Distributed Channel Selection for Ad-Hoc Networks in the Presence of Jamming Sources

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Abstract. We introduce a distributed scheme for the joint selection of a control (default) channel in an ad-hoc network, which could be subject to jamming and/or significant interference. The presented scheme enables nodes to independently agree on the appropriate channel for exchanging control packets required for networking protocols. If jamming is considered, the network can no longer rely on a predefined default channel. However, developing distributed protocols for adaptive default channel selection remains a difficult challenge as the restriction to local information exchange is in conflict with the need to coordinate on a channel. In our protocol, each node alternates between a channel probing-and-selection state and a normal operation state. This protocol endows the network with the ability to self-reconfigure once jamming is detected. Experimental results indicate that the proposed scheme induce stable channel selections that result in satisfactory network connectivity and fast recovery.

Keywords: Ad-hoc networks, network recovery, channel selection.

1 Introduction

The increasing density of wireless devices and rapidly build up of networks in infrastructure-less environments has awaken a great interest in the study of ad-hoc networking. Unlike highly structured communication networks, ad-hoc networks can not rely on a preexisting communication infrastructure. In this sense, ad-hoc networking protocols must be flexible enough to adapt to time-varying demands and operating conditions. In addition, complex interactions between physical, networking and application layers may require an integrated (as opposed to a layered) approach to protocol development.

MANET and sensor networks are perhaps, the most widely studied types of ad-hoc networks. The main goal of MANETs is to enable communication for applications involving mobile nodes. Sensor networks are built and deployed to detect specific events [2], [3]. In these types of ad-hoc networks, satisfactory performance of networking protocols relies heavily on the *continuous availability* of a default or control channel. Most protocols use a predefined control channel and do not consider other networks operating within the same geographical region (co-located networks), ignoring their potential (and perhaps inadvertent)

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interference [5] [6] [7]. Many applications may take place in hostile environments with jamming and significant interference. In these kind of environments, one can no longer assume a default or control channel is always available . There is a rather limited literature on this topic. For example, Ramachandran et al. [8] use a Channel Assignment Server (CAS) to define a default channel which has to be selected for at least one of the radios of each node. The default channel carries both control and data. Other approaches like [9] use nodes with equal number of radios with fixed and identical channel assignment.

In this paper, we propose a scheme that enable nodes to jointly select a default channel without requiring centralized decision making (as in the use of a Channel Assignment Server (CAS)). A distributed scheme relies only on local information and thus it is better suited to quickly react to changes in operating conditions. For example, nodes affected by jamming may autonomously search for new default and or control channel. As the default channel will carry the control messages, nodes ideally would reach an "agreement" on which of the available channels is to serve as default or control channel. In other words, the objective here is to generate a default channel selection that leads to a large and stable connectivity between nodes. The distributed nature of decision making renders this agreement on a default channel selection a non-trivial task. The channel selection policy is expected to be simple as it is to be executed in real time and nodes should not be overcharged in computing complexity [4].

2 Problem Definition

In the protocol we propose, each node launches a channel probing and selection phase when jamming is detected on the control channel in use. During this phase the nodes iteratively perform a channel selection scheme until some stopping rule is satisfied.

In order to introduce the distributed channel selection scheme, some mathematical notation is required. For ease of exposition, we assume that devices are equipped with a single wireless transceiver (the mathematical framework can be easily extended to cover the case with nodes with multiple radios). Let V denote a set of n nodes deployed in a compact subset of the Euclidean plane.

Let S_i denote the set of channels available for node i's utilization. Each node $i \in V$ is autonomous in deciding in which channel to operate, say $s_i \in S_i$. Let us denote by $\mathbf{s} = (s_1, s_2, \ldots, s_n) \in \prod_{i=1}^{n} S_i = \mathbf{S}$ a vector of channel selections by all nodes. Let $\mathcal{N}(i, \mathbf{s})$ denote the neighborhood of i under joint channel selection $\mathbf{s} \in \mathbf{S}$. In words, this is the set of nodes, that under current jamming conditions and joint channel selection $\mathbf{s} \in \mathbf{S}$, can effectively communicate with node i in "one hop".

