Analysis of Topology Control Algorithms in Multi-hop Cellular Networks

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***Abstract*—In multi-hop wireless networks, the way the network topology is defined has a strong impact on routing. This paper deals with topology control in cellular networks with relays. Several topology control algorithms taken from ad-hoc networks are adapted to cellular networks. Most of the algorithms considered here are based on proximity graphs. Performance analysis is carried out in a realistic scenario built from geographical data of a live network. Assessment is based on several performance criteria, namely connectivity, energy efficiency, sparseness, adaptability, throughput and interference. Results show that the properties of the graph obtained by topology control, which will be used later for routing, greatly depend on the specific algorithm.**

I. Introduction

The increase in data rates promised by fourth generation mobile communication systems cannot be achieved by traditional network structures, based on highly complex base stations located in prominent positions. The need to ensure line-of-sight conditions in the radio link requires increasing the density of base stations, which involves an investment in infrastructure that operators can hardly bear. As an alternative, it has been proposed the use of low-cost base stations, whose connection to the network operator backbone is made in a more cost-efficient way. The use of femtocells, whose return link is made through conventional ADSL lines, is widespread indoors. For outdoors, it has been proposed the deployment of multi-hop wireless networks using repeaters [1] [2]. These repeaters allow replacing traditional wired connection to the backbone by a radio link.

As in wireless mesh networks, in multi-hop wireless networks it is necessary to set the transmission range of each node, selecting, from all possible links, those most effective. Topology control is responsible for this task. In the literature, numerous topology control algorithms for ad-hoc and sensors networks have been proposed [3]. However, the problems associated with this type of networks are different from those of cellular networks. In the former, the aim is to maintain connectivity between nodes (usually with similar characteristics) with minimum energy consumption. In contrast, in cellular networks, energy consumption is less important than link throughput and delay. At the same time, in cellular networks, there are nodes of different classes (e.g., base station, repeater and terminal). Finally, topology control algorithms for ad-hoc and sensors networks are usually distributed, whereas in cellular networks it is possible to use centralized algorithms within the base station. The latter property allows using exact routing algorithms (i.e., optimal from a mathematical point of view), which are only feasible if the set of possible solutions is reduced. It is in this scenario where topology control is essential.

In this paper, topology control algorithms conceived for ad-hoc networks are adapted to the cellular environment. The proposed algorithms are based on proximity graphs, which only establish links between nearby nodes. It is assumed that repeaters are static, share band with base stations and terminals, regenerate the signal (i.e., operate at levels 2 or 3) and are not distributed [4], although most of the results presented are applicable to other types of repeaters. The rest of the paper is structured as follows. Section II formulates the topology control problem, section III describes various topology control algorithms, section IV compares topology control algorithms in a realistic scenario and section V presents the main conclusions.

II. Formulation of Topology Control

Network topology is defined as the set of links connecting the nodes that make up the network. Topology control aims to simplify the routing process by selecting a subset of links (referred to as routing graph) among all possible links (referred to as communication graph) [5]. Links in the routing graph must: a) maintain global connectivity between nodes, avoiding graph fragmentation, b) minimize power consumption and interference, and c) improve network performance in terms of network capacity and quality of service.

In wireless networks, the topology control problem starts by defining the communication graph. In a cellular network, the node set consists of Base Stations (BS), repeaters (Relay Station, RS) and terminals (Mobile Station, MS), while edges are the connections between nodes. The weight of edges might mean the number of hops per link (= 1), the distance between nodes, the propagation losses (including gains of antennas) or radio resources required to establish the link.

The length of a path between a pair of nodes is the sum of weights of edges in the path. Consequently, the best path is the shortest path. For simplicity, it is assumed that a link between two nodes is only possible if the link can be established in both directions. In these conditions, the communication graph is an undirected graph, defined by distance, propagation losses, signal-to-noise ratio (SNR) or signal-to-interference ratio (SINR) constraints.

