Selecting a Spatially Efficient Cooperative Relay

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***Abstract*—Cooperative relaying is a communication technique in wireless networks where neighboring nodes assist communication pairs to mitigate the negative effects of multi-path fading. The resulting performance strongly depends on the selected relays. Although a cooperative relay provides benefits to a given source-destination pair, overall network performance might be degraded due to the increased level of interference. So far almost all relay selection mechanisms consider mainly channel conditions to the potential relays. In this paper we propose a contention-based relay selection mechanism that can take into account also spatial efficiency of potential relays. For that the degree as well as relative position of the nodes are used for selection. With the proposed method a high successful relay selection probability can be achieved, while significantly reducing the amount of additional spatial resources blocked by the cooperative relay.**

***Index Terms*—Cooperative relaying, relay selection, radio resource allocation**

I. Introduction

Cooperative relaying has been shown to have great potential in assisting communication pairs in wireless networks by mitigating the effects of multi-path fading [1]. The benefits of cooperative relaying rely on the broadcast nature of wireless networks, where it is likely that several nodes can overhear an ongoing communication between a source-destination pair. Therefore, even if a packet cannot be delivered to a destination due to impaired channel conditions, a copy of the packet can be retransmitted by a neighboring node that has successfully overheard the direct transmission. Such form of cooperative diversity helps to overcome hardly predictable signal drops on the direct transmission channel and can eliminate the need for higher layer retransmissions [1].

While introducing a relay has clear advantages, it should be noted that it also results in use of additional space-time resources. In other words, a relay node can degrade the overall performance in its neighborhood by blocking communications that can take place if the relay is not used [2].

Relay selection is one of the main building blocks of cooperative relaying and commonly the channel conditions of the relay links are considered as main selection criteria. While this is necessary, the impact of choosing a given relay node on the communication of the surrounding nodes as well as the overall network also needs to be taken into account.

In this paper, we introduce a contention-based relay selection scheme that leads to an efficient cooperative resource utilization. To this end, we propose a nomination method for the relay nodes that uses only local information and depends on the number of neighbors of the relay as well as distances between the communicating nodes. We determine the probability that a potential relay node (i.e., a relay node that has acceptable channel conditions) should nominate itself for assisting the communication between a given source-destination pair. We study the performance of the proposed relay selection mechanisms for a random uniform network scenario as well as a simple isolated relay scenario. The performance metrics of interest are the *probability of successful relay selection* and the amount of *additional spatial resources blocked due to cooperation*. Our results show that with the proposed method a high success rate (above 90%) can be achieved for various network sizes and the spatial efficiency of the cooperative relay can be increased significantly.

The remainder of the paper is organized as follows. Section II summarizes the related work in relay selection. Resource allocation scenarios are introduced in Section III. The proposed relay selection mechanism is explained in Section IV. Section V provides performance results and discussions of our findings. Finally, Section VI concludes the paper.

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II. Related Work

The performance of cooperative relaying is mainly determined by the selected relaying node. The relay selection can be done once at network startup [3], periodically, at each transmission attempt [4], or on demand [5].

Bletsas et al. [4] in their relay selection scheme use timers to reflect channel conditions of each potential relay. The timer of the relay with the best channel conditions expires first, which triggers broadcast of a message showing relay willingness to cooperate. This scheme is extended in [6] to incorporate energy information of nodes, such that the relay which minimizes the overall energy costs for delivering a message is chosen.

In [7] Shan et. al. propose to group neighboring nodes according to their helping ability defined by resulting cooperative rate. After that a series of contentions is performed to determine a group of nodes for cooperation, then optimal nodes in the group, and finally a single relay. The selection mechanism terminates as soon as one optimal relay is found.

Chou et al. propose in [8] a medium access control (MAC) protocol based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) that incorporates cooperative relay selection. After exchanging signaling messages, neighbors determine their channel quality to the source and the destination. In case they can support the direct transmission, a cooperative relay is selected via a contention-based competition in a contention window of fixed size. The window size is chosen using the average node density at the network deployment.