Let the potential $P(\mathbf{s})$ of a channel allocation be defined as:

$$P(\mathbf{s}) = \sum\nolimits_{i \neq j} 1_{(i,j)}(\mathbf{s})$$

where $1_{(i,j)}(\mathbf{s}) = 1$ if nodes i and j can effectively communicate (by possibly multi-hopping) under joint channel selection $\mathbf{s} \in \mathbf{S}$ and current jamming conditions,

$1_{(i,j)}(\mathbf{s}) = 0$ otherwise. This is a measure of network's connectivity given the channel selection by nodes. We are interested in solving the optimization problem

$$\max_{\mathbf{s}\in\mathbf{S}} P(\mathbf{s}) \tag{P}$$

Our aim is to compute an approximate solution to problem (P) in a distributed fashion, by only making use of local information. Let us also define a total 'payoff' to node i, say $r_i(\mathbf{s}) + V_i(\mathbf{s})$, associated with the joint profile $\mathbf{s} \in \mathbf{S}$ where:

$$r_i(\mathbf{s}) = \sum_{j\in\mathcal{N}(i,\mathbf{s})} 1_{(i,j)}(\mathbf{s}) = |\mathcal{N}(i,\mathbf{s})|$$

$$V_i(\mathbf{s}) = \sum_{j\in V-\mathcal{N}(i,\mathbf{s})} 1_{(i,j)}(\mathbf{s})$$

where $|\mathcal{N}(i,\mathbf{s})|$ is the cardinality of the neighborhood $\mathcal{N}(i,\mathbf{s})$ and $V - \mathcal{N}(i,\mathbf{s})$ stands for set difference. Intuitively, $r_i(\mathbf{s})$ is a measure of local connectivity while $V_i(\mathbf{s})$ measures multi-hop connectivity. Let us further denote by $(\tilde{s}_i, \mathbf{s}_{-i})$ the joint profile of channel selections in which node i chooses $\tilde{s}_i$ and all other nodes choose a channel in accordance with $\mathbf{s}$. Note that

$$P(\tilde{s}_i, \mathbf{s}_{-i}) - P(s_i, \mathbf{s}_{-i}) \ = r_i(\tilde{s}_i, \mathbf{s}_{-i}) + V_i(\tilde{s}_i, \mathbf{s}_{-i}) - [r_i(s_i, \mathbf{s}_{-i}) + V_i(s_i, \mathbf{s}_{-i})]$$

Suppose joint channel allocation $\mathbf{s}$ satisfies

$$s_i \in \arg\max_{\tilde{s}_i\in S_i} \{r_i(\tilde{s}_i, \mathbf{s}_{-i}) + V_i(\tilde{s}_i, \mathbf{s}_{-i})\} \tag{1}$$

Thus, this joint channel selection is in a sense a 'local' optimal solution, as no individual node can achieve an improvement of the value of $P(\mathbf{s})$ by switching to a different channel. Let the history of joint channel choices up time t be denoted by $\{\mathbf{s}^0, \mathbf{s}^1, \ldots, \mathbf{s}^{t-1}\}$. Let λ_M^t denote the empirical distribution of joint channel choices within the last $M < t$ iterations. This M-truncated empirical distribution can be used to construct an approximation for the empirical average of local connectivity, say $E_t[r_i]$, as follows:

$$E_t[r_i] = \sum_{\mathbf{s}\in\mathbf{S}} r_i(\mathbf{s})\lambda_M^t(\mathbf{s})$$

In a similar manner, an approximation to the expected payoff for node i given a selection $\tilde{s}_i$, can be obtained by adding the following truncated averages:

$$E_t[r_i(\tilde{s}_i, \mathbf{s}_{-i})] = \sum_{\mathbf{s}\in\mathbf{S}} r_i(\tilde{s}_i, \mathbf{s}_{-i})\lambda_M^t(\mathbf{s})$$

$$E_t[V_i(\tilde{s}_i, \mathbf{s}_{-i})] = \sum_{\mathbf{s}\in\mathbf{S}} V_i(\tilde{s}_i, \mathbf{s}_{-i})\lambda_M^t(\mathbf{s})$$

We propose an algorithm in which node i chooses a channel at time t as follows:

$$s_i^t \in \arg\max_{\tilde{s}_i\in S_i} \{E_t[r_i(\tilde{s}_i, \mathbf{s}_{-i}) + V_i(\tilde{s}_i, \mathbf{s}_{-i})]\} \tag{2}$$