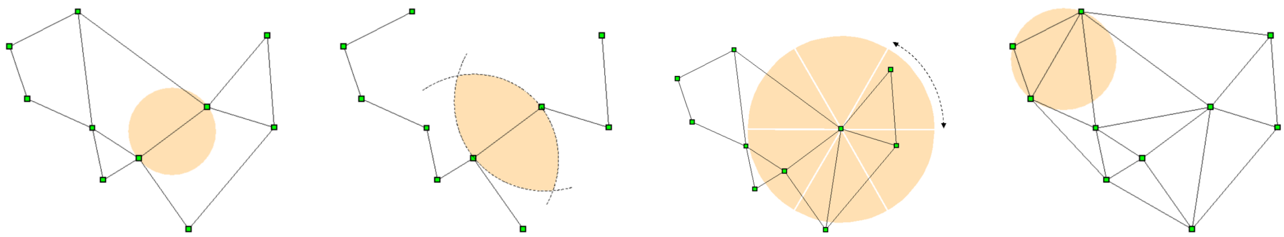


Fig. 1. Examples of topology control algorithms based on proximity graphs

Topology control defines a subgraph within the communication graph, referred to as routing graph, that must provide: a) connectivity between nodes, b) sparseness (so as to simplify the routing process), c) energy efficient links, d) robustness against changes in location and removal of nodes, and e) maximization of link capacity.

III. Topology Control Algorithms

In this section, several classic topology control algorithms, based on proximity graphs, are described. Then, it is proposed how to adapt them to cellular networks.

A. Gabriel graphs

In a Gabriel graph (GG), two nodes are connected by an edge if the disk having the nodes as a diameter is empty (i.e. contains no other node), as shown in Fig. 1 (a). Formally, an edge (v, w) exists in the Gabriel graph if no other node u satisfies the condition $d(u, v)^2 + d(w, u)^2 \leq d(v, w)^2$.

B. Relative neighbourhood graphs

In a relative neighbourhood graph (RNG), two nodes are connected by an edge if the intersection between the disks centred at the nodes and with radius equal to the distance between nodes is empty, as shown in Fig 1 (b). Formally, an edge (v, w) exists in the RNG if $d(v, w) \leq max\{d(v, u), d(w, u)\}$ for any other node u.

C. Yao graph

In a Yao graph (YG), the plane is split at each node in k equally spaced angular sections. At each angular section, the node is connected to the closest node within that section, as shown in Fig. 1 (c). In this paper it is set $k = 6$.

D. Delaunay graph

In a Delaunay graph (DG), edges form triangles in such a way that a triangle belongs to the graph if the circle defined by the triangle is empty (i.e. contains no other node), as shown in Fig. 1 (d).