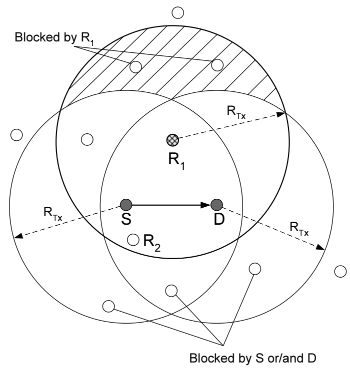
The use of nodes location information in communication protocols is shown to be beneficial in number of works. Zorzi and Rao in [9] use location of nodes for forwarding data from source to destination in multihop networks. At each hop a forwarding node closest to the destination is selected after the transmission. All nodes in the network build groups according to their distance to the destination. After receiving a message they participate in contention according to their group numbers. A contention resolution follows if necessary. In [10] authors propose an extension to the IEEE 802.11 Distributed Control Function (DCF) MAC that allows utilization of capture effects in ad hoc networks and increases overall network throughput by using local information of nodes location.

However, to the best of our knowledge there is no work that considers spatial resource efficiency of a cooperative relay as a selection criterion.

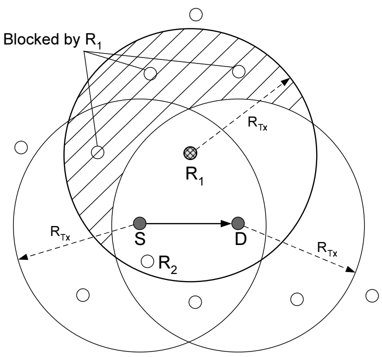
III. Resource Allocation Scenarios

Efficient spatial resource utilization by cooperative relaying can be achieved when a relay that blocks minimum additional nodes (transmissions) is selected. Resource utilization is closely coupled with the deployed MAC protocol. In this paper we consider two different approaches. The first approach (Scenario A) is a basic 802.11 DCF-based resource allocation. After a cooperative relay has been selected and the transmission is started all nodes in the range of the source S, the destination D, and the chosen relay are prevented from transmitting or receiving data from any other node during the allocated transmission period [5], [8]. In Fig. 1a we show the principles of such resource allocation on a simple disk model of wireless signal propagation, where the shaded area depicts the nodes blocked only by the chosen relay R_1. This model represents the case of medium over-reservation. As a result, the number of nodes additionally blocked by a cooperative relay corresponds to the minimum and can be considered as a baseline. Intuitively, to optimize spatial resource utilization in such a MAC, a relay node that is located closer to either the source or the destination should be preferred, since it shares a large part of spatial resources already allocated to the direct transmission.

It is well known that 802.11 DCF does not solve the exposed terminal problem and in that respect more efficient MAC protocols in terms of resource utilization can be implemented [7], [11]. The second MAC approach (Scenario B) addresses this problem. The principle of such resource allocation approach for cooperative relaying is depicted in Fig. 1b. Namely, the approach utilizes the fact that during data transmission the nodes that do not disturb the reception at D can transmit even if they are in the range of S. In addition, nodes in the range of D but out of the range of S can simultaneously receive data. As a result, a better overall network throughput and space-time utilization can be achieved. Clearly, the spatial efficiency of a cooperative relay in such MAC approach is improved when a relay closely located to the destination can be found. Although such a MAC is not exactly implemented yet, we use it to represent the case where cooperation can become a more significant problem for resource utilization.



(a) Scenario A.



(b) Scenario B.

Fig. 1. Two scenarios of resource allocation. a) 802.11 DCF-based scenario; b) Resource Efficient Scenario (S is transmitting)

Also note that the amount of additional blocked nodes not only depends on the distance of the relay to S or D, but also on the node distribution in the network. In a network with random uniformly distributed nodes, a relay that requires fewer additional spatial resources most likely will block fewer additional nodes. However, for an inhomogeneous node distribution around the communication pair this is most likely not true. We study both cases later in this paper.

IV. Relay Selection

Cooperative relay selection is a challenging task in wireless networks with distributed control. Commonly, relay selection decision is performed by source or destination. In following we assume that destination acts as a relay selecting node.