Note that the computation of (2) requires access to overall information of the channel choices by *all* nodes in the network. This goes against our intention to construct a fully distributed algorithm. Let us construct a localized “proxy” for $V_i(\mathbf{s})$:

$$v_i(\mathbf{s}) = \sum\nolimits_{j \in \mathcal{N}^2(i,\mathbf{s})} 1_{(i,j)}(\mathbf{s})$$

Where $\mathcal{N}^2(i, \mathbf{s})$ is the 2-hop neighborhood of node i, i.e.

$$\mathcal{N}^2(i,\mathbf{s}) = \bigcup\nolimits_{j \in \mathcal{N}(i,\mathbf{s})} \mathcal{N}(j,\mathbf{s}) - \mathcal{N}(i,\mathbf{s})$$

In words, $v_i(\mathbf{s})$ is a measure of 2-hop connectivity. In order to implement a distributed algorithm, we substitute rule (2) for

$$s_i^t \in \arg\max_{\tilde{s}_i \in S_i} \{E_t[r_i(\tilde{s}_i, \mathbf{s}_{-i}) + v_i(\tilde{s}_i, \mathbf{s}_{-i})]\} \tag{3}$$

The updating rule for the empirical distribution is

$$\lambda_M^{t+1}(\mathbf{s}) = \lambda_M^t(\mathbf{s}) + \frac{1}{M}(1_{\{\mathbf{s}^t = \mathbf{s}\}} - 1_{\{\mathbf{s}^{t-M} = \mathbf{s}\}}) \tag{4}$$

where $1_{\{\mathbf{s}^t = \mathbf{s}\}}$ is the indicator function of the event $\mathbf{s}^t = \mathbf{s}$. Now suppose $\lambda_M^t(\mathbf{s}^*) \to 1$ for some $\mathbf{s}^* \in \mathbf{S}$. From (3) it follows that

$$s_i^* \in \arg\max_{\tilde{s}_i \in S_i} \{r_i(\tilde{s}_i, \mathbf{s}_{-i}^*) + v_i(\tilde{s}_i, \mathbf{s}_{-i}^*)\}$$

In this sense, if $\lambda_M^t(\mathbf{s}^*) \to 1$ the algorithm is able to identify an approximately ‘locally’ optimal solution (in the sense formalized in (3)).

3 Performance Testbed

Our testbed consists of a number nodes equipped with one or two radios located in a plane (N_1 with one radio and N_2 with two). In order to account for co-located networks, a number (K) of jamming sources are present. Each jamming source has one channel and an influence area in which the respective channel is considered jammed. In our stylized model, this area is circular and will be defined by a given radius. Fig 1 represents a typical scenario with 100 nodes (*) equipped with one radio, 10 nodes equipped with two radios (◇) and 3 jamming sources (o). According to their nature, nodes should select one or two channels (in the case of nodes equipped with two radios) among a group of L channels.

In order to model possible changes in the transmission power of the co-located network devices, the influence radius of the jamming sources vary after every channel selection, according to a given distribution. Homogeneous scenarios are considered in section 3.2 and heterogeneous scenarios in section 3.3. Time varying conditions are implemented in both type of scenarios.

Notice that the nodes’ decisions are based on the last M channel selections of its 2-hop neighbors. Thus we say nodes have a memory size of M. When the

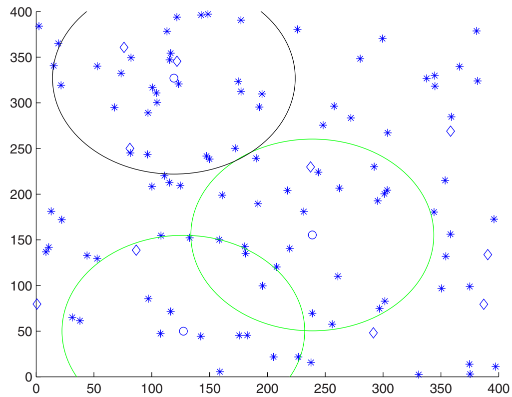


Fig. 1. Typical Scenario

jamming sources follow a given behavior pattern, having large values of memory will lead to a better knowledge of the jamming sources. On the other hand when the jamming sources drastically change their influence area, large values of M will lead to a non reliable knowledge of the jamming sources behavior. We expect to find a value of M that leads to an advantageous channel selection according to the historical behavior of the jamming sources, compromising as less as possible the adaptability to new conditions. This policy should prevent shifting caused by a fast changing environment and also facilitate a coordinated channel switch in case the actual channel becomes jammed.

