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Dynamic Topology Re-Configuration in Multihop Cellular Networks Using Sequential Genetic Algorithm

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ABSTRACT
Cellular communications has experienced explosive growth in the past two decades. Today millions of people around the world use cellular phones. Cellular phones allow a person to make or receive a call from almost anywhere. Likewise, a person is allowed to continue the phone conversation while on the move. Cellular communications is supported by an infrastructure called a cellular network, which integrates cellular phones into the public switched telephone network. The cellular network has gone through three generations.The first generation of cellular networks is analog in nature. To accommodate more cellular phone subscribers, digital TDMA (time division multiple access) and CDMA (code division multiple access) technologies are used in the second generation (2G) to increase the network capacity. With digital technologies, digitized voice can be coded and encrypted. Therefore, the 2G cellular network is also more secure. The third generation (3G) integrates cellular phones into the Internet world by providing highspeed packet-switching data transmission in addition to circuit-switching voice transmission. The 3G cellular networks have been deployed in some parts of Asia, Europe, and the United States since 2002 and will be widely deployed in the coming years.
The high increase in traffic and data rate for future generations of mobile communication systems, with simultaneous requirement for reduced power consumption, makes Multihop Cellular Networks (MCNs) an attractive technology. To exploit the potentials of MCNs a new network paradigm is proposed in this paper.
In addition, a novel sequential genetic algorithm (SGA) is proposed as a heuristic approximation to reconfigure the optimum relaying topology as the network traffic changes. Network coding is used to combine the uplink and downlink transmissions, and incorporate it into the optimum bidirectional relaying with ICI awareness.
Numerical results have shown that the algorithms suggested in this thesis provide significant improvement with respect to the existing results, and are expected to have significant impact in the analysis and design of future cellular networks.
Keywords*:* cooperative diversity, dynamic traffic distribution, intercell interference, multicast, multihop cellular network, network optimization, reuse factor, routing, scheduling, topology control.

I. 1 Introduction

1.1 Motivation

Multihop cellular networks (MCNs) are proposed in respond to the demand for next generation cellular systems to support high data rates with efficient power consumption, enlarge coverage area and provide good QoS for multimedia applications [1], [2]. Simultaneous need of increasing the capacity and reducing the power will require more spatial reuse. One technique under consideration toachieve this goal is the deployment of small cells. By scaling down the cell size and so increasing the total number of channels in space, the network capacity can be linearly increased, proportional to the number of new base stations (BSs) or the scaling factor. However, the deployment of more BSs and their interconnections to the wired backbone results in high network cost. This problem can be overcome by deploying wireless multihop routers instead of new BSs or allowing selected mobile terminals to act as routers, to establish a wireless MCN.

In this way, by shortening the links, the required transmit power is reduced which is highly desirable in interference-limited networks and provides the opportunity for capacity increase when suitable techniques are applied. MCNs are economically convenient due to the capability of providing faster deployment by using the existing infrastructure of cellular networks. Different architectures based on 2G, 3G and WiMAX can coexist and different types of networks such as femtocells, delay tolerant networks, WLANs might be used as an augmented technology.

The concept of adding ad hoc capabilities to cellular nodes is widely explored in MCNs [1], [2]. The advantages of this *hybrid* architecture include increasing the throughput of the network, enlarging the coverage area of the base station, decreasing the power consumption of the mobile users, and increasing the network scalability. In order to exploit those advantages, the selection of the most appropriate relays among the existing mobile terminals [3] should be jointly considered with routing and scheduling. The throughput on each hop and opportunity for spatial reuse increases with the number of hops, but the complexity of the system also increases. Consequently, a large number of possibilities results in a large scale optimization problem. Additionally, the delay from source to destination is increased with more hops, which may not be tolerated by delay-sensitive services. The above problem becomes more complex in the multicell scenario where intercell interference (ICI) is present. Thus, to exploit the potentials of MCN, a systematic approach to network optimization is needed to study the gains and trade-offs associated with this type of networks.