All relay selection methods considered in this paper are contention-based. Potential relays can make themselves known to the selecting node in a given contention-window of size w slots. The selection consists of three phases:

- *Qualification phase* starts after S and D exchange signaling messages to initiate cooperative relay selection. A third node can qualify itself as a potential relay for the given S-D pair if it can overhear signaling messages from both nodes and satisfy certain threshold requirements explicitly specified by S and D, e.g., source-relay and relay-destination Signal-to-Noise Ratio (SNR) thresholds.

- During the *nomination phase* all qualified potential relays can nominate themselves for cooperation to the selecting node. Each potential relay selects randomly a slot in the contention window and transmits its nomination message with a certain probability. The nomination probability is defined by a *nomination function* and can incorporate local information about the node.
- *Election phase* concludes the selection procedure. In this step, via an *election function* the selecting node chooses a cooperative relay among the potential relays that successfully sent their nomination messages. After that the destination notifies its potential relays about the outcome of the selection.

In our work, we focus on the last two phases and evaluate different nomination and election functions.

A. Nomination Phase

Observe that there is a trade-off between the quality of the relay chosen and the duration of the relay nomination procedure. In order to provide maximum number of options for the destination to choose the best relay during the election phase, all potential relays should nominate themselves. That requires, however, a sophisticated coordination algorithm and results in long selection delays when the number of potential relays is large. Moreover, in reality a selecting node can hardly precisely estimate the number of potential relays before the nomination. In this paper, we propose to use a contention window of a fixed size where potential relays access chosen slots with certain probability.

There are two aspects that characterize the success of the nomination phase. First and prime factor is the contention success probability meaning at least one nomination message from potential relays goes through contention. Secondary factor is the number of non-collided nomination messages successfully received at the selecting node. Intuitively, larger number of successful nominations combined with a smart election function at the selecting node can lead to a better choice of a cooperative relay. In this paper we present the results for the overall contention success probability.

1) Contention-optimal nomination function: In the following we derive an optimum nomination function that maximizes the probability of the contention success. We assume that there are N potential relays for a given S-D pair. Each relay chooses a random slot in the contention window of size w and transmits its nomination message with probability p in this slot.

The probability that exactly k nodes select a given slot is:

$$P_k = \binom{N}{k} \left(\frac{1}{w}\right)^k \left(1 - \frac{1}{w}\right)^{(N-k)}. \qquad (1)$$

Then, probability that from those k nodes exactly one node transmits is:

$$P_{1|k} = kp\left(1-p\right)^{k-1}. \qquad (2)$$

Summing up over all possible k's, we obtain the probability that there is exactly one nomination message in the given slot as:

$$P = \sum_{k=0}^{N} P_k \cdot P_{1|k} = \frac{\left(w-p\right)^{N-1} N \cdot p}{w^N}. \qquad (3)$$

The probability that there is at least one non-collided nomination message in the contention window is then given by:

$$P_s = 1 - \left(1 - P\right)^w. \qquad (4)$$

Taking the derivative of Eq. (4) with respect to p and equating to zero, we can find that the optimum p value that maximizes P_s is $\frac{w}{N}$. Using these findings, we first propose the following nomination function to achieve optimum success probability:

$$p = \begin{cases} 1, & N \le w, \\ \frac{w}{N}, & N > w. \end{cases} \qquad (5)$$

If $N > w$, on average w nodes send their nomination messages. Although in reality it is hard to estimate the exact number of current potential relays, such assumptions on the complete information can provide us an upper bound on the success of the nomination phase.

2) Degree-based nomination function: For this nomination function we assume that destination does not know the number of potential relays for current transmission. But we assume that each node in the network can estimate its number of neighbors. Due to the broadcast nature of wireless networks, nodes constantly overhear the channel and over time they can have an estimation about the number of nodes that transmit in their range. Although instantaneous information at the time of contention might not exactly be known, as our results later show, it is usually sufficient to know the average number of neighbors for selecting a cooperative relay.