3.1 Implementation of Distributed Channel Selection

In this section we discuss the implementation of the scheme formalized in (3) and (4). After each selection opportunity (i.e. (3) above), nodes undertake a probing mechanism in order to discover the selection of their neighbors. In this way, they are able to implement (4), albeit in a local fashion. Different approaches can be used in this probing phase, but in our testbed we assume that nodes are able to obtain information about the channel selection of its neighbors.

The M-truncated empirical distribution of the number of nodes within node's i's neighborhood using channel ℓ at time t will be denoted $\lambda_{i,\ell}^t$. Every node stores all of this information, as shown in the following table (for the case of 4 neighbors and 2 channels)

	# nodes n			
Channel ℓ	1	2	3	4
1	$\lambda_{i,1}^t(1)$	$\lambda_{i,1}^t(2)$	$\lambda_{i,1}^t(3)$	$\lambda_{i,1}^t(4)$
2	$\lambda_{i,2}^t(1)$	$\lambda_{i,2}^t(2)$	$\lambda_{i,2}^t(3)$	$\lambda_{i,2}^t(4)$

At each iteration, every node calculates a weighted average use for each of the channels based on the frequencies ($\lambda_{i,\ell}^t$) and the number of neighbors who used the channel. Let $E_{t,i}(\ell)$ be the weighted average that node i computes for channel ℓ after t iterations:

$$E_{t,i}(\ell) = \sum_{n=1}^{|S_i|} n\lambda_{i,\ell}^t(n)$$

To account for the channel selection choices of a node's neighbors, an extended weighted average is computed as follows:

$$\bar{E}_{t,i}(\ell) = \frac{1}{|\mathcal{N}(i)|}\left[E_{t,i}(\ell) + \sum_{j\in\mathcal{N}(i)} E_{t,j}(\ell)\right]$$

The channel with the greatest $\bar{E}_{t,i}(\ell)$ is chosen as the "best channel" for that particular iteration. Notice that these criteria considers the channel selection of the 2-hop neighborhood as stated in Section 2. The process will end only when a "stopping rule" is satisfied. The "stopping rule" states that a channel will be selected as the optimal channel only when the empirical frequency of the selection of that particular channel over the last M selection choices, is greater than a given threshold, say τ. The stopping rule is denoted as:

$$\frac{\#\text{ times channel } \ell \text{ has been chosen}}{M} > \tau$$

When this rule is satisfied, the node will settle for what is believed to be the overall best default or control channel.

The introduced scheme using the stopping rule, was successfully implemented by Manthe et al. [1] in a lab environment using 4 SunSPOTs and 2 channels. In our testbed simulations , we focus in the probing and channel selection phase. The following subsections present the results obtained with the introduced selection scheme for the probing and selection phase in homogeneous and heterogeneous scenarios. In the presented results we repeat the selection process for a given number of channel selection opportunities as specified in each scenario. This way we can measure a transit time and also a instability in the channel selection if the rule is applied indefinitely. With this measures we can evaluate the proposed scheme. However, the stopping rule, though not implemented, can be seen to provide an effective criteria to switch back to a normal operation state.

3.2 Homogeneous Scenarios

Scenarios with time varying and homogeneous conditions are expected if the power of the jamming sources is high enough, so that its respective channel will be jammed in most of the area where the network is deployed. In homogeneous scenarios *all* nodes will have the same available channels. The time varying conditions for these scenarios will be considered by giving to each channel l a probability p_l of being available after each selection opportunity, this probability is fixed and does not depend on previous availability.

In order to test the performance of the proposed scheme, tests were executed in a scenario consisting of 700 nodes randomly located in an area of 400mx400m in which neighborhoods are defined by a radius of 30m. Three channels are available with respective probabilities of $p_1 = 0.1$ $p_2 = 0.3$ and $p_3 = 0.5$. Notice that for this type of scenarios the jamming sources can be located anywhere as long as their influence area covers the whole area of the network.

In the test the following performance indicators were measured:

– Connectivity (%): The number of nodes in the largest connected network as a percentage of the maximum achievable. Note that as the location of the nodes is random, there is no guarantee that all of them can be connected. For example, it can happen that a group of 20 nodes are isolated because of their random location. Thus the maximum network size (100%), contains 680 nodes instead of 700.
– Transit time: The time it takes for the network to achieve 80% of its maximum size. This time is measured in channel selection opportunities.
– Channel selection instability: The number of nodes that change their channel in a channel selection opportunity.

