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Improved channel access protocol for cooperative *ad hoc* networks

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Abstract: Efficient utilisation of bandwidth and high data rates have a great impact on the performance of *ad hoc* wireless networks. The use of cooperative diversity, where neighbouring stations may act as relay nodes to transfer the source data to the desired destination node through an independent relay channel, has shown to provide diversity gain and consequently improve the achievable bit rate. However, this is usually attained at the expense of loosing some wireless resources such as bandwidth. On the other hand, the use of directional antennas has shown to offer an effective way for efficient bandwidth utilisation. Here, the authors propose a new channel access protocol for transmission over cooperative *ad hoc* networks. The proposed protocol, which aims at minimising the number of blocked nodes and consequently improving the system throughput, employs directional antennas at both the source and relay stations. The network performance under the proposed settings is modelled using continuous Markov chains. The steady-state transmission blocking probability and the average network throughput are obtained by analysing the derived Markov model. The analytical results, which are validated through simulations, show the improvement in performance compared to the carrier sense multiple access with collision avoidance protocol that employs omnidirectional antennas.

1 Introduction

The past few years have witnessed a quickly rising interest in radio access technologies for providing mobile as well as fixed services for voice, video and data. As part of this massive interest, *ad hoc* networks have emerged as an alternative to mobile cellular networks. Mobile *ad hoc* networks are distributed and infrastructure-less networks where mobile stations can communicate with each other without the help of any centralised control or access point which makes them robust to failures, easier to deploy and more flexible to reconfigure.

In mobile *ad hoc* networks, channel fading is considered to be a seriously damaging phenomenon that can degrade the overall network performance. Throughout the literature, diversity techniques have been proposed to mitigate the effect of channel fading [1]. Recently, multiple-input multiple-output technology has been introduced to improve the reliability of the received signal and support high data rates [2–4]. The notion of diversity is further expanded to include cooperative networks, where the concept of user cooperation diversity is applied [5, 6]. 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]. 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.

Carrier sense multiple access with collision avoidance (CSMA/CA) is one of the most commonly used channel access techniques in *ad hoc* networks. When omnidirectional antennas are used with CSMA/CA, each sender, receiver and relay blocks the neighbouring stations within its transmission range from possible transmissions. This criterion results in one of the main problems associated with cooperative networks, namely increased transmission blocking probability. In [8], an analytical model for evaluating the transmission blocking probability for *ad hoc* networks as a function of total number of nodes was developed. In [9, 10], this work was extended to cooperative *ad hoc* networks.

The diversity gain achieved in cooperative *ad hoc* networks is attained at the extra cost of loosing some wireless resources, such as available bandwidth, for the relaying phase since the relay nodes use these resources to relay the signal from the source to the destination node. On the other hand, the use of directional antennas has shown to offer an effective way for efficient bandwidth utilisation.

To enhance the performance of cooperative networks, we propose a new channel access protocol for transmission over cooperative *ad hoc* networks. The proposed protocol, which aims at minimising the number of blocked nodes, employs directional antennas at both the source and relay stations. The network performance under the proposed setting is modelled using continues Markov chains. The steady-state transmission blocking probability and the average network throughput are obtained by analysing the derived Markov model. The analytical results, which are validated through simulations, confirm the improvement in performance compared to the CSMA/CA protocol that employs omnidirectional antennas.

The rest of the paper is organised as follows. In the following section, we describe the proposed protocol and determine the optimum value for the beamwidth of the directional antennas of the source and relay nodes. The expected value of the average blocked area associated with a given number of transmissions is determined in Section 3.1 and a Markov chain model for the network performance under the proposed setting is developed in Section 3.2. The simulation results that validate the proposed model are presented in Section 4.

2 Proposed protocol

In cooperative systems, each time frame is divided into two slots. The source transmits the packet to both the destination and the chosen relay in the first slot. In the second slot, the relay amplifies and forwards the received packet to destination. In order to avoid interference from other ongoing transmissions, when using CSMA/CA, the neighbouring nodes of any transmitter, relay or destination must remain silent, that is, they are blocked during the duration of the transmission. All the neighbouring nodes of the source, relay and destination set their network allocation vector (NAV) to the period during which a node cannot use the channel to transmit packets [11]. In other words, as shown in Fig. 1*a*, each of the source, relay and destination blocks a full circle with radius $d_{\max}$, where $d_{\max}$ denotes the maximum transmission range, which we assume to be the same for all nodes.

