so that they are able to correctly recover the data packets transmitted in the first half of the time slot. Each node is equipped with a battery of limited energy E_{tot}, corresponding to P_{tot} power units, which is periodically replaced at the end of each time interval T. In other words, residual energy left at any node after T is wasted. In order to ensure QoS, the nodes employ a selective-repeat ARQ protocol.

Let $A_c = \pi d_{max}^2$ denote the area of the circle blocked because of any ongoing single transmission. We start our analysis by studying the performance of nodes within such a circle. Let N_c represent the number of nodes that are involved in one transmission. Thus

$$N_c \simeq \frac{A_c}{z^2} M \qquad (1)$$

If each file transmission is supported by R relays, then R must satisfy

$$R \leq \left\lfloor N_c \frac{\theta}{360} \right\rfloor - 2 \qquad (2)$$

The power consumption of the nodes is assumed to be dominated by the transmission power. In other words, we ignore the power consumed by the nodes during the receiving process, and hence all the P_{tot} power units will be consumed by the nodes when they are acting as either transmitters or relays.

If the required transmission power, to achieve a prespecified BER, is divided equally between the source and relay nodes, then each source or relay node consumes P_B power units (to transmit one packet) where P_B is given by

$$P_B = \frac{10^{0.1(E_b/N_0)}}{L} E(\alpha_k^2) \qquad (3)$$

where E_b/N_0 denotes the energy per bit to noise ratio, $L = R + 1$ is the diversity order at the destination, and α_k is the channel fading amplitude assumed to have $E(\alpha_k^2) = 1$.

Let

$$\psi = \sqrt{\frac{P_B}{1 + P_B}} \qquad (4)$$

If we assume that the data packets are recovered correctly by the relay nodes, then the BER at the destination is given by [1]

$$\begin{aligned} \mathrm{BER} &= \left[\frac{1}{2}(1-\psi)\right]^L \sum_{k=0}^{L-1} \frac{(L-1+k)!}{k!(L-1)!} \left[\frac{1}{2}(1+\psi)\right]^k \\ &= \left[\frac{1}{2}(1-\psi)\right]^L \sum_{k=0}^{L-1} \frac{\prod_{i=0}^{i=k}(L-1+i)(L-1)!}{\prod_{i=0}^{i=k-1}(L-1-i)(L-1-k)!k!} \\ &\quad \times \left[\frac{1}{2}(1+\psi)\right]^k \\ &\simeq \left[\frac{1}{2}(1-\psi)\right]^L \sum_{k=0}^{L-1} \frac{L^k}{L^{k-1}} \frac{(L-1)!}{k!(L-1-k)!} \left[\frac{1}{2}(1+\psi)\right]^k \\ &\simeq L\left[\frac{1}{2}(1-\psi)\right]^L \sum_{k=0}^{L-1} \frac{(L-1)!}{k!(L-1-k)!} \left[\frac{1}{2}(1+\psi)\right]^k \\ &\simeq L\left[\frac{1}{2}(1-\psi)\right]^L \sum_{k=0}^{L-1} \binom{L-1}{k} \left[\frac{1}{2}(1+\psi)\right]^k \\ &\simeq L\left[\frac{1}{2}(1-\psi)\right]^L \left[1 + \frac{1}{2}(1+\psi)\right]^{L-1} \end{aligned} \qquad (5)$$

The quality of the above approximation is depicted from Fig. 4. At high SNR, the BER in (5) can be approximated as [1]

$$\mathrm{BER} \simeq \binom{2L-1}{L} \left(\frac{1}{E_b/N_0}\right)^L$$

where the achieved diversity order is $L = R + 1$.

During data transmission, nodes employ selective repeat ARQ protocol in order to ensure QoS. The expected number of time slots required to transmit a data file is then given by [18]