Results are presented in Table 1 and Figures 2 and 3. The values in tables and graphs represent the mean of 100 random scenarios with 100 channel selection opportunities for each scenario. For statistics of the network connectivity and channel selection instability, only values after the transit time were considered.

Table 1. Performance indicators in homogeneous scenarios

M	**1**	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
Connectivity (%)	39	52	69	66	70	67	69	65	65	66	67
Transit time	8.05	5.7	5.95	5.55	6.25	6.5	5.35	5	5.85	6.05	5.95
Ch. Sel. Inst.	370	183	50	30	18	18	15	16	18	16	15

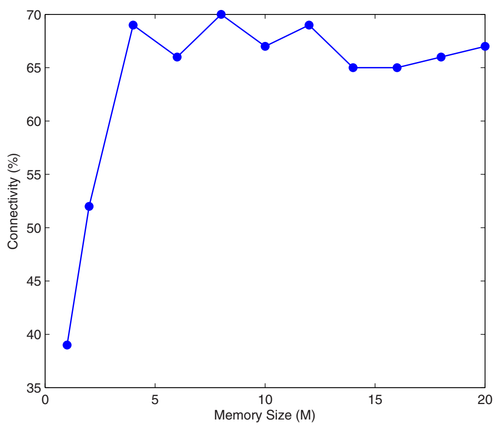


Fig. 2. Connectivity vs. Memory Size

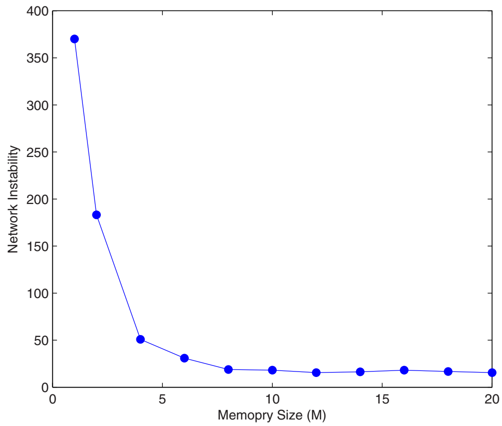


Fig. 3. Network Instability vs. Memory Size

From the results, it can be concluded that nodes with similar but changing channel conditions can be helped with memory structures. For this type of scenarios the memory structures let the nodes to massively select the channel with the highest expected availability; leading into a wide and stable connectivity. Notice that the transit time is decreased from 8 when $M = 1$ to values close to 6 when $M > 1$. This indicates that if the scenario drastically change (e.g. the most widely used channel becomes permanently jammed), the network is expected to adapt to the new conditions in $6 + M$ selection opportunities. Thus it can be said that memory endows the network with self-healing capability for temporary channel damage, but very large values of memory size (M) will slow the adaptation to a completely new scenario.

3.3 Heterogeneous Scenarios

Heterogeneous scenarios are those in which channels are jammed locally. Thus, all of the nodes will not necessarily have the same available channels. Fig. 1 is an example of a heterogeneous scenario. Heterogeneous scenarios are expected if the power of the jamming sources is such that channels result jammed only in a sector of the area in which the network is deployed. The time varying conditions are due to changes on the power of the jamming sources. In our model this will be considered by making the radii of the jamming sources uniform random variables.

Heterogeneous scenarios, can be treated as several homogeneous scenarios. Consider the scenario in Fig. 4. In this figure, circles represent an area in which a particular channel is jammed, channel selection transitions can be expected between these areas. Suppose this is the case in the figure, where nodes can select between two channels (* and v). Suppose now that the source on the left, jams channel * and the one on the right jams channel v. Notice that for nodes

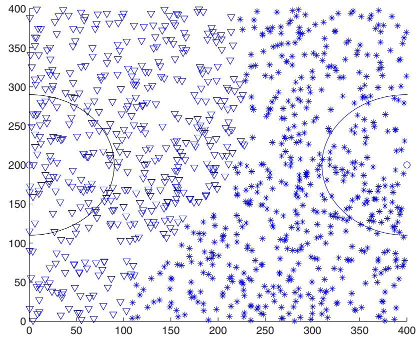


Fig. 4. Heterogeneous scenario as multiple homogeneous scenarios

on the left, channel v results a better option, and * is preferred by nodes on the right. This generates a transition zone as shown. Notice that nodes on the left side of the transition have different conditions to those on the right side. Thus two homogeneous zones are present in this scenario.