The second proposed nomination function of a potential relay i with a degree of n_i (i.e., with n_i nodes in its transmission range) is given by:

$$p_i = \begin{cases} 1, & (n_i - 2) \le w, \\ \frac{w}{n_i - 2}, & (n_i - 2) > w \end{cases} \qquad (6)$$

where we discard S and D since they are neighbors of all potential relays by default.

With this function, potential relays use their degree to get an estimate of the number of potential relays. However, this nomination function does not really take into account any spatial resource utilization.

3) Distance-and-degree-based nomination function: In order to reflect additional space-time resources required for a cooperating node, illustrated in Fig. 1, we propose to include information about relay distances to S and D in the nomination function. Estimating distances between communicating nodes is trivial when they have GPS devices and can exchange their coordinates. But even without such hardware it would be possible to estimate local positioning of the nodes in the network [12], [13].

For the third proposed nomination function named *distance-and-degree-based* nomination, we assume that potential relays know their distances to S and D as well as their degree and use this information in the nomination process.

For Scenario A (see Fig. 1) the closer a potential relay is to either S or D, the higher the nomination probability should be so that fewer space-time radio resources are affected by the cooperating node. On the other hand, for Scenario B, the potential relays that are closer to D should have a higher nomination probability for better resource utilization. The proposed nomination function for a potential relay i is then given by:

$$p_i = \begin{cases} 1, & (n_i - 2) \le w, \\ \min\left(\frac{1-d_i}{d_i} \frac{w}{n_i - 2}; 1\right), & (n_i - 2) > w \end{cases} \quad (7)$$

and d_i is given by:

$$d_i = \begin{cases} \frac{\min(d_{is}, d_{id})}{r}, & \text{for Scenario A} \\ \frac{d_{id}}{r}, & \text{for Scenario B} \end{cases} \quad (8)$$

where d_{is} and d_{id} are the distances from potential relay i to S and D, respectively, and r is the transmission range of the nodes in the network.

B. Election Phase

If after the nomination phase the selecting node correctly receives more than one nomination message, the election phase starts. A simple election method is to choose a relay node randomly among the nominated ones. However, the potential relays that successfully go through the contention are not equivalent in terms of required resources and a more effective election method can be found. For instance, election function can select a cooperative relay with the highest nomination probability from a set of successfully nominated nodes. We name such election function *maximum-nomination-probability* function. In case there are several potential relays that went through the contention and all have same highest nomination probability, a cooperative relay is chosen among them randomly. We illustrate the impact of various election functions on resource utilization for a clustered topology in the next section. In addition to the *random* and *maximum-nomination-probability* methods, we also study *minimum-neighbor* and *minimum-distance* elections, which elect the potential relay with minimum number of neighbors and minimum distance to S or D (for Scenario A) and to D (for Scenario B), respectively.

V. Results and Discussion

In this section, we first study the performance of the nomination methods proposed in the previous section in a network with random uniform node placement. Two performance metrics are considered: the probability of successful contention and the number of nodes blocked only by the selected cooperative relay. Both metrics are studied for resource allocation schemes of Scenario A and Scenario B introduced in Section III. The performance is evaluated versus node density, contention window size and percentage of not cooperating nodes in the network.

In addition, in the isolated relay scenario we look at the case where degree of potential relays strongly varies. In this scenario we also study the impact of various election function on the selection performance.

We assume that the normalized transmission range of all nodes is 1. Without loss of generality we assume that S and D are located at a distance (normalized by the transmission range) of $d_{sd} = 0.7$ from each other. Unless otherwise noted, the contention window size is set to 5 slots and the node density is 7 nodes per square unit. The simulation area is set to include all nodes in the range of potential relays.

A. Random Uniform Network

In this subsection, we consider random uniform node distribution in the network. Fig. 2 shows the probability of successful contention versus network node density for the proposed nomination functions. The success probability for the degree-based and contention-optimal nomination functions is independent of the used resource allocation scenario, since no distance information is used. The contention success probability of the proposed degree-based and distance-and-degree-based nomination functions is just slightly lower than the upper bound, where information about exact number of potential relays is available.