E. Adaptation to the Cellular Environment

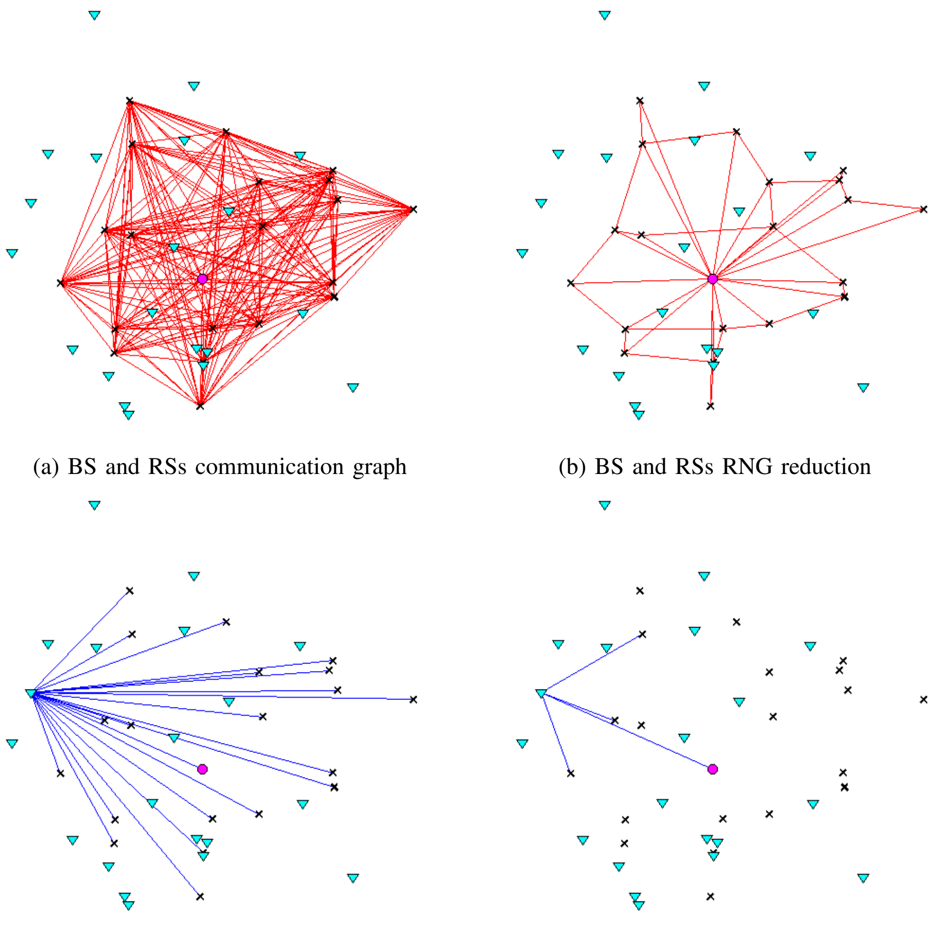
In cellular networks there are different types of nodes. While BSs and MSs are the origin and termination of all communications, RSs are mere relays. If it is assumed that a RS can only be assigned to a BS (i.e., the relay scheme is not distributed), the BS es the origin / termination of all downlinks / uplinks of its service area. As an additional restriction, it is often required that the number of hops between BS and MS does not exceed 3-4 in order to limit the delay caused by the use of RSs. On this premise, an ideal topology control algorithm should keep direct links to the BS (i.e., BS-RS and BS-MS) in the routing graph whenever possible.

Under these conditions, the proposed method generates the routing graph for each BS separately. For each BS, the algorithm comprises the following steps:

1) Identify the subset of nodes comprising the BS and the RSs served by the BS.
2) Create the communication graph with these nodes based on a threshold criterion (e.g., minimum SNR).
3) Generate the routing graph by applying a proximity graph to the communication graph, preventing RS-BS edges from being removed.
4) Take the RS-BS and RS-RS edges from the resulting routing graph.
5) For each MS served by the BS:
   a) Identify the subset of nodes comprising the MS under consideration, its serving BS and the RSs served by the BS.
   b) Create the communication graph with these nodes based on a threshold criterion (e.g., minimum SNR).
   c) Generate the routing graph by applying a proximity graph to the communication graph, preventing MS-BS edges from being removed.
   d) Take the MS-RS and MS-BS edges from the resulting routing graph.
6) Assemble all the edges taken in previous steps to build the resulting routing graph.

Therefore, MS-RS and RS-RS links are selected by applying proximity graphs, whereas RS-BS and MS-BS links are selected by applying the same threshold condition used to build the communication graph (as stated by steps 3 and 5-c in the algorithm). It must be noted that, in the communication graph, RS-RS and MS-RS links are in the majority, given that there are tens of RSs and MSs per BS. With the proposed method, only RS-RS and MS-RS links are removed, producing sparse graphs while maintaining all feasible BS-RS and BS-MS links as well as limiting the number of hops between any MS and the BS.

Likewise, it can be observed that, in the communication graph, direct links to the BS have been considered separately



(a) BS and RSs communication graph

(b) BS and RSs RNG reduction

(c) MS communication graph

(d) MS RNG reduction

Fig. 2. RNG routing graph generation within a site

(as stated by the 'prevent' condition in steps 3 and 5-c), not regarding the BS as one more RS. Otherwise, the routing graph may not include direct links between BS and MSs (and RSs) at the boundary of the cell and, as a result, paths between the BS and MSs may become arbitrarily long. Similarly, MSs are considered independently from other MSs (as stated by step 5), applying proximity graphs to the subsets formed by each MS and its neighbouring RSs. Otherwise, prohibited MS-MS links could appear in the routing graph.