In our protocol, we assume that all nodes are equipped with directional antennas. To evade collisions between ongoing transmissions and newly initiated ones, a narrow band channel is dedicated for the channel reservation protocol and the remaining spectrum is dedicated for the data transmission. The channel reservation protocol employs two types of 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 relay within the area covered by the source directional antenna is

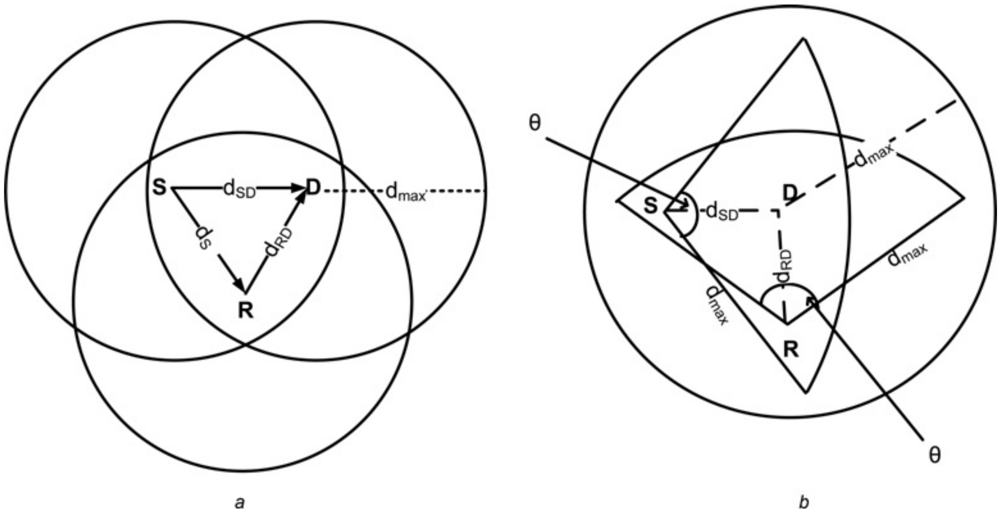

Figure 1 *Blocked area for one transmission*

a CSMA/CA protocol
b Proposed protocol

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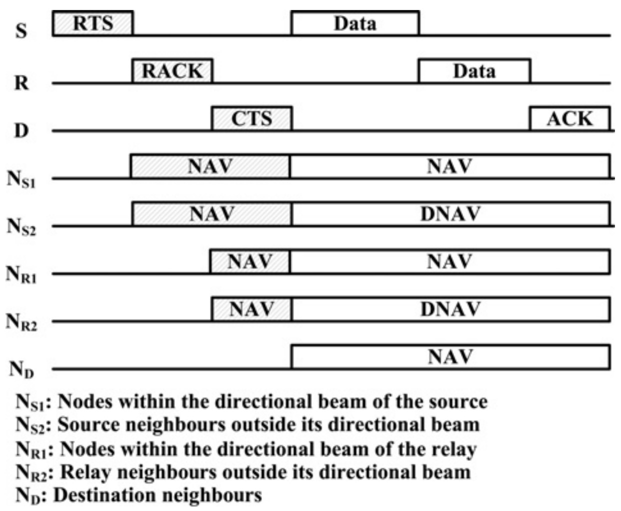

Figure 2 *Timing diagram of the proposed protocol*

chosen. When a request to send (RTS) is broadcasted by the source, the relay replies with a relay acknowledgment packet (RACK). Both the source and the relay use their omnidirectional antennas to send the RTS and RACK packets. The RTS and RACK packets inform all nodes, within their transmission range, with the source, relay 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 relay 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. A clear to send is broadcasted by the destination using its omnidirectional antenna. Consequently, the destination node blocks a full circle with radius of $d_{\max}$. 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.