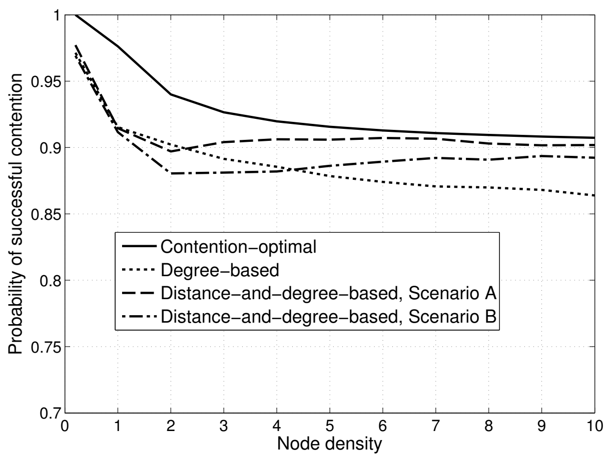


Fig. 2. Probability of successful contention vs. node density, when $w = 5$.

Scenario A has slightly better success probability than Scenario B, since in former case more nodes participate in the nomination with higher probability.

As shown in Fig. 3, contention window size has significant influence on the outcome of the relay selection procedure. A larger contention window provides a larger potential relay pool to the selecting node and, hence, a higher success rate for all nomination functions. However, recall that a larger contention window would also cause a longer selection duration. Further work is necessary to determine the optimum contention size for a given node density and desired contention success probability.

Next, we study the impact of various nomination functions on the additional resources required for cooperative transmission. Maximum-nomination-probability election concludes the selection procedure. Fig. 4 shows how many additional nodes are blocked by the selected cooperative relay at various

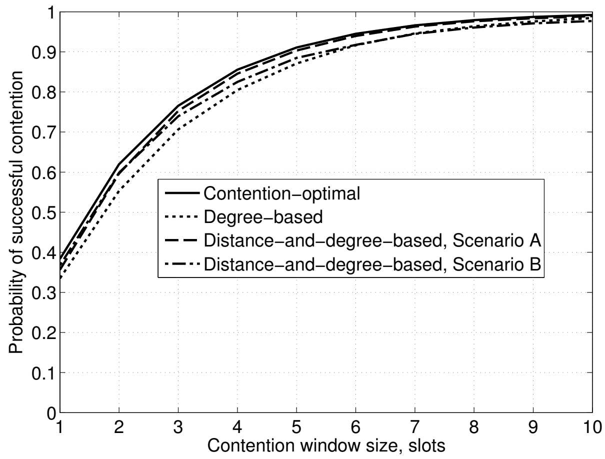


Fig. 3. Probability of successful contention vs. contention window size, when node density is 7 nodes per sq. unit.

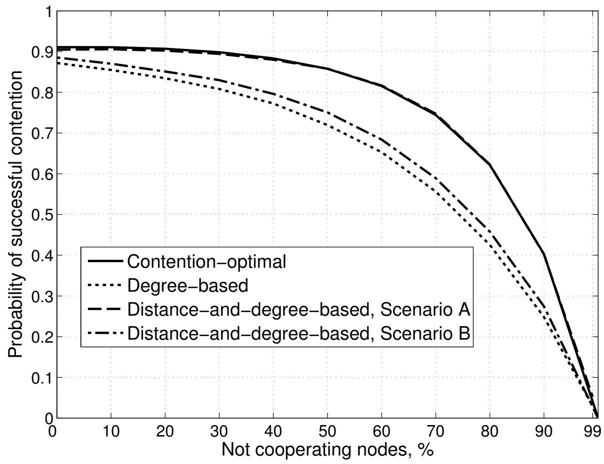


Fig. 5. Probability of successful contention versus percentage non-cooperating nodes, when $w = 5$ and node density is 7 nodes per sq. unit.