$$T_f = \frac{B_f}{(1 - \mathrm{BER})^b} \qquad (6)$$

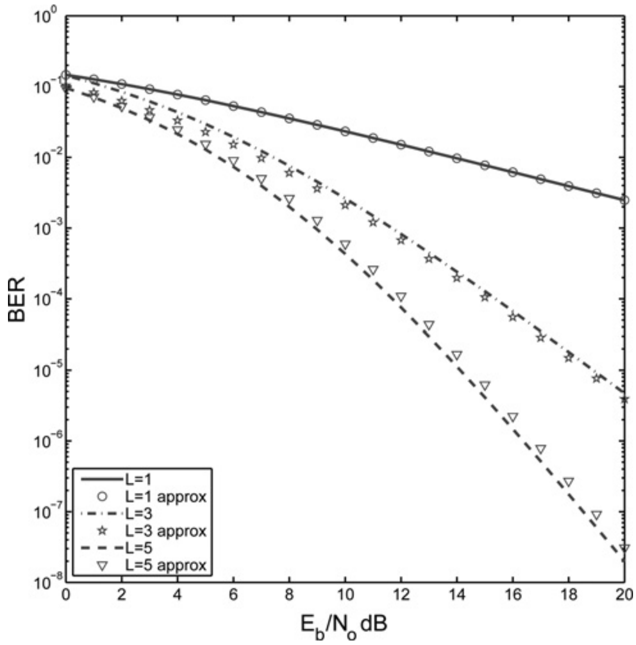

Fig. 4 *BER approximation*

doi: 10.1049/iet-com.2010.0035

where BER is given by (5), B_f and b denote the number of packets per file and the number of bits per packet, respectively. Thus the maximum number of data files that can be transmitted in T interval is, approximately, bounded by

$$N_{f_{max}} \simeq \frac{T}{T_f} \quad (7)$$

Since the beamwidth of the source covers $\theta/360$ of the circle around the destination, then the number of active nodes (i.e. nodes that still have some residual energy) during the jth file transmission is given by

$$N_a(j) \simeq \left\lfloor \frac{N_c P_{tot} - (j-1) L T_f P_B}{P_{tot}} \right\rfloor \quad (8)$$

Let $p_{tr}(j)$ denote the probability that the jth file transmission is carried over, that is, the probability that a source, destination, and R relays are available within the beamwidth of the source to support this transmission. Thus

$$p_{tr}(j) = \begin{cases} 1, & \frac{\theta}{360} N_a(j) \geq L+1 \\ 0, & \text{otherwise} \end{cases} \quad (9)$$

where $(\theta/360)N_a(j) \geq L+1$ implies that

$$\frac{N_c P_{tot} - L(j-1)T_f P_B}{P_{tot}} \geq \frac{360}{\theta}(L+1) \Rightarrow$$
$$N_c - \frac{L(j-1)T_f P_B}{P_{tot}} \geq \frac{360}{\theta}(L+1) \Rightarrow$$
$$\frac{L(j-1)T_f P_B}{P_{tot}} \leq N_c - \frac{360}{\theta}(L+1) \Rightarrow$$
$$j \leq \left(N_c - \frac{360}{\theta}(L+1)\right)\frac{P_{tot}}{L T_f P_B} + 1$$

Let $\Delta = (N_c - (360/\theta)(L+1))(P_{tot}/LT_f P_B) + 1$, then the average number of possible file transmissions is given by

$$N_f = \min\left(\sum_{j=1}^{\Delta}(p_{tr}(j) = 1), N_{f_{max}}\right) = \min\left(\frac{P_{tot}}{L T_f P_B}\left(N_c - \frac{360}{\theta}(L+1)\right) + 1, N_{f_{max}}\right) \quad (10)$$

Using (10), the average throughput of the nodes within a circle of radius d_{max}, in bits per time slot, that can be achieved over T time slots is given by

$$TH_c = \frac{F N_f}{T} \quad (11)$$

where $F = bB_f$ represents the average number of data bits per file.

Since all concurrent file transmissions in the network must occur within non overlapping circles, the overall system throughput can be calculated as

$$TH = TH_c \frac{M}{N_c} \quad (12)$$

Finally, by substituting (6) and (10) into (12), the network throughput can be approximated by

$$TH \simeq \min\left\{\left(1 - \frac{360}{\theta}\frac{L+1}{N_c}\right)\frac{MbP_{tot}(1-BER)^b}{TLP_B}, \frac{Mb(1-BER)^b}{N_c}\right\} \quad (13)$$

4 Optimal performance

In this section, we investigate the effect of the number of relays and transmitted power (expressed in terms of E_b/N_0) on the system throughput. In particular, we determine the optimum transmission power for a given number of relays and the optimum number of relays for a given transmission power.