A number of radio resource management (RRM) schemes, such as relay selection and radio resource partition, along with a number of routing and topology control algorithms have been proposed for ad hoc networks [4]. Some of the earliest information theoretic work by Cover and El Gamal [5] gave capacity bounds for the simple relay channel, while more recent work by Gupta and Kumar [6] expanded this work to give asymptotic results for general ad hoc relay networks. However the problems associated with this type of networks are different from those of cellular networks, so the results are not directly applicable to cellular multihop relay scenarios. A number of potential opportunities and challenges are related to MCNs. To take advantage of such potentials, it is necessary to overcome important technological challenges, such as the design and joint optimization of robust, adaptive and context aware multihop routing protocols, as well as scheduling and energy efficient radio resource allocation. Different architectures, protocols, and analytical models for MCNs have been proposed in the literature where different system aspects were investigated. This chapter aims to provide a survey of the major research issues and challenges in MCNs.

1.2 Research challenges in multihop cellular networks

1.2.1 Overview

In this section, some of the most important research issues in MCNs are summarized, and in each subsection the main solutions for the introduced problems are presented. The architecture of MCNs consists of cellular and ad hoc relaying components as shown in Fig. 1. In such *hybrid* network architecture, MCNs combines the benefits of single-hop cellular networks (SCNs) and ad hoc networks. The SCNs have reliable performance and mature technology support.

However, their infrastructure is costly to build and suffers from some limitations on the channel data rate when the number of mobile users is high or there is heavy traffic during peak hours. They also have limitations on system capacity and network expansion. On the other hand, ad hoc networks are cheap to deploy but channel contention and interference between nodes are more difficult to predict and control, and the end-to-end paths between source and destination are more vulnerable to node mobility and failure. To preserve the advantages and cope with the limitations of both networks when operating standalone, a number of factors should be taken into account for designing a MCN.

The most important factors are multihop routing, topology control, the design of RRM protocols, particularly for the management of the ICI, and load balancing schemes. These factors are closely inter-related and affect power consumption, capacity, coverage and QoS provisioning.

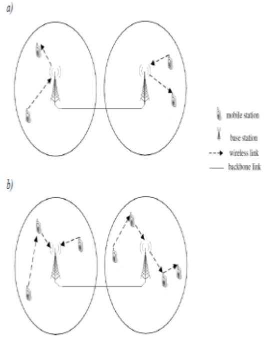

Fig. 1. a) Single hop cellular network; b) Multihop cellular network.

In Fig. 2 we represent the protocol stack indicating where each of those functions is located. A number of papers have shown that by exploiting useful interactions of protocols in different layers, the network performance can be improved significantly (cross-layer optimization). For example, the coordination between routing and resource scheduling in MCNs is crucial and warrants careful investigation [7]. A cross-layer routing protocol with constrains in relay node selection and source to destination path selection is proposed in [8] for a singlecell scenario. In [9] a cross-layer throughput analysis is presented for fixed topologies and without optimization of the power allocation. The jointly optimization of ICI avoidance and load balancing schemes in a multicell network is addressed in [10].

The above examples are just few, from a vast variety of issues addressed in the literature of MCNs. In the remainder of this section, each of those main problems is discussed in detail in separate subsections to bring more insight in their impact on overall characteristics of MCNs.

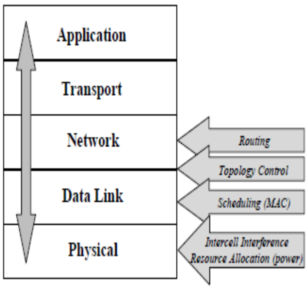

Fig. 2. Protocol stack illustrating different design decision factors in MCNs.