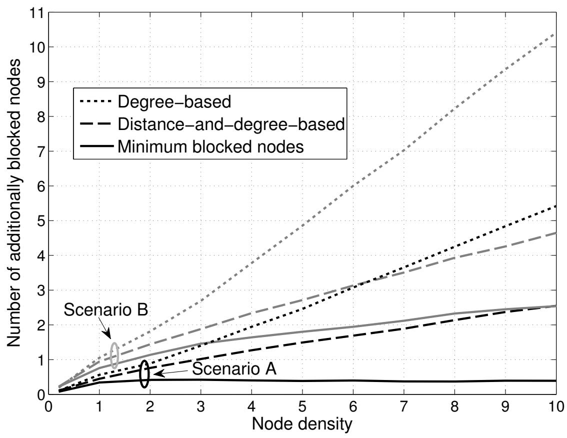


Fig. 4. Number of additional blocked nodes by the chosen relay versus node density, when $w = 5$.

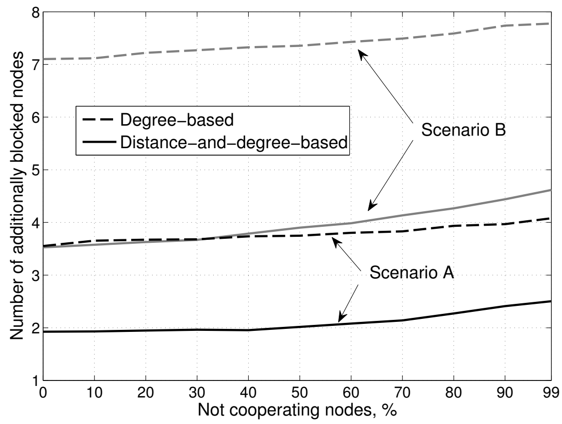


Fig. 6. Number of additional blocked nodes by the chosen relay versus percentage non-cooperating nodes, when $w = 5$ and node density is 7 nodes per sq. unit.

node densities for both resource allocation scenarios. As a comparison, the optimum case where the potential relay blocks the minimum number of additional nodes is also provided for both scenarios. The performance trends are equal for both proposed nomination functions. But, as expected, the number of additional blocked nodes is higher in Scenario B. This is because in Scenario B nodes in the range of S can be counted as blocked by the relay. Nevertheless, Fig. 4 shows that the nomination functions that include the distances of relay nodes provide significantly better results than those without it. The impact becomes more profound in dense networks, where the distance-and-degree-based nomination function shows a 50% gain compared to the degree-based nomination. Although results from the nomination function given in Eq. (7) are much better than Eq. (6), there is still room for improvement in terms of minimizing wasted resources.

We also studied the impact of the contention window size on the number of additionally blocked nodes. For both nomination functions, the number of blocked nodes decreases only slightly with increase of the contention window size.

So far we assumed that all nodes in the range of S as well as D are qualified as potential relays and participate in the nomination phase. In reality, not all nodes in range necessarily nominate themselves for cooperation. For instance, they might not satisfy the SNR requirements, have low battery, be in sleep mode, or simply might be unable or unwilling to cooperate. In Fig. 5 we illustrate the contention success probability versus percentage of nodes that are not cooperating. Such nodes are chosen randomly in the given network. Observe that the success probability decreases sharply when the ratio becomes large. This is due to the fact that although fewer nodes enter the nomination phase, the nomination probability is computed assuming every neighboring node qualifies as a potential relay.

The blocked resources are not significantly affected by the non-cooperative nodes (see Fig. 6) and increase only slightly. This implies that with proposed nomination functions for the random uniform topology number of nodes additionally blocked by a chosen relay can be kept low.

B. Isolated Relay Scenario

Next, we analyse a simple clustered topology illustrated in Fig. 7 and illustrate the impact of the election phase on the relay selection performance. The topology is setup such that there is a single potential relay R_1 located at the edge of the transmission ranges of S and D and has no other neighbors. A cluster of randomly uniform distributed nodes is located out of range of R_1. It is positioned in a way that some of the nodes in the cluster can be potential relays for the S-D pair and participate in the selection process. Clearly, if R_1 satisfies all other selection requirements, such as SNR thresholds, it should be selected as the cooperative relay, since it does not block any additional nodes, although it is located far away from both S and D.