Fig. 2 shows a graphical description of the proposed algorithm in one BS, being the BS represented by a circle, RSs by crosses and MSs by triangles. Fig. 2 (a) corresponds to the RS-RS and RS-BS links in the communication graph (created in step 2 of the algorithm). Note the large number of edges, most of which are RS-RS links. Fig. 2 (b) shows the resulting RS-BS routing graph obtained when applying, in this case, a RNG proximity graph (step 3 of the algorithm). This figure illustrate the significant edge reduction achieved in the RS-BS links, where most edges are removed. Similarly, Fig. 2 (c) corresponds to the MS-RS and MS-BS links in the communication graph for one single MS served by the BS. Fig. 2 (d) shows the reduction achieved when applying a RNG proximity graph to the MS-RS and MS-BS links. Again, most edges are removed and only the shortest edges are maintained. In both cases, RS-BS and MS-BS links are always preserved, as determined by the 'prevent' condition in steps 3 and 5-c of the algorithm.

IV. Analysis

The proposed method is tested on a scenario built upon data taken from a real network. The experimental methodology is described first and the results are then discussed.

A. *Experimental methodology*

The considered scenario, shown in Fig. 3, corresponds to the geographical area covered by three base station controllers of a GSM-UMTS network in an urban environment comprising 68 BSs. For the sake of simplicity, only macro-cells sites in the area have been considered, representing BSs by circles, RSs by crosses and service areas by polygons. Also for simplicity, each site is modelled as a single omnidirectional BS. Real sites commonly have tri-sectorized antennas (i.e., each site has 3 BSs).

The topology control problem is evaluated and solved independently for each BS, so there are 68 instances of the

TABLE I
SCENARIO PARAMETERS

Carrier frequency / Duplex mode	2GHz / FDD
Channel bandwidth	10 MHz (UL) / 10MHz (DL)
Nº physical resource blocks	50 (UL) / 50 (DL)
BS/RS/MS location	25 / 5 / 1.5 m
BS/RS/MS max EIRP	60 / 35 / 22 dBm
BS/RS/MS noise figure	6 / 6 / 9 dB
BS-RS propagation model	37.6.*log(d[km])+124.5, σ=6 dB
BS-MS propagation model	37.6.*log(d[km])+128, σ=8 dB
RS-MS propagation model	36.7.*log(d[km])+140.7, σ=10 dB
RS-RS propagation model	WINNER B1 [6]
Interference model	Continuous transmission from non-adjacent cells

TABLE II
TOPOLOGY CONTROL PERFORMANCE

Indicator	CG	GG	RNG	YG	DG
Edge reduction factor	- -	0.19 (0.21)	0.15 (0.17)	0.25 (0.28)	0.29 (0.31)
Edges per BS	40 (40)	40 (40)	40 (40)	40 (40)	40 (40)
Edges per RS	40 (40)	10.9 (14)	8.3 (12)	17.3 (24)	16.1 (20)
Edges per MS	21 (21)	5.4 (7)	4.0 (5)	6.2 (7)	7.0 (9)
Connectivity	Yes (Yes)	Yes (Yes)	Yes (Yes)	Yes (Yes)	Yes (Yes)
Articulation nodes	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Hop stretch factor	- -	1 (1)	1 (1)	1 (1)	1 (1)
Losses stretch factor [dB]	- -	8.3 (18.1)	9.4 (19.4)	14.8 (22.6)	6.1 (15.4)
SNR stretch factor [dB]	- -	2.5 (16.4)	3.5 (15.9)	11.1 (32.3)	1.0 (12.9)
SNR DL 50 % percentile [dB]	18.6 (8.0)	42.7 (24.7)	46.7 (28.7)	23.2 (8.7)	34.9 (20.6)
SINR DL 50 % percentile [dB]	-26.0 (-32.7)	-2.2 (-10.8)	1.8 (-7.2)	-22.08 (-31.1)	-10.0 (-18.3)

