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A centrality-based topology of ICN for wireless mesh networks

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ABSTRACT

Nodes in wireless multi-hop networks establish links with their neighbours, which are used for data transmission. In general, in this kind of networks every node has the possibility of acting as a router, forwarding the received packets when they are not the final destination of the carried data. Due to the routing protocol procedures, when the network is quite dense the overload added by the routing management packets can be very high. To reduce the effects of this overload a topology control mechanism can be used, which can be implemented using different techniques. One of these techniques consists of enabling or disabling the routing functionality in every node. Many advantages result from selecting just a subset of nodes for routing tasks: reduction of collisions, protocol overhead, interference and energy consumption, better network organization and scalability. In this paper, a new protocol for topology control in wireless mesh networks is proposed. The protocol is based on the centrality metrics developed by social network analysts. Our target network is a wireless mesh network created by user hand-held devices. For this kind of networks, we aim to construct a connected dominating set that includes the most central nodes. The resulting performance using the three most common centrality measures (degree, closeness and betweenness) is evaluated. As we are working with dynamic and decentralized networks, a distributed implementation is also proposed and evaluated. Some simulations have been carried out to analyze the benefits of the proposed mechanism when reactive or proactive routing protocols are used. The results confirm that the use of the topology control contributes to a better network performance.

1. Introduction

Smart environments, smart devices, smart interaction, computing anytime and anywhere, ..., the accelerated development of information technologies and mobile devices results in people and/or “things” increasingly dependent on the online services offered through the Internet. In such scenario, Wireless Mesh Networks (WMNs) have evolved as a cost effective possible solution for user uninterrupted access to networking facilities. Valued features like robustness, reliability, easy deployment and maintenance, self-forming and self-configuration, make WMNs an important alternative to achieve an always-on connectivity. Among the three typical architectures of WMNs [1], the present work focus on the client meshing one. In this case, the end-user devices are able to simultaneously provide application interface, routing and network configuration capabilities. Nowadays, the most common hand-held device used by an increasing number of people is the smart phone. The evolution of such mobile devices with their variety of embedded sensors results now in a not only communication equipment, but a complete sensing system [2]. Numerous applications are emerging in many fields like health, traffic, human behavior, environment monitoring, social networking and commerce [2]. With this perspective it is entirely feasible to consider a WMN composed by mobile phone users moving around a city as a cost-effective complement to commercial cellular networks. One of the major concerns in this kind of devices is related to their energy consumption. Therefore, optimization techniques that aim to reduce it are always required [3].

Topology control techniques have been developed to improve the energy efficiency and the battery lifetime of a variety of networks. It also aims to reduce collisions, protocol overhead, and interference by means of a better control over the network connections and redundancy [4]. In general, there are three main types of topology control approaches [4]. First, power control techniques [5, 6], adjust the communication range of the wireless nodes by means of the transmission power of their transceivers. This way, nodes are able to better manage their neighborhood size, interference level, power consumption and connectivity. Secondly, power mode mechanisms [7, 8] control the active or sleep operation modes of the nodes to dispense with redundant stations and still achieve the desired connectivity. Finally, hierarchical clustering approaches [9, 10, 11] aim to construct an efficient virtual backbone for data forwarding by the selection of a connected dominating set (CDS). From graph theory, a CDS of a graph is a connected subset in which all the nodes that does not pertain at that subset have at least one adjacent neighbor inside the subset. Due to the reduced number of nodes developing routing task, the main advantages of this CDS-based topology control are: collisions, protocol overhead and energy consumption reduction, efficient network organization and scalability improvement. In this work we evaluate an alternative method for this last category of topology control based on social network analysis metrics.

In this context, thanks to the increasing availability of network maps which depicts the behavior of complex systems and the universality of their characteristics [12], network science appears as the renewed study of the structure and the dynamic behavior of a variety of networked systems [13]. Accordingly, social network analysts have developed an important set of measures and metrics which allow understanding the behavior and quantify the topology features of a diversity of networks [14]. Specifically, in this work we focus on centrality metrics developed to identify the most important actors (nodes) in a network by means of graph theory definitions and concepts.