It should be noted that the use of out of band dedicated control channel to perform various control and resource allocation operations has been suggested in many other publications (e.g. [12]). In general, it was found that dedicated control channel protocols, at the cost of two radios, outperform other protocols when data packets are long [13].

Since the destination uses an omnidirectional antenna, it always blocks a full circle with 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. 1*b*. Assume that the fixed beamwidth of the deployed directional antenna is θ. In what follows, we prove that by keeping $\theta \leq 120^\circ$ we can minimise the blocking area to a circle with radius $d_{\max}$.

Consider two intersected circles, each with radius $r = d_{\max}$, and centres C and B, respectively, where B represents the destination and C represents either the source or the relay. Fig. 3*a* shows the case where the source (or relay) is located very close to the destination, that is, $CB \simeq 0$. In this case, any choice for $\theta = \angle ACF \leq 180^\circ$ would satisfy the above constraint, that is, it would keep the total blocked area to a circle with radius $d_{\max}$ around the destination.

In the extreme case, depicted in Fig. 3*b*, the source (or relay) is located at distance $d_{\max}$ from the destination, that is, at the perimeter of the destination's blocked circle. In this case, $\overline{CB} = d_{\max}$. Satisfying the above constraint implies that we need to have $\angle ACB = 60^\circ$, therefore $\theta = \angle ACF = 120^\circ$. Fig. 3*c* represents the case where the source (or relay) is at a distance CB, $0 < CB < d_{\max}$, away from the destination. In this case, keeping $\theta = \angle ACF \leq 120^\circ$ would also satisfy the above constraints.

From the above argument, it is clear that restricting the maximum beamwidth to less than or equal to 120° optimises the blocking area by ensuring that it is reduced to one circle with radius $d_{\max}$ around the destination. On the other hand, maximising the probability of finding a relay within the transmission beamwidth of the source requires that θ is maximised. Thus, throughout the rest of this work, we set $\theta = 120^\circ$.

3 Performance analysis

In this section, we determine the expected value of the average blocked area associated with a given number of transmissions. We also develop a Markov chain model for the network performance under the proposed setting.

3.1 *Average blocked area*

Let $A_c = \pi d_{\max}^2$ denote the area of the circle blocked because of any ongoing single transmission. It is clear that, at any point of time, nodes can be blocked because of more than one transmission. In other words, as shown in Fig. 4, the circles corresponding to areas blocked by different transmissions may overlap. Assuming a relatively dense network, then estimating the average number of nodes involved (i.e. either being a source, destination and relay or blocked) in a specific number of transmissions is equivalent to determining the average area blocked because of these transmissions.

Let $A_I(l) = A_1 \cap A_2$ denote the area of intersection between two circles, A_1 and A_2, with radius $d_{\max}$ and centres separated by $l \leq 2d_{\max}$. Then we have

$$A_I(l) = 2d_{\max}^2 \cos^{-1}\left(\frac{l}{2d_{\max}}\right) - \frac{1}{l}\sqrt{4d_{\max}^2 - l^2} \qquad (1)$$