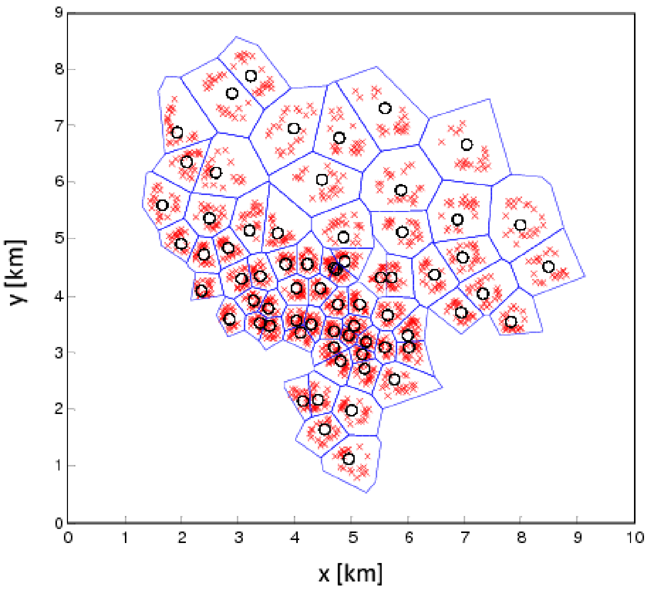


Fig. 3. Test scenario

problem. At each BS, the dominance area of the associated cell is obtained by applying Voronoi diagrams [7]. Once the dominance area is known, 20 MSs and 20 RSs are located in a random manner. Consistent with the assumption that the relay scheme is not distributed, RSs locations are restricted to a strip ranging from 25 to 75 % of the cell radius, as suggested by [8]. Fig. 4 shows the result of this process in one of the 68 BSs. As in Fig. 2, the BS is represented by a circle, RSs by crosses and MSs by triangles. The strip for RSs location is highlighted in grey.

Table I reflects the values of the main parameters in the scenario, inspired in Long Term Evolution - Advanced (LTE-A) technology and mostly taken from [9]. The analysis only considers the interference received from cells not located in the first ring of neighbours. Thus, it is assumed that the radio resource management algorithm implemented in the BS is able to avoid intra-cell interference, while neighbouring cells are coordinated in order to reduce inter-cell interference. Interference calculations are made assuming that the BS and the RSs within each cell transmit at maximum power but not simultaneously.

The analysis starts by building the communication graph with links having SNR > -15 dB. By considering SNR instead of SINR, topology control is not affected by interference conditions, which might vary depending on radio resource algorithms in the network.

Four variants of the proposed method are compared, as a result of applying GG, RNG, YG and DG graphs to the RS-RS and RS-MS links. The implementation takes advantage of the fact that GG and RNG are subgraphs of DG, generating the former from the latter more efficiently.

Several indicators have been defined in this paper to assess the performance of topology control algorithms. Such indi-

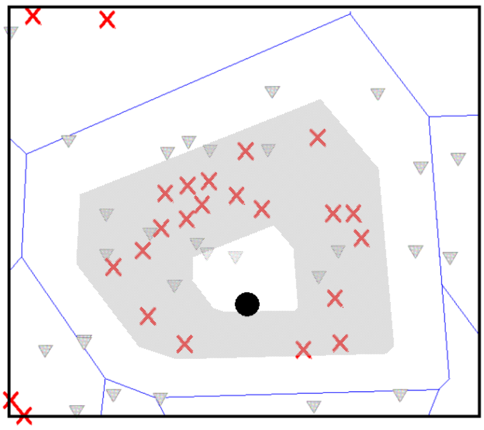


Fig. 4. Distribution of users and repeaters within a site

cators are calculated by processing and comparing both the communication and routing graphs in the 68 BSs. In particular:

- As a measure of connectivity, it is checked whether the routing graph is connected.
- As a measure of adaptability, it is counted the number of articulation nodes[1].
- As a measure of sparseness, the ratio of number of edges in the routing graph to those in the communication graph is evaluated .
- As a measure of energy efficiency, it is determined the stretch factor, defined as the maximum increase in weight between any pair of nodes after the graph is simplified.
- Finally, as a measure of capacity and interference, SNR and SINR percentiles are evaluated on the links of the routing graph.