In summary, the purpose of this work is to present and evaluate an alternative topology control mechanism based on centrality measures borrowed from social network analysis. This topology optimization has been applied to a client wireless mesh network formed with user hand-held devices.

The rest of the paper is organized as follows. In Section 2 we report and analyze the related work. Section 3 provides a background on centrality metrics. Section 4 presents and evaluates the proposed topology control mechanism. A performance evaluation has been carried out by means of simulations, taking into account both reactive and proactive routing protocols. The results are presented in Section 5. Finally, the conclusions and future works are summarized in Section 6.

2. Related work

Nowadays, the application of complex networks techniques and social network analysis concepts to improve the performance of wireless ad hoc networks is growing as a fertile research area [15]. Some recent works are summarized in the following. [16, 17, 18] apply the small world phenomena, re-popularized by [19], to reduce the average path length of the network. The basic idea of these proposals is to modify the physical topology of the network based on the social features of the underlying graph. The small world property (or low average path length) could be achieved either by the aggregation of long-ranged links [17] or by a combination of rewiring, deletion and/or addition of links/nodes [16]. Authors in [18] combine centrality measures with directional beamforming to create long-range links between more central nodes. The same authors extend their study to sparse highly partitioned networks in [20].

SimBet [21] is a routing protocol designed for delay-tolerant MANETs. It uses two social network analysis metrics (centrality and similarity) for message forwarding decisions. Betweenness centrality is selected to identify more suitable bridge nodes, and the similarity measure is used to find nodes that are closer to the destination neighborhood. A utility function combines the similarity and the betweenness utilities and allows adjusting the relative importance of them. For performance evaluation both utilities has been assigned the same importance. For their part, authors in [22] apply social network analysis metrics to detect critical nodes in a WMN. They show how network reliability substantially degrades when coordinated attacks are directed to highest centrality nodes. Simulations evince that nodes with high betweenness centrality exhibit a greater impact than nodes with high degree or closeness centrality. Authors also propose a socially-aware TDMA channel access scheduling algorithm. The main idea is to give higher priority (assigning more time slots) to nodes with high closeness centrality values. Simulations show important throughput improvements at the expense of increased delay.

The time-evolution of the topological characteristics of vehicular networks from the perspective of graph theory and social network analysis is the subject addressed in [23]. It is confirmed that relevant and useful information about the behavior of the VANETs could be inferred from the centrality metrics. The importance of nodes with high centrality values on the design of more efficient VANET protocols is also discussed.

A topology control algorithm for WSN based in edge betweenness centrality [24] is proposed in [25]. This metric is used to identify most relevant edges or links between nodes, regarding energy consumption. For each node, the aim of the proposal is to select a set of logical neighbors that minimize energy consumption and fulfill QoS requirements. Simulation results show better performance of this proposal in comparison with traditional topology control methods in terms of number of logical neighbors, energy consumption, latency and hit-ratio (percentage of served queries).

Authors in [26] propose a routing protocol based on a connected dominating set (CDS). A simple marking process is used to establish the initial CDS: a node is designed as gateway if it has at least two unconnected neighbors. This initial CDS is reduced by the application of rules based on the node IDs. An extension of the selective removal rules are presented in [9]. In this case the degree and the energy level of the nodes are considered to reduce the CDS and to achieve balanced energy consumption. In [27] Connected Dominating Sets with bounded diameters are taken into account. To construct these DS with the smallest size, authors propose and evaluate two centralized algorithms and one distributed version. On the other hand, given the fact that the transmission ranges of all network nodes are not necessarily equal, authors in [28] model the network by means of a Directed Graph and propose two different solutions for the case in which all the network links are bidirectional. A recent and extensive survey on energy-aware distributed topology control algorithms is presented in [4].

Many topology control mechanisms are intended to sensor networks in which the dominant data flow traditionally goes from the sensor nodes to the sink. In this work we focus on mesh networks in which it is more common that every node may be origin or destination of the data flow. On the other hand, we evaluate the use of centrality metrics which are calculated both in a centralized or a distributed way. Besides, we propose and evaluate a distributed implementation of the router selection mechanism, as well as different possibilities to achieve total network connectivity.