The probability density function of the distance l between

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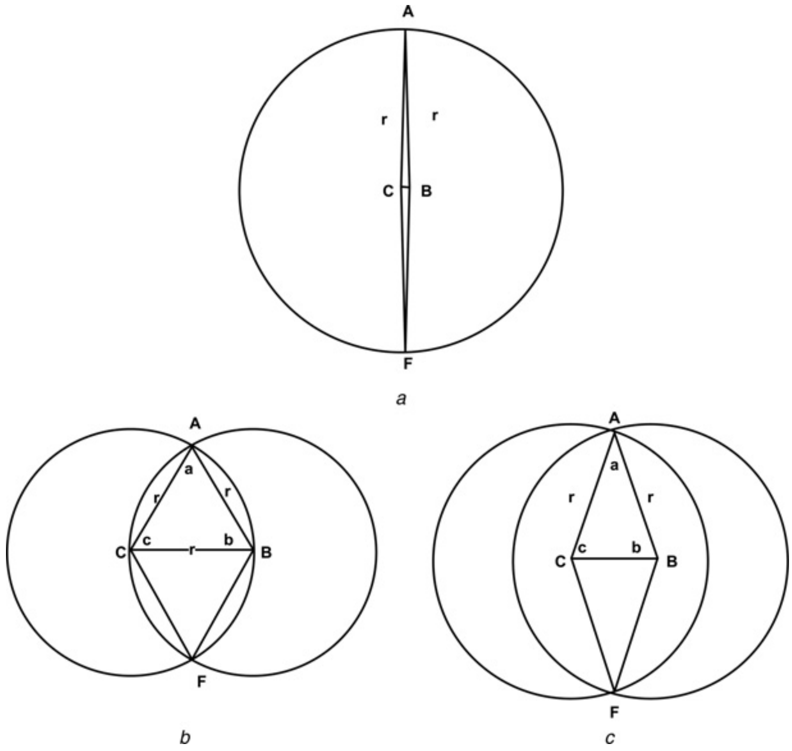

Figure 3 *Restrictions on beamwidth*

a $CB \to 0$
b $CB = r$
c $CB < r$

any two uniformly distributed nodes within a transmission area of z^2 is given by [14]

$$p(l) = \begin{cases} \dfrac{2l}{z^2}\left(\dfrac{l^2}{z^2} - \dfrac{4l}{z} + \pi\right), & 0 \le l \le z \\ \dfrac{2l}{z^2}\left(4\sqrt{\dfrac{l^2}{z^2} - 1} - \left(\dfrac{l^2}{z^2} + 2\right)\right. & \\ \quad \left. + 2\left(\sin^{-1}\left(\dfrac{z}{l}\right) - \cos^{-1}\left(\dfrac{z}{l}\right)\right)\right), & z \le l \le \sqrt{2}z \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

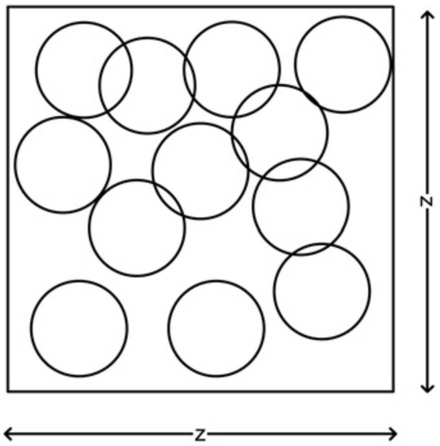

Figure 4 *Example for overlapped blocked areas*

To allow two transmissions within two intersected circles, we must have $l \ge d_{\max}$, otherwise the two destinations would block each other. Hence, the expected value of the area of intersection between any two transmissions is given by

$$\begin{aligned} \overline{A}_I &= \frac{\int_{d_{\max}}^{2d_{\max}} p(l) A_{\mathrm{I}}(l)\,\mathrm{d}l}{1 - \int_0^{d_{\max}} p(l)\,\mathrm{d}l} \\ &= \frac{\pi d_{\max}^4((3d_{\max}^2/4z^4) - (11d_{\max}/5z^3) + (3\sqrt{3}/4z^2))}{1 - ((d_{\max}^4/2z^4) - (8d_{\max}^3/3z^3) + \pi(d_{\max}^2/z^2))} \end{aligned} \tag{3}$$

Using the inclusion exclusion principle [15], the total area occupied by x transmissions is given by

$$\begin{aligned} A(x) = &\sum_{i=1}^{x} A_i - \sum_{i,j:1 \le i < j \le x} (A_i \cap A_j) \\ &+ \sum_{i,j,k:1 \le i < j < k \le x} (A_i \cap A_j \cap A_k) - \cdots \\ &+ (-1)^x (A_1 \cdots A_x) \end{aligned} \tag{4}$$

Deriving the expected value for the higher-order terms in the above equation seems an intractable problem. However, as confirmed by our simulations, at moderate node density, the expected value for $A(x)$ can be well approximated by considering only the first two terms of

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the above equation, that is, we have

$$\overline{A(x)} \simeq xA_c - \binom{x}{2}\overline{A}_I \tag{5}$$

Fig. 5 confirms the quality of the above approximation. The simulations were conducted for $M = 1800$ nodes distributed uniformly over a square area of 100 km^2.