As a novelty, different stretch factors are proposed, expressed in terms of number of hops, path losses and SNR. To this end, it is introduced the concept of effective distance, $d_{eff}(u, v)$, between two nodes u and v, which will be used as the weight of each edge. This allows to consider the scenario as a homogeneous one with nodes sharing a common graph model. As the case may be, effective distances are defined as follows:

- In terms of hops, $d_{eff(hop)}(u, v)$ is 1 for all links.
- In terms of propagation losses, $d_{eff(pl)}(u, v)$ provides the same losses as using a reference propagation model shared by every link with no shadowing considered.
- In terms of SNR, $d_{eff(snr)}(u, v)$ is defined as the inverse of the SNR of the link (in linear scale). Thus, in terms of SNR, the worst link in the path dominates the effective distance between nodes (consistent with the use of repeaters regenerating the signal).

It should be pointed out that, in the current analysis, proximity graphs are only based on euclidean distances, whereas performance assessment is based on effective distances. Applying effective distances to the proximity graphs would require a transformation of coordinates, which is left for further study.

[1]Articulation nodes are those that, if removed, the graph is no longer connected

B. Results

Table II compares performance indicators of the four variants of the proposed algorithm. The first column, used as a reference, represents the values of the indicators in the communication graph (CG), whereas the other columns represent the values of the indicators in the four resulting routing graphs. The two values of each indicator correspond to the mean value and, in brackets, the worst case value (minimum or maximum, as appropriate) across the 68 instances. For brevity, only the medians of the SNR and SINR distributions in the downlink (DL) are presented, since the uplink (UL) showed similar values in all cases.

From the edge reduction factor shown in the first row, it can be deduced that RNG is the graph which simplifies the routing graph the most, while DG is the one which simplifies the least. In particular, RNG reduces the number of edges in the routing graph by 85 % compared to the communication graph. Also, the low average number of edges per RS and MS (8.3 and 4 respectively) in RNG, makes the resulting routing graph less sensitive to changes in the network, thus improving network adaptability.

On the other hand, DG reduces the number of edges only by 30 %, being the one which offers better connectivity. In spite of the large edge reduction obtained, all routing graphs remain connected and none of them have articulation vertices. It is worth noting that the reduction could have been greater if the proximity graph would have also been applied to BS-MS and BS-RS links (at the expense of losing direct links and, consequently, increasing the number of hops in most paths).

Upon treating the BS separately, numerous BS-RS and BS-MS links are added to the routing graph, therefore reducing the impact of the topology control algorithm. As a result, the number of edges per BS in the routing graphs is 40 in all cases (20 BS-RS and 20 BS-MS). As these BS-MS direct links are preserved by the topology control, the best path between BS and MS in terms of number of hops is unaltered after topology control, resulting in a hop stretching factor equal to 1 in all cases. In contrast, the SNR and propagation losses stretch factor may change, due to the fact that the direct link may not be the best path.

From these indicators, it can be seen that DG is the graph that impairs propagation losses and SNR the least (6.1 and 0.98 dB on average, respectively). In contrast, YG is the one that impairs these indicators the most, contrasting with its modest edges reduction (25 % versus 15 % in RNG). Despite the high SNR values obtained, the SINR values are particularly low in all variants, although significantly higher than those obtained in the communication graph. This is due to: a) the low transmit power of RSs compared to (interfering) BSs, and b) to the assumption that interfering nodes (i.e., BSs and RSs) transmit all the time at full power (i.e., full traffic load of interferers). These results evince the need for inter-cell interference coordination mechanisms [10].

V. Conclusions

In this paper, the problem of topology control in multi-hop cellular networks has been studied. Several classic topology control algorithms based on proximity graphs have been adapted to cellular networks. The main distinctive feature of these networks, compared to ad-hoc networks, is the different types of nodes making up the radio access network: base stations, relays and terminals. The proposed algorithms have been validated in a scenario built upon data from a real network. Results have shown that, if direct links with the base station are kept, the relative neighbourhood (RNG) algorithm is the one that simplifies the graph the most and achieves better links, while maintaining an acceptable degree of connectivity.

Future work will focus on centralized routing algorithms that take advantage of the network graph obtained by the proposed topology control algorithm. Also, it is being considered the introduction of coordinates transformations in the proximity graphs algorithms in order to handle the concept of effective distance at the low level.

Acknowledgements

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