3. Background on centrality

Centrality is one of the most useful mathematical measures developed by social network analysts to capture the structural properties of social relationships. It aims to identify the most important actors/vertices within a graph that represents any physical network. Centrality metrics could be based mainly on the degree of a vertex (number of edges connected to it [14]) or on the geodesic distances between them [15]. In the following we present a summary of the three most useful centrality metrics.

Degree Centrality is the simplest centrality metric. It is defined as the number of edges (links) attached to a vertex (node) [29]. In a WMN the degree centrality of a mesh station can be viewed as the number of one-hop neighbors with which it has been established a peer link. This centrality is generally scaled by the number of nodes N in order to be a measure independent of the network size. Then, the degree centrality Dc_i for the node i is computed as:

$$Dc_i = \frac{\sum_{j=1}^{N} x_{ij}}{N-1} \qquad (1)$$

where x_{ij} = 1 if there is a link between node i and node j and x_{ij} = 0 otherwise. In some networks, it could result logical to think that a node which has links to many others (high degree centrality) has greater impact in the network than nodes with few links.

Closeness Centrality aims to identify nodes that spread messages in shorter time [29]. For that, this metric uses the concept of geodesic path, which is the path with the shortest distance between two nodes. The closeness centrality Cc_i for node i is computed as:

$$Cc_i = \frac{N-1}{\sum_{j=1}^{N} d_{ij}} \qquad (2)$$

where i 6= j and d_{ij} is the geodesic distance between nodes i and j. In social networks, actors with high closeness centrality can communicate their ideas faster than actors with lower closeness centrality [14].

Betweenness Centrality measures the proportion of shortest paths between any pair of nodes passing through a specific node [30]. The control over communications, connections and information flows could be dominated by nodes with high betweenness centrality. The betweenness centrality Bc_i for node i is computed as:

$$Bc_i = \sum_{j=1}^{N} \sum_{k=1}^{j-1} \frac{g_{jk(i)}}{g_{jk}} \qquad (3)$$

where i 6= j 6= k, g_{jk} is the total number of geodesic paths between node j and k, and $g_{jk(i)}$ is the number of geodesic paths between node j and k that pass through node i.

4. Topology control mechanism and centrality evaluation

In this section we propose and evaluate a topology control mechanism based on centrality metrics. We start with a description of the dynamic wireless mesh network subject to analysis. Then, a centralized implementation and evaluation is presented in order to identify the most appropriate centrality metric for our purpose. At this point, different considerations are done for a practical distributed implementation. Finally, the practical implementation of the protocol is presented.

Scenario under consideration

For the experimental evaluation we have considered a dynamic wireless mesh network generated by the ns-3 network simulator [31]. The mesh stations (nodes) are based on the IEEE 802.11s amendment which is currently incorporated in the IEEE 802.11-2012 standard [32]. The simulation scenario consists of 100 mesh stations uniformly distributed in a 1040 x 520 m area. According to [33] these values guarantee minimal quality criteria for stringent protocol evaluation. Specifically, the average shortest-path hop count is greater than four hops (to avoid that most of the data packets be interchanged just among one or two-hop neighbors) and the average network partitioning is lesser than 5% (to avoid an excessive number of isolated nodes). The nodes move according to a random walk 2D mobility model inside the rectangular bounds. Each node moves with a speed chosen randomly between 2 and 4 m/s. The direction and speed of the nodes are updated after they have moved 100 m. These values are selected with the assumption that the mobile nodes are transported by people moving around a segment of a city. The initial node positions and their trajectories are shown in Fig. 1. For the wireless channel, the log-distance propagation loss model has been considered.

According to [32], before the transmission of data frames, mesh stations must create and maintain a logical topology using the mesh peering management protocol. Every mesh station discovers its mesh neighbors (peers) by means of beacon frames which are periodically sent. When a new neighbor has been discovered, the mesh station starts a peer link open handshake. It begins with a Peering Open management frame that contains mesh configuration parameters. If the target station agrees with such parameters, it responds with a Peering Confirm frame. The same procedure is executed in the opposite direction to ensure bidirectional links. Only if the complete handshake procedure is successfully executed, a peer link is established between two mesh stations. Standard does not specify why or when a peer link must be closed. The ns-3 mesh networking implementation [34] triggers a close peer link procedure when the number of successive lost beacons achieves a maximum configurable value. By default this threshold is set to 5. If there is an active data flow, the ns-3 mesh model also executes a close procedure when a station is unable to transmit to a peer a number of successive frames. This value is also set by default to 5.