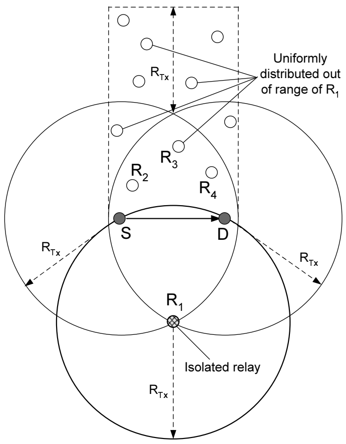


Fig. 7. Isolated relay topology

We first study the impact of network topology on the relay selection performance, when maximum-nomination-probability election is employed. Since the contention success probability of all nomination methods performs similar to the case with random uniform topology, these results are omitted. Instead, we look at the probability of relay R_1 being chosen. Recall that for all the nomination methods, R_1 will nominate itself with probability 1 in one of the w slots. In Fig. 8 we show the probability that R_1 is chosen for various nomination methods versus the number of nodes in the cluster. When the cluster size is small all nomination techniques perform similar since several relays nominate with probability one. Observe that the probability of choosing R_1 significantly decreases with increasing number of nodes, when the optimum nomination function Eq. (5) is used. In this case, all potential relays including R_1 use the same nomination probability. As a result, the probability that a potential relay other than R_1 is chosen also grows. For the rest of the nomination functions, R_1 nominates itself with probability one and is almost always selected after successfully going through contention.

Next, we investigate the performance of random, minimum-neighbor, minimum-distance, and maximum-nomination-probability election methods with the distance-and-degree-based nomination function for Scenario B. Note that, while omitted here, the trends for Scenario A are similar to Scenario B. Figures 9 and 10 show the probability that R_1 is chosen for different election methods versus number of nodes in the cluster (when $w = 5$) and contention window size (when number of nodes in the cluster is 90), respectively. Observe that as the number of nodes in the cluster increases the performance of maximum-nomination-probability election approaches to that of minimum-neighbor election, which chooses R_1 if it successfully goes through contention. Minimum-distance election, on the other hand, performs the worst since R_1 is located far away from both S and D and is not elected even if it successfully goes through contention.

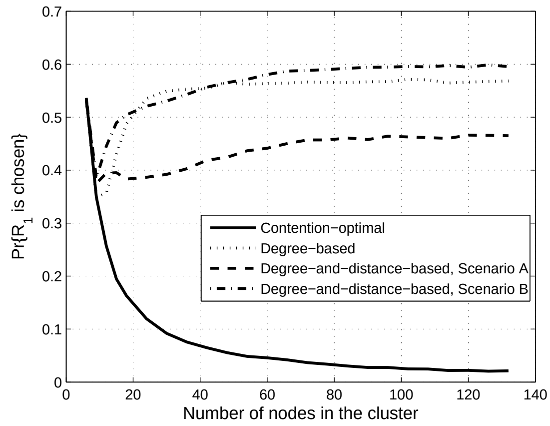


Fig. 8. Probability that R_1 is chosen versus number of nodes in the cluster, when $w = 5$.

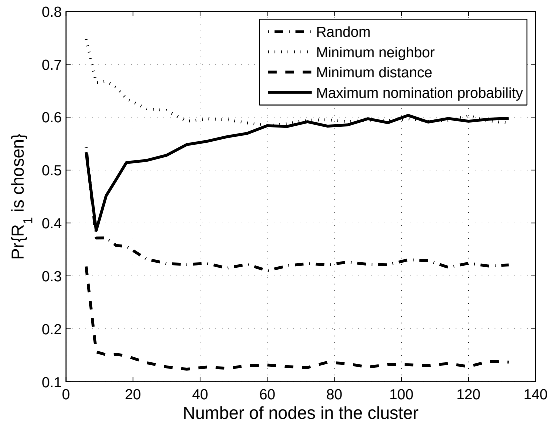


Fig. 9. Election comparison: probability that R_1 is chosen versus number of nodes in the cluster, when $w = 5$.

Similarly, both random and minimum-distance election methods fail to elect R_1 with increasing contention window size (see Fig. 10), since more potential relays participate in the election process. On the other hand, R_1 is selected by minimum-neighbor and maximum-nomination-probability elections more than 50% of the time for all of the given contention window sizes.