From the previous work we can say that memory structures will lead to connectivity between nodes inside a homogeneous zone, which does not imply connectivity with the rest of the network.

In heterogeneous scenarios, regions with different channel preferences will show up as a natural response to jamming sources. Complete uniformity is not achievable if there is at least one jamming source per available channel. By increasing the memory buffer (for larger values of M), we expect to obtain uniformity and stability in the channel selection inside each homogeneous zone. Thus we require the use of nodes equipped with two radios to connect this zones.

In order to test the performance of the policy in heterogeneous conditions, the scenarios shown in Figures 5 and 6 were considered. In the presented scenarios there are three channels and one jamming source per channel, in order

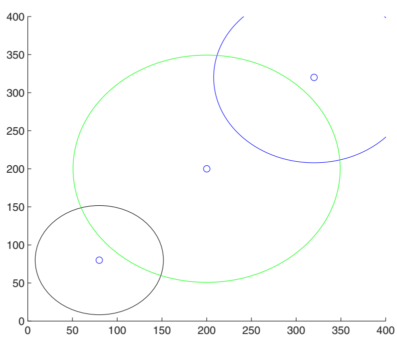


Fig. 5. Heterogeneous scenario 1

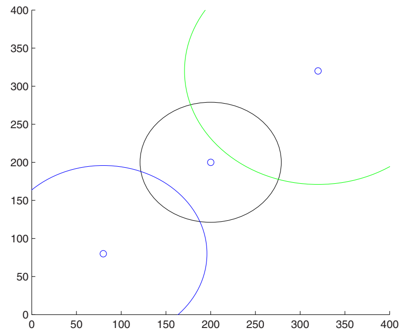


Fig. 6. Heterogeneous scenario 2

to guarantee transition zones. Every jamming source k has a different radius r_k. The first one has the smallest and the third one has the largest one. Thus, the first jamming source has the smallest influence area and the channel it damages is the most preferable by the system as it is available for most nodes.

The two scenarios are described as follows:

– Scenario 1: Grid Size = 400mx400m with the following jamming sources:
  1. Location=(80,80); $r_k \sim$ U(60,90)
  2. Location=(320,320); $r_k \sim$ U(90,120)
  3. Location=(200,200); $r_k \sim$ U(120,150)

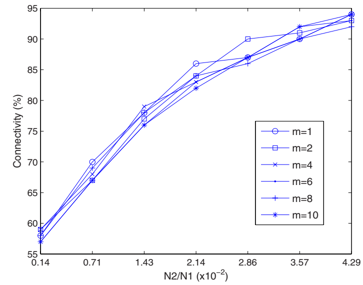
– Scenario 2: Grid Size = 400mx400m with the following jamming sources:
  1. Location=(200,200); $r_k \sim$ U(60,90)
  2. Location=(80,80); $r_k \sim$ U(90,120)
  3. Location=(320,320); $r_k \sim$ U(120,150)

Note that there is a clear difference among these scenarios; in the first one, the jamming source that jams the most advantageous channel is in a corner, while in the second one it is in the middle. This will let us notice if there is any difference when the jamming source is on the borders or inside the area in which the network is deployed.

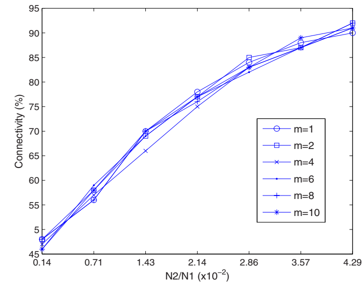
Tests were executed in both scenarios with 700 nodes equipped with a single radio ($N1$) changing the number of nodes equipped with two radios ($N2$) and memory size (M). The performance indicators are the same as in homogeneous scenarios (Sec. 3.2), but in this case we assume the maximum network size to be equal to the number of nodes.

Results are presented in Figure 7. The values in the graphs represent the mean of 200 trials, with 200 channel selection opportunities for each trial. One trial is characterized by a random location of the nodes. For the statistics of the connectivity and the channel selection instability, only values after the transit time were considered.