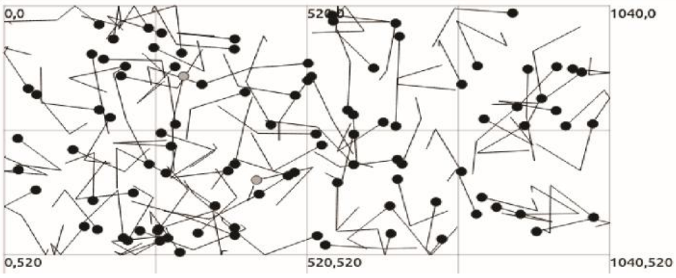


Figure 1: Initial node positions and their trajectories.

Centralized implementation

Based on the presented scenario, first of all we have analyzed several snapshots of the mesh network dataset taken every 5 s. For each snapshot and for each node inside the network we compute its degree, closeness and betweenness centrality metrics. ORA [35] and UCINET [36] software have been used to centrality calculations, while network graphics are done with ORA. With the centrality values, we are able to rank and identify the most central nodes from those three points of view. Fig. 2 shows this ranking for one specific snapshot (at time=5 s) and for the three metrics. Blue nodes represent the most central stations and the red ones the least. As expected, Fig. 2 confirms that different nodes are selected as most central ones for each different metric. This is because each metric evaluates a very different parameter and there is no relationship among them.

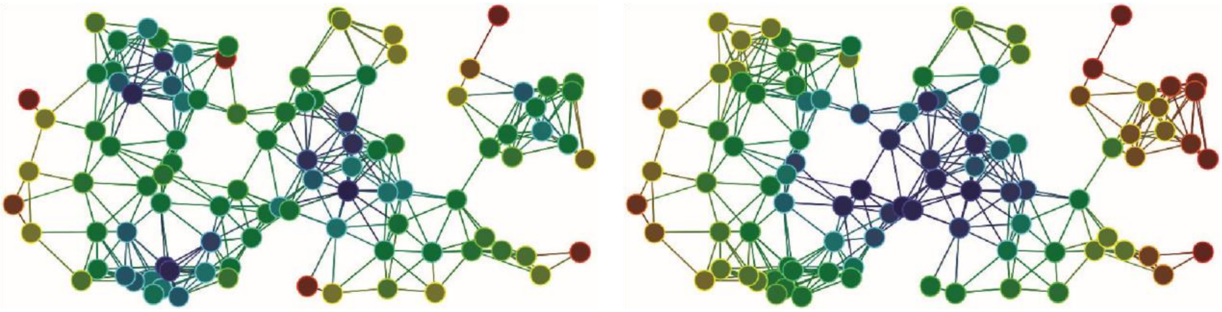
As previously said, to reduce the complexity, communication overhead and energy consumption of the network, we want to find a subset of mesh stations that forms a connected dominating set. So, instead of allowing each node to perform routing tasks, we choose only the most central stations to do it. In a roughly first approach, we limit the number of routers to the forty (40%) most central nodes for each network dataset and for each centrality metric. We virtually remove all the links between non-router stations and keep all the other. If a non-router station has a link with more than one router, we keep all these links in order to preserve network resilience and to enable future load balancing and fair energy consumption improvements. Fig. 3 shows the resulting virtual topology for each centrality metric and for the same snapshot considered in Fig. 2. Blue nodes represent the selected routers, the green are the mesh stations that have a link with at least one router and the red represents the isolated nodes.