1.2.2 Multihop routing

The relaying technology has been studied intensively for applications in MCNs and is included in most third- and fourth-generation wireless system developments and standardizations [11]-[12]. The relay channel was introduced in [13] by assuming that there is a source that wants to transmit information to a single destination and a relay terminal that is able to help the destination (*relayassisted transmission*). The relaying concept is the basis of multihop routing and cooperative transmission too [14]. Routing is a major issue in MCNs because it affects packet delay and system throughput. In mobile ad hoc network (MANET) many routing algorithms havebeen proposed [15]. These algorithms are designed with network infrastructure nonexistence in mind, and their main objective is to establish/maintain network connectivity, rather than to maximize system capacity. As a result, these algorithms are not suitable for MCNs.

A routing algorithm in MCN introduces extra signaling overhead when broadcasting route information which adds extra interference. The effect of the interference is normally ignored in MANETs but cannot be neglected in cellular networks. This is mainly because the transmission power of nodes in MCNs can be several orders of magnitude higher than that of nodes in MANETs. In both MANETs and MCNs, the amount of signaling overhead mainly depends on the chosen routing algorithm. The routing algorithms can generally be classified into two categories:

a) *proactive* routing
b) *reactive* routing [16], [17].

Proactive routing mechanisms discover and calculate routes all the time. Each node periodically exchanges its routing information with its neighbors by continuously broadcasting hello/topology messages, and thus, its signaling overhead depends on the broadcasting interval and the number of nodes in the network. On the other hand, reactive routing schemes find and maintain routes only when needed. The signaling overhead of reactive routing increases with the increasing number of active communication pairs as well as with the number of nodes [16], [17]. In MCNs, the radio resources are centrally controlled, and thus, a mobile terminal has to establish a connection with the BS before data is transmitted. In such an environment, reactive routing offers several advantages over proactive routing.

First, reactive routing produces less signaling overhead, as there is no routing unless data transmission is required. Second, reactive routing only maintains necessary routing entries. Most of the routing entries maintained by proactive routing could be obsolete due to discontinuous reception (DRX) [18] or users' mobility. In reactive routing, a source node normally utilizes flooding to deliver a route request (RREQ) packet to the destination. Once an RREQ reaches its destination, the destination reports a route response (RRES) back to the source along the nodes that the RREQ has traversed. In the case when multiple RREQs are received, the route with the best performance metric would be reported. During the route-discovery phase, the RREQ can be broadcast to the entire network (*i.e.*, complete flooding) or a certain part of it (*i.e.*, directed flooding).

For example, dynamic source routing (DSR) [19] utilizes complete flooding to find a route to its destination if a source cannot reach the destination in a single hop. In contrast, the Ad-hoc On-Demand Distance Vector (AODV) routing protocol [20] uses incremental scoped flooding to find a route. A source gradually enlarges the flooding diameter until it finds a destination or the search diameter reaches a predefined "time-to-live (TTL)" threshold (*i.e.*, the maximum number of relay nodes in the routing path). AODV should use complete flooding if no route is found when the search diameter hits the threshold. The drawback of the proactive routing is the delay in the data transmission.

It seems that for MCNs that enable DRX the reactive routing approach would be a better choice. Hence, the existing routing protocols proposed for MCNs normally adopt DSR to discover the best route. Some routing protocols utilize a scoped flooding approach to reduce the signaling overhead of DSR. Generally, the TTL threshold can be derived based on the given system level constraints of MCNs. For example, the TTL threshold may depend on the maximum intracell interference [22], the end-to-end delay requirement of the multihop transmission [23], the maximum route discovery time [21], or the performance metric of the routing protocol [18].

When designing a routing protocol, the control strategy and path selection metric (cost function) need to be defined. As MCNs contain coordinators (BSs or APs) and mobile users, routing control may be *centralized*, *de-centralized*, or *hybrid*. In centralized routing, BSs are responsible for route discovery and maintenance. BSs have unlimited power supply and high computational power which helps to avoid consuming the limited battery power of mobile nodes for route information exchange and route computation. In CAHAN [24], a central controller periodically receives the location information from each user in the cell to determine the route of the *ad hoc* subnet (cluster) heads with which mobile users communicate.