From (13), the optimum transmission power E_b/N_{0opt} for a given number of relays, R, is obtained by solving for E_b/N_0 for which

$$\left(1 - \frac{360}{\theta}\frac{L+1}{N_c}\right)\frac{MbP_{tot}(1-BER)^b}{TLP_B} = \frac{Mb(1-BER)^b}{N_c}$$

to obtain

$$E_b/N_{0opt} = 10\log\left(\frac{P_{tot}}{T}\left(N_c - \frac{360}{\theta}(R+2)\right)\right) \quad (14)$$

Similarly, the optimum number of relays R_{opt} for a given transmission power is given by

$$R_{opt} = \left\lceil \frac{\theta}{360}\left(N_c - \frac{10^{0.1E_b/N_0}T}{P_{tot}}\right) - 2 \right\rceil \quad (15)$$

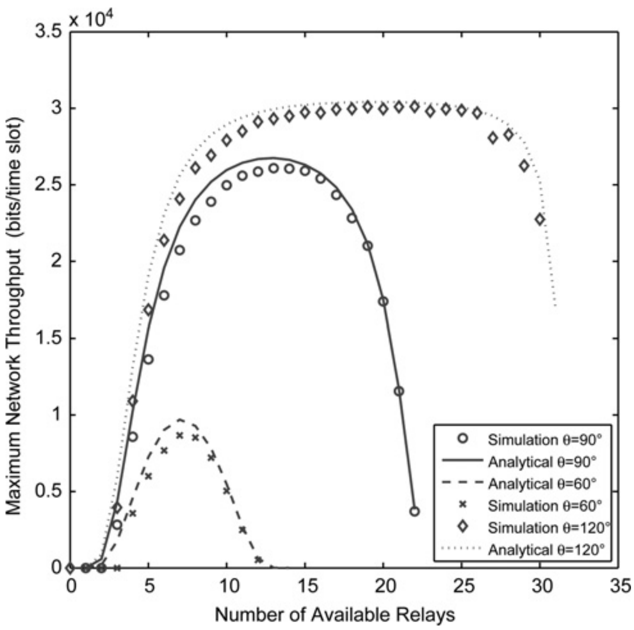

Fig. 5 *Optimum throughput for different number of relays*

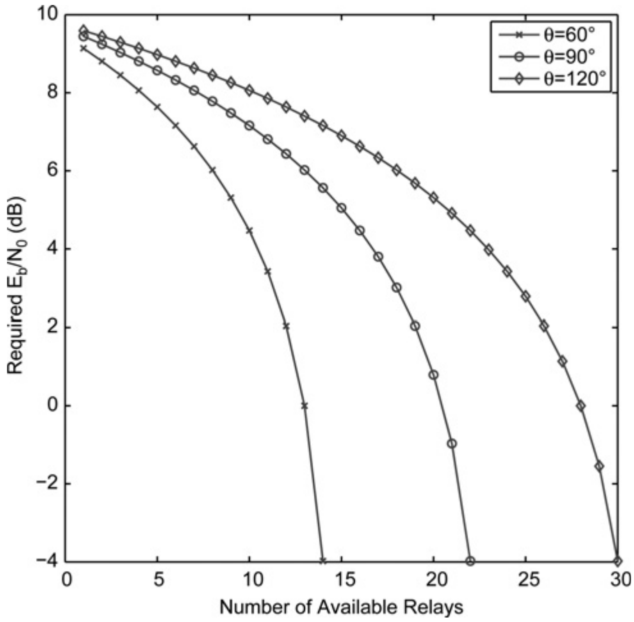

Fig. 6 *Optimal E_b/N_0 for different number of relays*

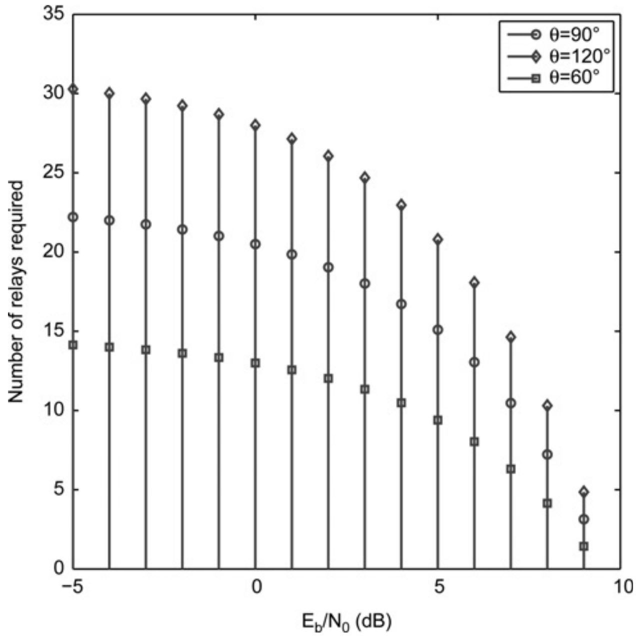

Fig. 8 *Optimal number of relays for different E_b/N_0*

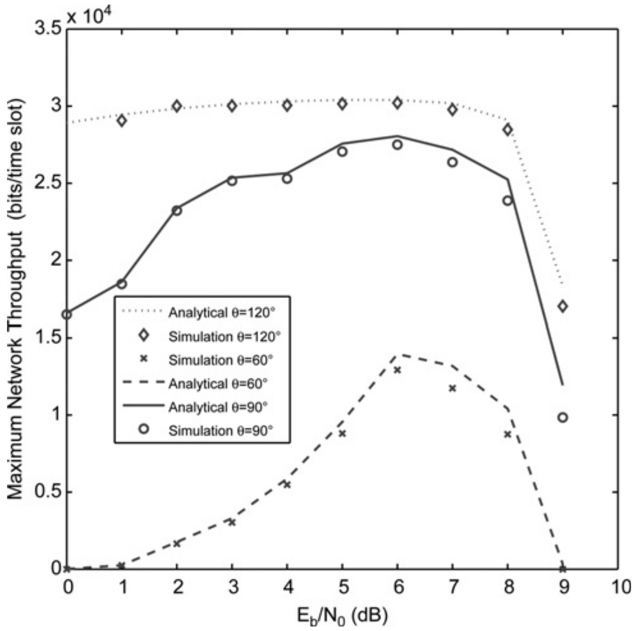

Fig. 7 *Maximum throughput for different E_b/N_0*

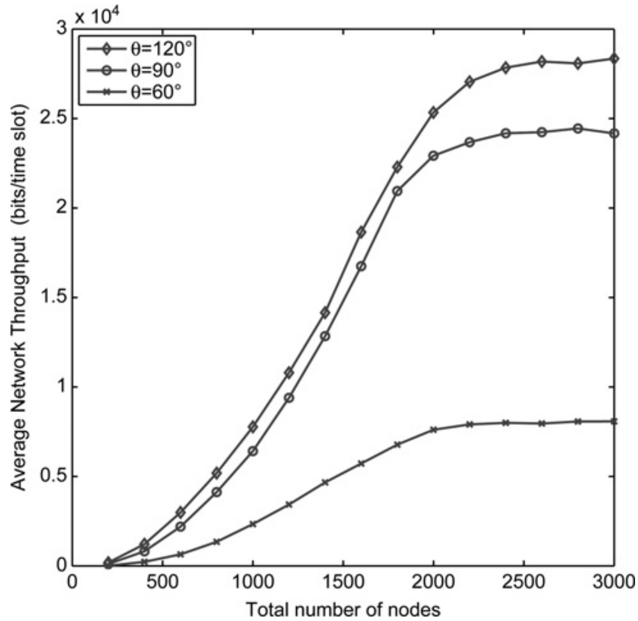

Fig. 9 *Average throughput for different node density*

and the optimum throughput is given by