To determine which of the centrality metrics is the most suitable for our topology control application, we compare (for all the network datasets and for the three centrality metrics) the resulting network fragmentation *F*, that is, the proportion of nodes in a network that are disconnected from each other. It can be computed in an efficient way through the following equation [37]:

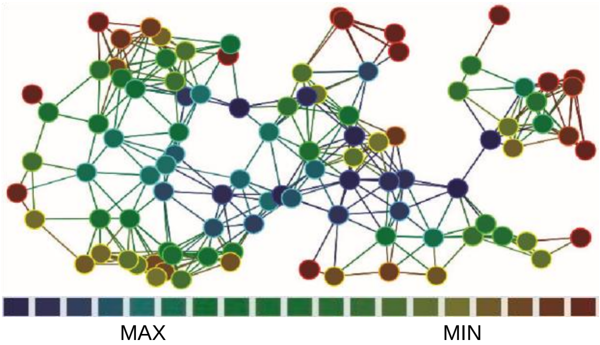
$$F = 1 - \frac{\sum_k s_k (s_k - 1)}{N (N - 1)} \qquad (4)$$

where s_k is the number of nodes of the k^{th} component of the graph that represents the network.

Fig. 4 shows the time-evolution of the network fragmentation for the three centralities and for two different percentages of selected routers. As can be seen, the values for the betweenness centrality are considerably lesser than for the other two centrality metrics. And as expected, for all the centralities the fragmentation decreases when a greater percentage of nodes are selected as routers. Besides, Table 1 summarizes the average, the standard deviation and the maximum values for this measure. As can be observed, the mean and maximum fragmentation using the betweenness centrality are much lesser than with the other two options. Furthermore, the betweenness-based selection exhibits a more stable (confident)

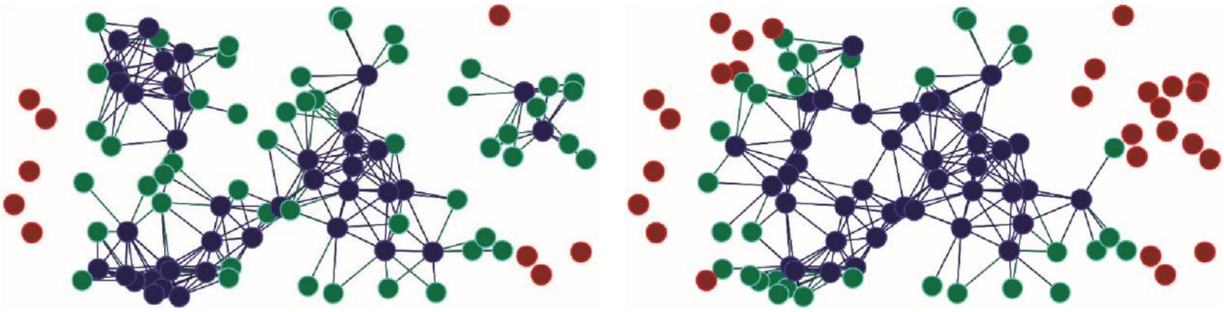


(a) Degree centrality (b) Closeness centrality

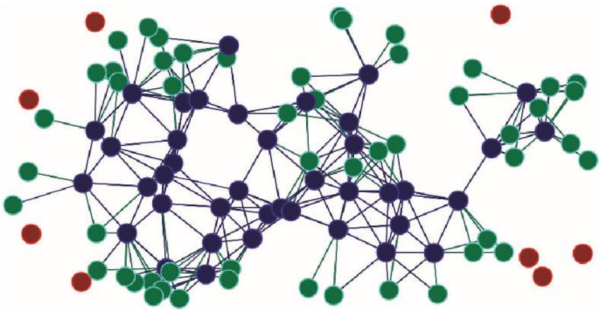


(c) Betweenness centrality

Figure 2: Centrality metrics for one of the WMN snapshots.



(a) For degree centrality(b) For closeness centrality



(c) For betweenness centrality

Figure 3: Resulting topology with the 40% most central nodes as routers.