However, when mobiles are outside of the maximum transmission range of a BS or an A P, a decentralized (distributed) routing scheme, such as DSR, is desirable. Some MCN proposals employ distributed routing schemes. For example, in mobile-assisted data forwarding (MADF) [25], mobile nodes may be willing to relay data packets based on their local traffic condition.If the traffic is less than a certain threshold, they broadcast a message to their neighboring mobile nodes indicating that they have available channels for relaying data packets. Then, a mobile node in a congested cell chooses a relaying node to relay its data packets to a less congested neighboring cell based on the link quality between itself and the relaying node and estimated packet delay.

In MCNs, a hybrid routing approach is commonly used. Route control is shared by the BS and mobile users. For example, in cellular based routing (CBR) and cellular based source routing (CBSR) [27], mobile nodes collect information about the neighborhood and send it to the BS for route computation. This helps reduce the route computation overhead at relaying nodes. In addition, not only source node can initiate a relaying request, a relaying node can also take the initiative by advertising their free channels (available capacity) for relaying [25, 26, 28]. Hence, routing overhead is shared amongst source nodes and relaying nodes.

Different routing protocols consider different path selection metrics. Metrics include BS reachability, hop count, path loss, link quality, signal strength, bit error rate (BER), carrier-to-interference ratio (C/I), delay-sensitivity, throughput, power, battery level, mobile speed, and energy consumption. If BS reachability information is available e.g., provided by relaying nodes, mobile nodes can select the best next hop relaying node to reach the BS. Limiting the number of hops helps bound the packet delay, but reduces the chance of obtaining relaying paths, and, hence, the reachability. This can be overcome by using topology control as it will be explained in the next subsection. Nevertheless, choosing paths based on the smallest number of hops also raises fairness and energy efficiency issues.

Several routing algorithms have been proposed for MCNs based on e.g., location, path-loss transmission-power, and congestion. In the relay station overload problem is considered in the route selection protocol. But in these approaches the selected routes are not necessarily optimal in terms of the system resource utilization and the signaling overhead was ignored. Link quality may be expressed as a function of path loss, BER, and C/I. Delay and throughput are common metrics because they reflect the network performance directly. Minimum power routi ng is important in CDMA-based MCNs to reduce interference and achieve high cell capacity. Battery level, mobile speed, energy consumption are useful for assuring the reliability of relaying paths. Other possible metrics include traffic load, mean queue length, and number of packets queued along the path.

Multipath routing

The "cooperative diversity" concept in multihop relaying networks is explored in [14]. The main objective of the cooperative diversity is to improve the performance of cellular networks by using multiple nodes between the user and BS to simultaneously carry the same information. This idea resembles Multiple Input Multiple Output (MIMO) systems in a distributed manner. Since it is physically difficult to deploy multiple antennas on a single palm-sized mobile host, receiving multiple replicas of the main message from different relay nodes may improve the system performance due to its diversity nature. Multipath routing is one way for such cooperation by using multiple parallel paths between source and destination nodes, where the main data stream is split into streams of lower data rates and routed to the destination through the MCN. Multipath cellular networks are capable of supporting high data rate services with less transmission power consumption.

Several works explore the idea of multipath routing in MCNs. However, sufficient attention is not given for resource allocation and power conservation in these works. The key issues related to cooperation in multipath cellular networks are efficient relay selection and resource allocation. The aim is to find the best set of relays nodes that can cooperate with the user and the BS to establish a high data rate cellular connection and, a resource allocation algorithm that assigns appropriate transmission power and data rates to each of the selected relay nodes. Relay nodes will be selected among all idle nodes based on their willingness to cooperate, their channel quality, and their remaining battery resources.