$$\mathrm{TH_{opt}} = \max_{L, E_b/N_0} \min\left\{\left(1 - \frac{360}{\theta}\frac{L+1}{N_c}\right)\frac{MbP_{\mathrm{tot}}(1-\mathrm{BER})^{\mathrm{b}}}{TLP_{\mathrm{B}}}, \frac{Mb(1-\mathrm{BER})^{\mathrm{b}}}{N_c}\right\} \quad (16)$$

The above model was applied to a network where $M = 3100$ nodes are distributed over a square area of $z^2 = 100\,\mathrm{km}^2$. Each node has a transmission range of $d_{\max} = 1\,\mathrm{km}$ and maintains a total power of $P_{\mathrm{tot}} = 100$ units over time interval $T = 1000$. The nodes are assumed to be fully loaded with FTP traffic where the file length distribution is modelled as a truncated lognormal distribution with file size between $a = 0.5$ K bytes and $c = 500$ K bytes which is obtained from the lognormal distribution

$$f(x) = \frac{1}{\sqrt{2\Pi}\sigma x}\exp\frac{-(\ln x - \mu)^2}{2\sigma^2}, \quad x \geq 0$$

with $\sigma = 2.0899$ and $\mu = 0.9385$ [19]. The transmitted files are divided into data packets with $b = 1000$ bits per packet.

Fig. 5 shows how the maximum network throughput varies with the number of utilised relay nodes. As depicted in this figure, when the number of relays is small, each additional relay results in a relatively large improvement in the network performance. However, as the number of used