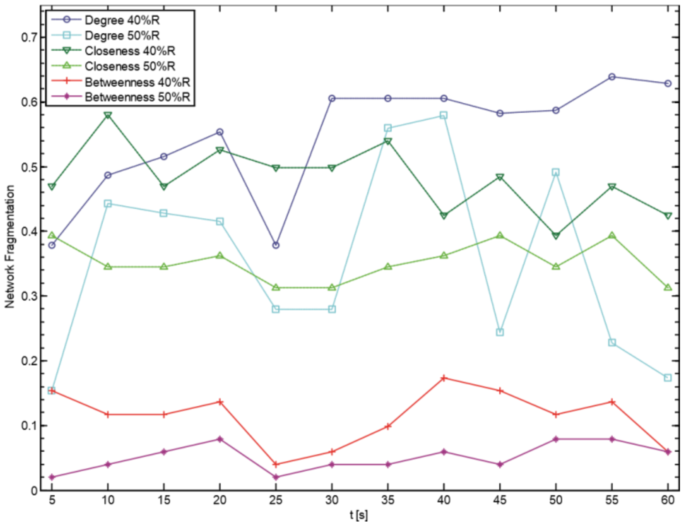


Figure 4: Time evolution of the network fragmentation for the three centrality metrics and for 40 and 50% selected routers.

Table 1: Summary of the resulting network fragmentation and the number of links per connected node values.

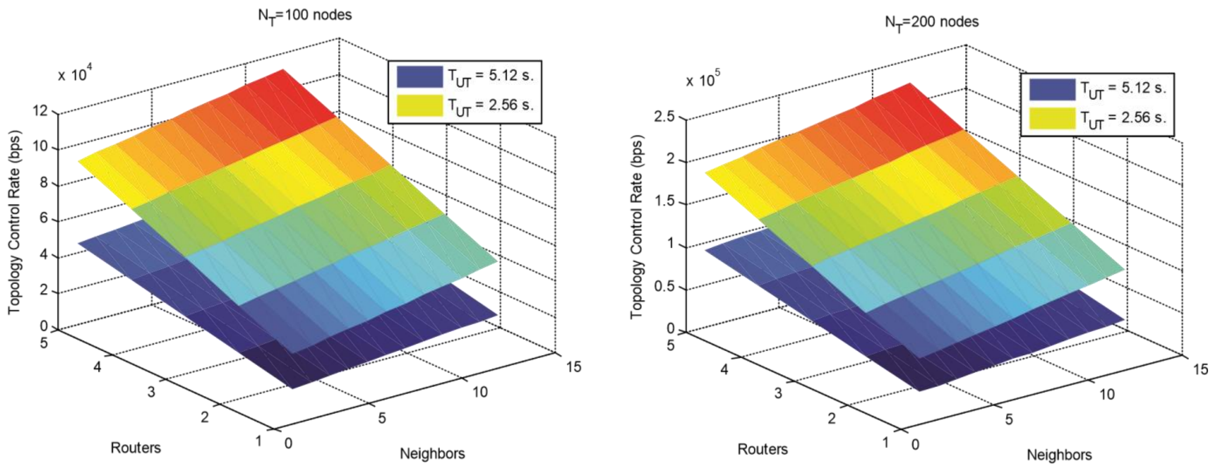
Centrality	**%R**	**Network Fragmentation**			**Links per connected node**		
		Mean	SD	Max	Mean	SD	Max
Degree	40	0.547	0.090	0.639	7.405	0.839	8.635
	50	0.356	0.148	0.579	7.226	0.424	8.158
Closeness	40	0.481	0.053	0.580	6.511	0.371	7.205
	50	0.352	0.030	0.393	6.796	0.362	7.395
Betweenness	40	0.113	0.042	0.173	5.430	0.212	5.691
	50	0.051	0.021	0.079	6.123	0.299	6.573

behavior since its standard deviation is the least among the three options. Another metric that we use to compare the three different centralities is the average number of links which remain active after router selection per connected node. Again, betweenness centrality exhibits better performance since on average it requires lesser number of links for each node that remains connected. The maximum and the standard deviation of this metric are also the least among the analyzed options. Other centrality metrics like hub, authority, and bridging have also been evaluated and for all the cases the betweenness centrality exhibits better outcomes. Based on this, we can conclude that by far the betweenness centrality is the metric that better identifies the subset of nodes that should be considered as routers.