1.2.3 Topology control

Topology control was originally developed for wireless sensor networks to reduce energy consumption and interference. It works as a middle ware, connecting routing and lower layers as shown in Fig. 2. Topology control focuses on network connectivity with the link information provided by medium access control (MAC) and physical layers. When constructing network topology in MCNs, topology control takes care about the interference and link availability prediction. The way the network topology is defined has a strong impact on routing. Topology control aims to simplify the routing process by providing:

a) connectivity between nodes,
b) energy efficient links,
c) robustness against

changes in location and removal of nodes, and d) maximization of link capacity. From routing perspective, it is expected that data packets are routed via a stable and reliable path to avoid frequent rerouting problem, since frequent rerouting may induce broadcast storm to the network, waste scarce radio resources and degrade end-to-end network performance such as throughput and delay [51] which is especially critical in MCNs.

1.2.5 Load balancing

Another important issue in multi cell networks is to resolve the load imbalance problem between cells. In order to balance the load among different cells, it is needed to transfer the over-loaded traffic from "hot" cells to neighboring "cooler"ones. Various dynamic load balancing schemes to deal with the unbalanced traffic problem are proposed in the literature. We can broadly classify them into four groups: a) Strategies based on channel borrowing from cooler cells b) Strategies based on BS selection c) Strategies based on power control and cell breathing and d) Strategies based on relay-assisted traffic transfer The basic idea of channel borrowing is to borrow a set of channels from "cooler" cells (with less traffic load) to "hot" cells. However, this will change the pre-defined spectrum reuse pattern and introduce more cochannel interference. Also, as future cellular networks move towards to universal frequency reuse, there is little space for channel borrowing schemes. In BS selection schemes, mobile users in hot cells will try to associate with a BS in a neighboring cooler cell and get service, but the throughput is limited due to low signal strength. The cell breathing effects allow adjustment of transmit power to reduce the size of hot cells to release over-loaded traffic to neighboring cooler cells. Sang *et al.* proposed an integrated framework consisting of a MAC layer cell breathing technique and load aware handover/cell-site selection to deal with load balancing. Bu *et al.* were first to rigorously consider a mathematical formulation of proportional fairness PF [98] in a network-wide manner with users' associations to BSs. They showed that the general problem is NP-hard and proposed a heuristic algorithm to approximately solve the problem. extends this network-wide PF to the multi cell network with partial frequency reuse where each BS has limited resources based on ICI pre-coordination scheme and independently runs a PF scheduler. Therefore, in cell breathing schemes, close cooperation among adjacent cells is required to guarantee full coverage and mitigate ICI. The last strategy consists of taking the advantage of MCNs to relay over-loaded traffic from hot cells to cooler cells. Load balancing in MCNs not only involves balancing among cells, but also balancing among relaying nodes and the choice of relaying device. Compared with previously discussed dynamic load balancing schemes, relay-based load balancing schemes are more flexible and will introduce less interference.

II. overview

2.1 Overview and background

A comprehensive survey of the previous work on interference avoidance topology control is presented the potential for network performance improvement by topology reconfiguration in time-varying environments is emphasized and the limited research work done so far in topology control for MCNs is outlined. Recently, there have been increasing interests in applying biologically inspired approaches to topology control in MSNs and MANETs.

However, the problems associated with these types of networks are different from those of cellular networks. For this reason, in this chapter we present a sequential genetic algorithm for dynamic topology control in MCNs. The efficiency of our algorithm is achieved by considering dynamic joint optimization of relaying topology, routing (power) and inter relay scheduling in multi cell MCNs. In the remaining of this subsection, we provide an overview on GAs and their efficiency in solving dynamic problems which justifies its selection to solve our problem.

Basic concepts of Genetic Algorithms

Genetic Algorithms (GAs) are adaptive methods based on the mechanics of natural selection. The basic principles of GAs are described in many texts. The first step in GA is to encode the problem as a chromosome or a set of chromosomes that consist of several genes. The solution in its original form is referred to as *phenotype*, whereas its binary encoded version is called *genotype* or simply *chromosome*. Next, a pool of feasible solutions to the problem, called initial population, is created. Each chromosome in the population is associated with a fitness value that is calculated using a fitness function that indicates how good the chromosome is.