Let $N(x)$ denote the number of nodes that are involved in x transmissions (blocked, source and relay and destination nodes). Thus

$$N(x) = \frac{A(x)}{z^2}M \tag{6}$$

where M is the total number of nodes and z^2 is the total area. Therefore the average number of blocked nodes associated with x transmissions is given by

$$B(x) = N(x) - 3x \tag{7}$$

where the term $3x$ denotes the number of source, relay and destination nodes. Let Ω denote the maximum number of transmissions that can be conducted simultaneously in an area of z^2 km^2. Then $A(\Omega) = z^2$. Thus Ω can be approximately estimated using (5) by setting

$$A_c\Omega - \binom{\Omega}{2}\overline{A}_I = z^2 \tag{8}$$

and solving for Ω as

$$\Omega = \frac{(A_c + (\overline{A}_I/2)) - \sqrt{(A_c + (\overline{A}_I/2))^2 - 2\overline{A}_I z^2}}{\overline{A}_I} \tag{9}$$

In the following section, a Markov chain model for the network performance under the proposed setting is developed.

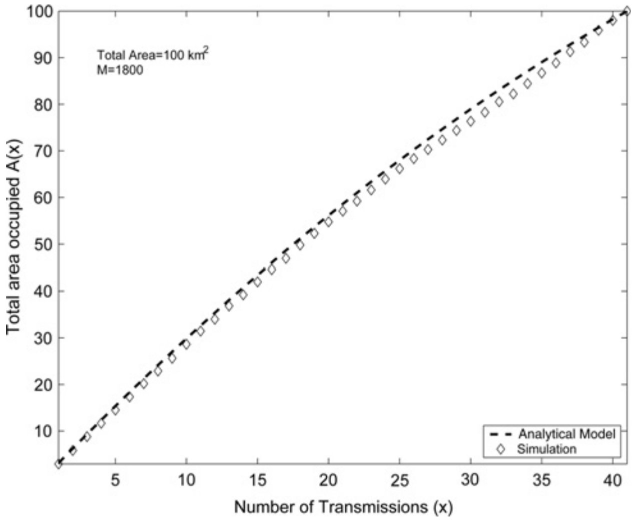

Figure 5 *Expected value of A(x)*

3.2 Modelling the number of transmissions

Throughout our work, we assume that all nodes are distributed uniformly over the covered area. We also assume that the traffic is distributed uniformly over all nodes. The packets inter-arrival and processing times are exponentially distributed with arrival and service rates of λ and μ, respectively. Each node is assumed to serve only one packet at a time, that is, if the node is blocked or busy, the incoming data packets are dropped.

Our system resembles the M/M/C/C queueing system [16], where customers have i.i.d exponentially distributed inter-arrival times with mean $1/\lambda$, and i.i.d. exponentially distributed service times with mean $1/\mu$. Assuming that the inter-arrival and service times are independent, then the above system can be modelled as a continuous-time Markov chain (see Fig. 6).

Throughout the rest of this section, let x denote the number of ongoing transmissions at time t, λ_x denote the transition rate from state x to state $x+1$, μ_x denote the service rate from state x to state $x-1$, $p_S(x)$ denote the probability that a source is not blocked or used when there is an active x transmission, p_D denote the probability that there is a destination available within the transmission range of the destination, p_R denote the probability that there is a relay available within the transmission range of the destination and p_{DR} denote the probability that both the destination and relay are within the beamwidth of the source to support this transmission. Thus, λ_x, is given by

$$\lambda_x = \lambda \times (M - N(x)) \times p_S(x) \times p_D \times p_R \times p_{DR} \tag{10}$$

where

$$p_S(x) = \frac{M - N(x)}{M} \tag{11}$$

$$p_D = \frac{N(1) - 1}{N(1)} \tag{12}$$

$$p_R = \frac{N(1) - 2}{N(1)} \tag{13}$$

In the above equations, $N(1)$ denotes the average number of nodes located in the transmission range of the destination