doi: 10.1049/iet-com.2010.0035

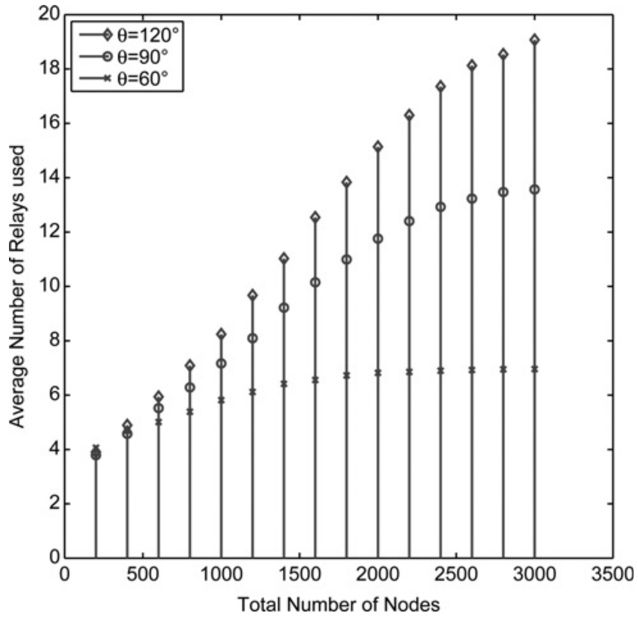

Fig. 10 *Average number of relays used per transmission for different node density*

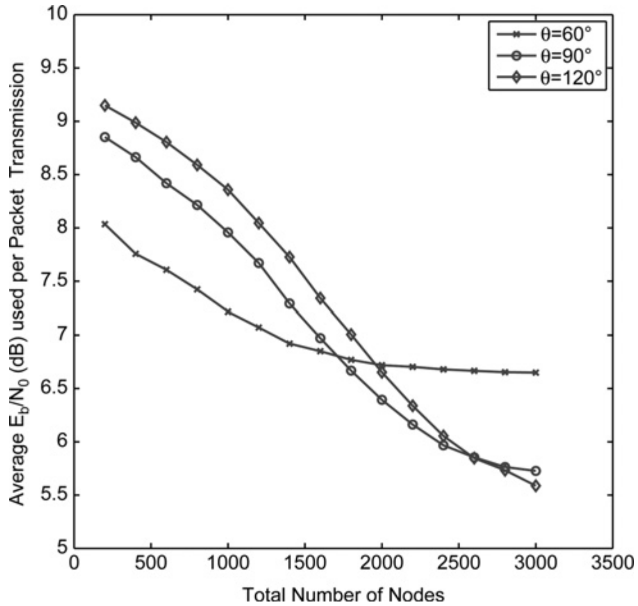

Fig. 11 *Average E_b/N_0 used transmission for different node density*

relays gets larger, increasing the number of relays above certain threshold decreases the network throughput since more nodes exhaust their battery power in relying. Hence, the number of active nodes with enough power for transmission gets lower which degrades the overall network throughput. Fig. 6 shows how the optimal transmission power, E_b/N_{0opt}, varies with the number of relays.

Fig. 7 shows how the maximum achievable network throughout varies with E_b/N_0. For small values of E_b/N_0, increasing the transmission power reduces the BER and, consequently, improves the network throughput. On the other hand, as depicted from the figure, increasing the transmission power above some threshold results in a severe degradation in the achievable throughput since more nodes exhaust their battery power before the end of their battery replacement interval. Fig. 8 shows how the optimal number of relays, R_{opt}, varies with E_b/N_0.

The result of our simulations that examines the variation of the achievable throughput of our proposed protocol with the node density is shown in Fig. 9. Following the proposed protocol, if the number of available relays is below the threshold that results in a degradation of the network throughput, then all these relays are utilised and the transmission energy is set to E_b/N_{0opt} corresponding to this number of relays (for the above specified network parameters, this corresponds to $R \le 20$, 14, 7 for $\theta = 120^\circ$, 90° and 60°, respectively, see Fig. 5). On the other hand, when the number of available relays exceeds this threshold, then R and E_b/N_0 are set to the value that maximises the expression in (16).

Figs. 10 and 11 show the corresponding average number of relays and average transmission power, respectively. The saturation of the average transmission power for $\theta = 60$ for large node densities can be explained by noting that, in order to optimise the overall network throughput, the number of utilised relays is limited to 7 (see Fig. 5). Hence, the network performance in this case is limited by the battery life irrespective of the node density.

5 Conclusion

We derived an analytical model for the throughput of energy-constrained cooperative *ad hoc* networks in terms of several important network parameters such as the battery replacement interval, total battery energy, node density, number of cooperative relays and the nodes' average transmission power. Using this model, we determined the optimum number of relays for a given transmission power, and the optimum transmission power for a fixed number of relays. Consequently, these optimum parameters were utilised to develop a cooperative relaying protocol that maximises the achievable throughout in such energy-constrained networks. Our results also show that increasing the number of relays, transmission power, or the node density do not always improve the overall network throughput which is bounded by the limited battery life of the nodes.

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