Finally, we study the impact of the election method on the number of additional blocked nodes. First, we study the impact for different network sizes when $w = 5$. Observe from Fig. 11 that the number of additional blocked nodes is severely affected by the election method and increases with cluster size.

Assuming that the number of nodes in the cluster is fixed to 90, as shown in Fig. 12, the number of additional blocked nodes does not change with the contention window size if the latter is sufficiently large. As expected, minimum-distance

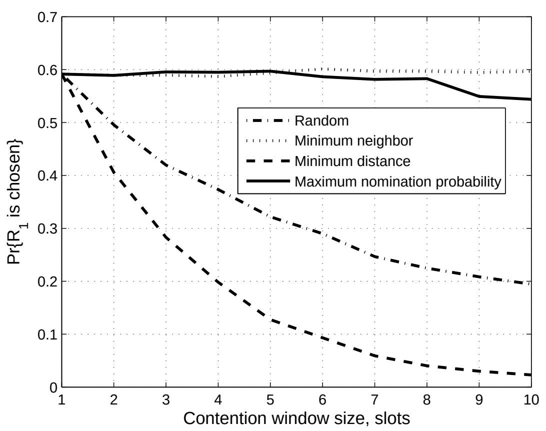


Fig. 10. Election comparison: probability that R_1 is chosen versus contention window size, when number of nodes in the cluster is 90.

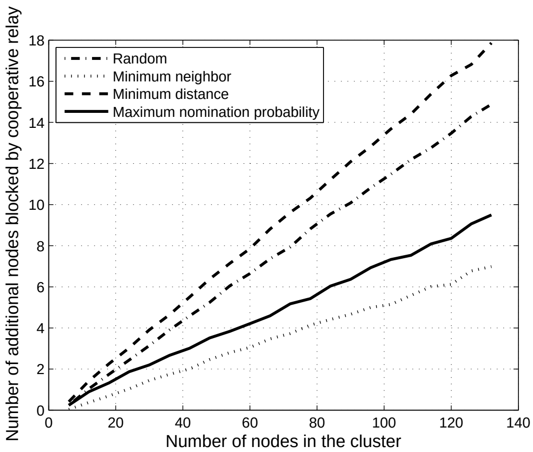


Fig. 11. Election method comparison: number of additional blocked nodes by the cooperative relay versus number of nodes in the cluster, when $w = 5$.

and random election mechanisms perform significantly worse than the others. Similar to the random uniform topology, an optimum contention window size might exist for a given node density.

VI. Conclusions

In this paper, we have proposed a relay selection mechanism that utilizes the degree and position information locally available to the potential relay nodes. We have investigated the performance of several nomination and election methods in terms of probability of successful relay selection and the amount of extra spatial resources used by the cooperative relay. We have shown that while the proposed nomination method is not the optimum in terms of spatial reusability, combined with an efficient election method a high success probability for relay selection ($> 90\%$) as well as significant reduction of blocked nodes ($> 50\%$) can be achieved. We have also provided insight into the impact of MAC protocol resource allocation and network topology on the spatial efficiency and relay selection performance via simple scenarios. Further work is necessary to incorporate the topology information into the nomination process of the potential relays.

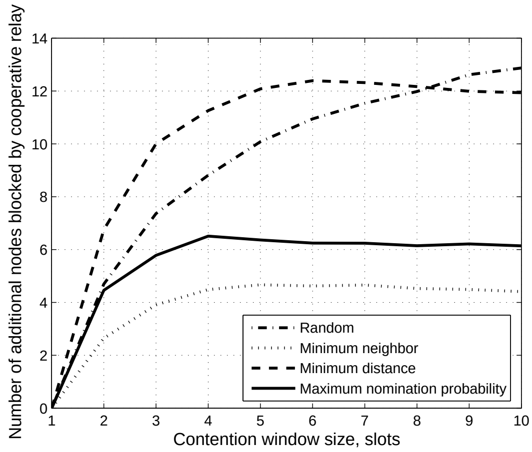


Fig. 12. Election method comparison: number of additional blocked nodes by the cooperative relay versus contention window size, when number of nodes in the cluster is 90.

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