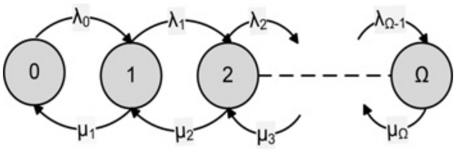

Figure 6 *Example for Markov process*

and is given by $N(1) = (A_c/z^2)M$ (see (6)). To satisfy the proposed blocking criterion, the probability that a destination and relay are found is equal to the probability that there is at least two nodes in one-third of the area that is covered by the source transmission range.

From Section 2, we obtain $\theta = 120^\circ$. In this case, the beamwidth of the source covers 1/3 of the circle around the destination. Therefore

$$p_{\mathrm{DR}} = \sum_{i=2}^{N(1)} \binom{N(1)}{i} \left(\frac{1}{3}\right)^i \left(\frac{2}{3}\right)^{N(1)-i} \tag{14}$$

The service rate μ_x is based on the service rate per existing transmission, μ, and the number of current transmissions, x, hence

$$\mu_x = x\mu \tag{15}$$

The transmission blocking probability is defined as the probability that a transmission is blocked given that a packet has arrived. Therefore

$$P_{\mathrm{B}}(x) = 1 - p_{\mathrm{S}}(x) p_{\mathrm{D}} p_{\mathrm{R}} p_{\mathrm{DR}} \tag{16}$$

In what follows, we present the steady-state analysis for our system. As mentioned above, our system resembles the M/M/C/C queuing system [16] for which the steady-state probability of any state x can be obtained from the balance equations

$$\begin{aligned} \lambda_0 \pi(0) &= \mu\pi(1) \\ \lambda_1 \pi(1) &= 2\mu\pi(2) \\ &\cdot \\ &\cdot \\ \lambda_{x-1} \pi(x-1) &= x\mu\pi(x) \end{aligned} \tag{17}$$

By solving the above system of equations we obtain

$$\pi(x) = \frac{\prod_{i=0}^{x-1} a_i}{x!} \pi(0) \tag{18}$$

where $a_i = \lambda_i/\mu$ and λ_i is given by (10). $\pi(0)$ can be obtained by solving the normalisation equation

$$\sum_{j=0}^{\Omega} \pi(j) = 1 \Rightarrow \pi(0) = \frac{1}{\left(\sum_{j=0}^{\Omega} \left(\prod_{i=0}^{j} a_i/j!\right)\right)}$$

Substituting into (18), we obtain

$$\pi(x) = \frac{\left(\prod_{i=0}^{x-1} a_i/x!\right)}{\left(\sum_{j=0}^{\Omega} \prod_{i=0}^{j} a_i/j!\right)} \tag{19}$$

The average number of ongoing transmissions is given by

$$\overline{N}_{\mathrm{T}} = \sum_{\forall x} \pi(x) x \tag{20}$$

One should realise that, for each packet transmission, it takes two time frames to deliver the packet to destination. Hence, the effective data rate is given by $R/2$, where R denotes the data rate per frame. Therefore the total average throughput of the network is given by

$$\overline{TH} = \overline{N}_{\mathrm{T}} \frac{R}{2} \tag{21}$$

The steady-state blocking probability is given by

$$P_{\mathrm{B}} = \sum_{\forall x} \pi(x) P_{\mathrm{B}}(x) \tag{22}$$

where $P_{\mathrm{B}}(x)$ is given by (16).

4 Simulation results

Our analytical results are verified using an event-driven Monte Carlo simulation written in C++. Throughout our simulations, we considered a network where all nodes are distributed uniformly over 10 km × 10 km square area. The source and destination pairs are chosen at random. If the destination is not in the transmission range of the source (1 km), a new destination is chosen at random. The relay is chosen such that it is a neighbour of both the source and destination. Packets inter-arrival and processing times are assumed to be exponentially distributed with inter-arrival and service rates of $1/\lambda$ and μ, respectively. Each node is assumed to serve only one packet at a time and if the node is blocked or busy, the incoming data packets are dropped. The presented results are averaged over 100 random topologies. The simulation and analysis parameters are given in Table 1. For the purpose of comparison, we also simulated the cooperative network protocol in [10], which employs only omnidirectional antennas.