5. Performance evaluation

In this section, extensive simulations have been carried out to evaluate the performance of WMNs with the proposed centrality based topology control mechanism. For the evaluation, we consider the following metrics and parameters:

- The rate of routing management messages.
- The total number of forwardings per successfully received packet.
- The network efficiency in terms of packet delivery ratio.



(a) 100-nodes mesh network(b) 200-nodes mesh network

Figure 12: Topology control protocol bit rate for different N_T and TUT values.

- The energy consumed on a node by node basis.
- The end-to-end packet delay.
- The transmission bit-rate savings taking into account the overload added by the topology control protocol.

We take into account the two routing modes of the hybrid wireless mesh protocol (HWMP). In the reactive on-demand mode, a source mesh station starts a path discovery procedure only when it has a data packet to send to any destination. This operation mode is more suitable for peer to peer communication inside the mesh network. On the other hand, proactive mode is more appropriate when a single or a few mesh stations are configured as gateways for external communications and therefore they are the targets of most of data connections. In this mode, a single or few mesh stations are configured to be path tree roots, and they periodically initiate path selection procedures.

All simulations are done with the ns-3 network simulator. To model the mesh network, we have used one of the network snapshots described in Section 4.2. It consists of 100 IEEE 802.11s-based mesh stations randomly distributed in a 1040 x 520 m rectangular area. For all the experiments, we compare the performance of the mesh network when all the station are configured as routers with the case that only 40 most central nodes are selected as routers (from now they will be called the All R and Top 40R topologies for convenience). All the simulations are 500 s long and we have carried out 100 statistically independent runs for every experiment. The average of these runs with 95% confidence interval is shown for all the results.

6. Conclusions

In this paper we have evaluated the feasibility of using the centrality metrics from social network analysis to create a topology control mechanism based on a connected dominating set. Specifically, for a dynamic wireless mesh network formed by user hand-held devices, we have proposed and evaluated some mechanisms to select which of those devices must act as routers, forwarding the packets received from other handheld to their destination. The mechanism implementation has been proposed in two ways, centralized and

istributed. For the centralized approach, we have evaluated the three most common centrality measures: degree, closeness and betweenness centrality. In all those cases, the more central nodes have been selected to form the backbone. The experimental analysis has shown that the network fragmentation using the betweenness centrality is considerably lesser than the resultant with degree or closeness centralities. Thus, it is possible to conclude that by far the betweenness centrality is the metric that better identifies the stations that should be considered for routing tasks. In the second place, taking into consideration that a centralized implementation could be unfeasible in most scenarios, a distributed implementation has been proposed. In this case only the betweenness centrality has been considered. To distribute the responsibility, the concept of the egocentric network perspective of each station is needed. That is, every station computes its own centrality knowing only its own established links (neighbors). Besides, due to the dynamic and time evolving nature of the network with which we are dealing, we also discuss and evaluate different distributed mechanisms to select the central stations that will act as routers. First of all, every station selects the node in its neighborhood with the highest centrality. This mechanism works well in most cases if a minimum density of nodes exists. Then again, the complete connectivity is not assured. To guarantee that connectivity, some approaches have been proposed and compared in terms of overload and effectiveness. As a future line of work, the minimum number of routers per neighborhood needed to guaranty a desired connectivity in the distributed implementation will be studied.

The effectiveness of this centrality-aware topology control protocol has been verified through extensive simulations. The evaluation has been carried out for both reactive and proactive path selection modes. For all the studied cases the efficiency of the network was improved or at least remain equal but always with a considerably lower amount of transmission/reception energy consumption. Another common factor in all the simulation results is the reduction of the packet end-to-end delays. This is a direct consequence of the global bit-rate savings which implies lower channel contention. The reduction of the number of mesh stations involved in the path selection procedure also improves the scalability when the variability of the network demands faster path updates. Finally, we confirm that greater energy savings are obtained in the proactive path selection case because of the greater overhead present with this operation mode.

As current and future lines of work we are carrying out performance evaluations considering human mobility models. Besides, we are designing and evaluating a multi-metric protocol which assigns different weights to the egocentric betweenness centrality and the node remaining energy values.

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