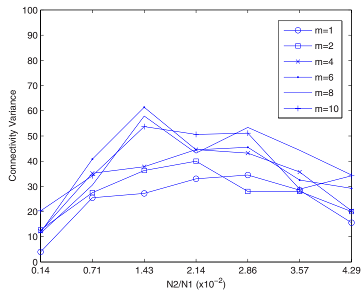
Again, the memory has an effect on reducing the channel selection instability. From Figure 7 it can be said that the use of nodes equipped with two radios



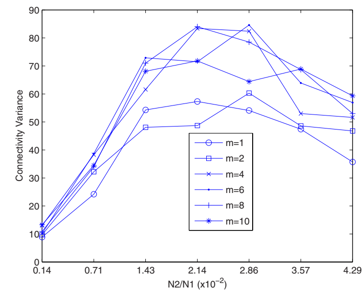
(a) Connectivity Scenario 1



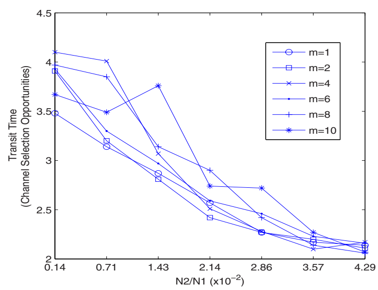
(b) Connectivity Scenario 2



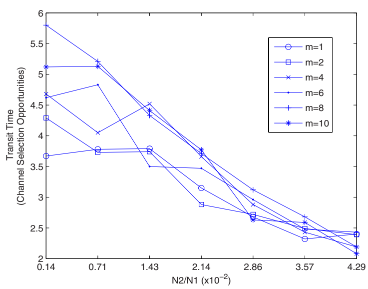
(c) Connectivity Variance Scenario 1



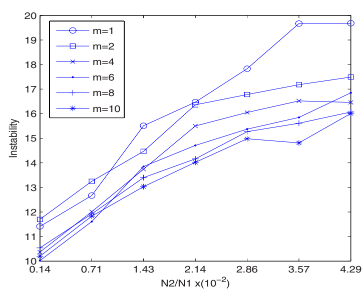
(d) Connectivity Variance Scenario 2



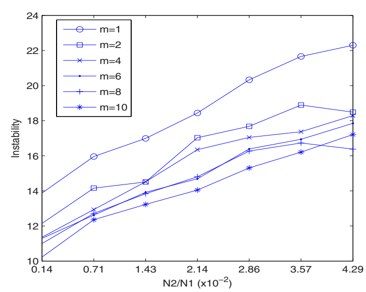
(e) Transit Time Scenario 1



(f) Transit Time Scenario 2



(g) Instability Scenario 1



(h) Instability Scenario 2

Fig. 7. Performance Indicators for Heterogeneous Scenarios

increases the connectivity and reduces the transit time but it also increases the instability. By increasing the $N2/N1$ ratio from 1/700 to 3/70, the expected connectivity is increased from 57% to 92% in scenario 1 and from 47% to 90% in scenario 2. The transit time is reduced for both scenarios, from values close to 3.7 to values close to 2 for scenario 1 and from values close to 4.5 to values close to 2.2 for scenario 2. It can be noticed that as the $N2/N1$ ratio starts to increase, so does the connectivity variance. This is because the random location of the nodes creates situations in which connectivity can either be helped or not by these nodes with two radios. At some point (close to $N2/N1 = 0.02$) the density of nodes equipped with two radios is such that if some nodes are not helping the connectivity some others will do it and the variance starts to decrease.

Both scenarios achieve different results for connectivity and transit time, but those differences are reduced as $N2/N1$ increases. Better results are generally obtained when the jamming source is in the border of the network area.

4 Conclusion and Future Work

Local information and memory structures can be used to implement a default channel selection policy for Ad-hoc networks. This policy can be helpful in situations where the otherwise predefined control channel can be jammed.

For homogeneous scenarios the introduced policy increases connectivity and stability as memory increases, but having a memory size larger than 8 does not seem to bring additional benefits and it will increase the adaptation time to new conditions.

It can be noticed that for heterogeneous scenarios as considered here, memory wont cause connectivity between areas with different channel conditions. In order to increase connectivity in such scenarios, the use of nodes equipped with two radios is required. The use of these nodes is also helpful in decreasing the transit time, but it increases the instability of the network. Further work can be done in order to assess the location of the nodes equipped with two radios.

It was found that jamming sources in the border of the network area are less harmful than those located in the center. This differences decrease as the density of nodes equipped with two radios increases.

Finally it can be said that the introduced policy is scalable since each node only has to interact with nodes that are up to two hops from itself.

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