It should be noted that the optimum node density in an ad-hoc network depends on several parameters including the transmission range of the nodes and the mobility assumptions. In practical applications, the number of nodes should be chosen to guarantee the full network connectivity given these parameters [17, 18]. The wide range for the number of nodes used in our simulations aims to compare our protocol with previously published results (which typically vary between 2 and 30 nodes per km^2 for similar choice of parameters but with omnidirectional antennas). Thus we also considered a larger number of nodes in order to test the effect of high node density on the performance when using directional antennas.

Table 1 Simulation and analysis parameters

total area (z^2)	100 km^2
transmission range (d_{max})	1 km
λ	0–0.9
μ	1
total number of nodes (M)	100–11 000
data rate (R)	1 Mbps

Fig. 7 shows the simulation results for the average network throughput as a function of the beamwidth used at the source and relay stations. It is clear that for small node density (two nodes per km^2) the best throughput is achieved at beamwidth of 180°. This can be explained by noting that for low densities, it is hard to find a relay that lays within the source beamwidth and hence a wider beamwidth provides a better performance. As the node density becomes higher, the best throughput is achieved for beamwidth $\leq 120°$.

Figs. 8 and 9 show how our protocol improves the transmission blocking probability (22) and throughput (21) relative to the CSMA/CA protocol in [10] for different utilisation factors, $\rho = \lambda/\mu$. It is clear that by using the proposed protocol, the blocked area by each transmission is reduced, and hence more users are free (i.e. not blocked) to transmit, receive or relay, which results in a better performance. It is also clear that the performance depends on the utilisation factor ρ. The case $\rho = 0$ corresponds to a completely idle system with no arrival packets. Consequently, despite the zero blocking probability, the average throughput is also zero. As ρ starts to increase, more data packets will be available for transmission which results in an increase in the network throughput.

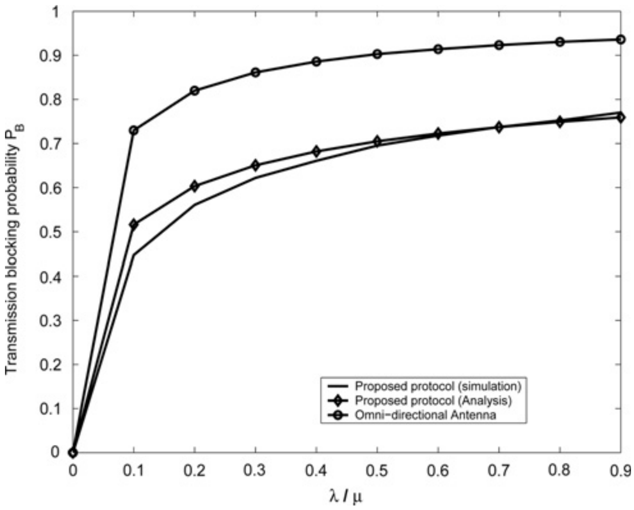

Figure 8 *Transmission blocking probability (ten nodes per km^2)*

The variation of the average network throughput (21) with the node density is shown in Fig. 10. It is clear that for small node density, adding more nodes significantly increases the network throughput since it makes it easier to satisfy the conditions for finding a proper relay. Also, one can realise that the protocol using omnidirectional antennas [10] saturates at lower node density as the criterion of choosing a relay in this case has less constrains than the criterion used in our protocol. On the other hand, for large node density, the network throughput is more influenced by the utilisation factor. It is also clear that the throughput of our protocol saturates

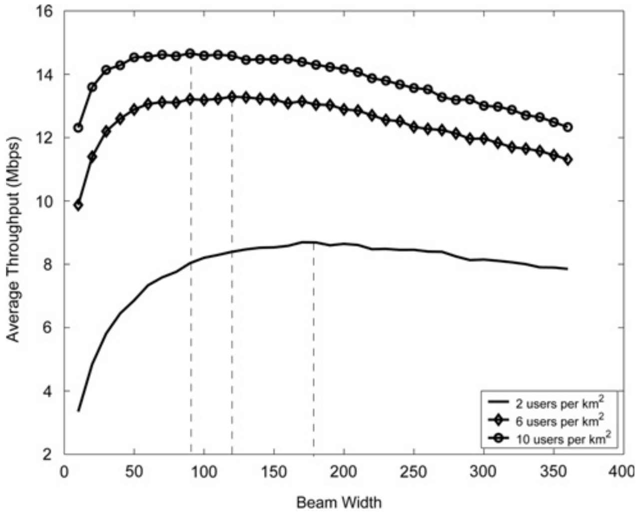

Figure 7 *Average network throughput as a function of the beamwidth*

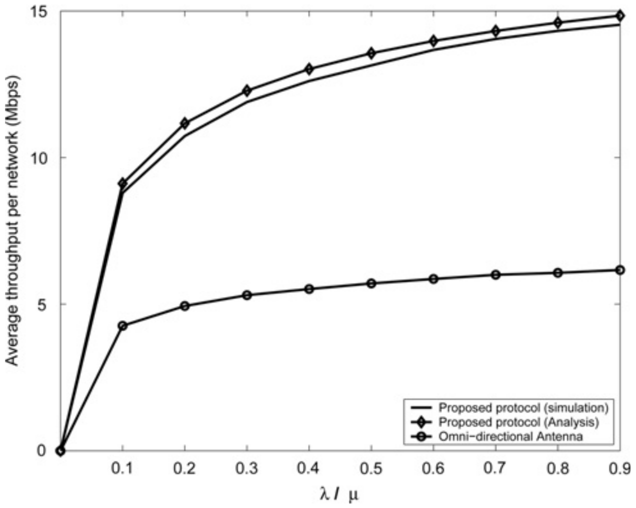

Figure 9 *Average network throughput as a function of utilisation factor (ten nodes per km^2)*

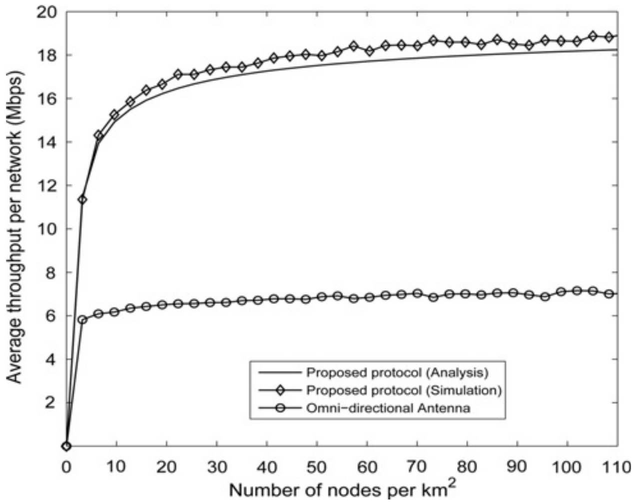

Figure 10 *Average network throughput as a function of the number of nodes ($\lambda/\mu = 0.9$)*

at a much higher value compared to the protocol using omnidirectional antennas. Both the analytical results above, and its matched simulation results, confirm that our proposed protocol outperforms the protocol using omnidirectional antennas [10].

5 Conclusions

In this paper, we proposed a new channel access protocol for transmission over cooperative *ad hoc* networks. By utilising directional antennas at both the source and relay stations, the proposed protocol improves the transmission blocking probability and the average network throughput.

Markov chain modelling is used to study the network performance under the proposed settings. The steady-state results for transmission blocking probability and average network throughput are obtained by analysing the above Markov model and validated throughout simulations.

It should be noted that equipping the destination node with two directional receive antennas (one directed at the source and one at the relay) may provide further improvement in the network throughput. Providing a channel access protocol that utilises this additional hardware seems to be an interesting future extension for this work. Incorporating the effect of the physical layer of the transmission channel provides another useful research direction.

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