Genetic operators' *selection*, *crossover*, and *mutation* operate on the population to generate a new generation of population, *i.e.*, a new set of feasible solutions, from the old ones. Good feasible solutions are selected with higher probability to the next generation, in line with the idea of *survival of the fittest*.

The standard *crossover* operation recombines arbitrarily selected chromosomes pair wise, by interchanging portions of them, producing new chromosomes to explore the search space. An occasional *mutation* operation is performed on a chromosome to facilitate jumping of solutions to new unexplored regions of the search space. As the algorithm continues and newer generations evolve, the quality of solutions improves.

Genetic algorithms for dynamic environments

Genetic Algorithms have been shown to be a useful alternative to traditional search and optimization methods, especially for problems where the space of all potential solutions is too high to be searched exhaustively in any reasonable amount of time. They are very efficient in directing the search towards relatively prospective regions of the search space. Empirical studies have shown that Gas do converge on global optima for a large class of NP-hard problems .

A key element in a genetic algorithm is that it maintains a population of candidate solutions that evolves over time. The population allows the genetic algorithm to continue to explore a number of regions of the search space that appear to be associated with high performance solutions. The distributed nature of the genetic search provides a natural source of power for searching in changing environments. As long as the population remains distributed over the search space, there is good reason to expect the genetic algorithm to adapt to changes in the utility function by reallocating future search effort towards the region of the search space that is currently favored by the utility function.

A number of previous studies have addressed the use of genetic algorithms in changing environments such as dynamic shortest path routing in MANETs, dynamic coverage and connectivity problem in WSN, dynamic resource allocation problem in cellular networks and dynamic network coding problems.

In the sequel, a novel sequential genetic algorithm is presented for dynamic topology reconfiguration in MCNs. A special encoding scheme, crossover and mutation operations are proposed to search for the optimum topology when the traffic in the network changes. Improvement in the fitness function is sequentially controlled as newer generations evolve and whenever the improvement is sufficiently increased the current topology is updated by the new one having higher fitness. Numerical results show that SGA provides high performance improvements in a dynamic network environment.

2.2 System model and assumptions

In this section, we extend the model considered in to include duplex transmission (uplink/downlink) in MCNs. We consider a cellular network with a set I {*i*} of base stations. It is assumed that the area of the cell is divided into concentric rings as before with index *mr* for the reference cell *i* = *r* and *mi* for the interfering cell. We assume that one co-channel user from each ring has bidirectional connection with the corresponding access point. Conventional relaying scheme (CONR) is used. Let us consider that a reference *mobile* user *mr1* (located in ring *mr1*) is transmitting (relaying) to another *mobile* user *mr2* (located in ring *mr2*) in the reference cell *r* and, at the same time, a co-channel *interfering mobile* user *mi1* is transmitting to another *mobile* user *mi2* in cell *i*.To keep the notation general, in the uplink last-hop transmission *mr2* denotes the reference base station *APr*, and on the downlink *APr* refers to *mr1*. The same applies for the interfering base station *APi*. By this generalization, the physical layer model is described again by (8)-(17). As an illustration, for the two cells scenario, the extension to downlink topology is shown in Fig. 19b.

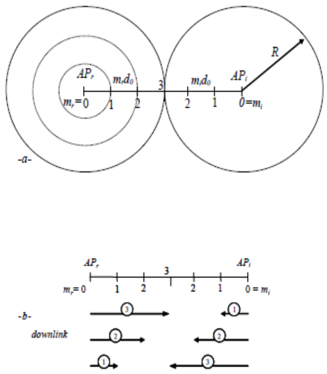

Fig. 3. a) Modeling interfering users positions for 2-cells; b) Possible transmission schedule for downlink.

In the example shown in Fig. 5b for uplink, 4 slots were needed to complete the transmission. In this case, for the scenario presented in Fig. 19b for downlink, as the hopping distance is larger, the transmission is completed in 3 slots. So, only 7 time slots are required for all 6 users to transmit on the up and down link. Classical TDMA scheme would require 6 + 6 = 12 slots. The optimum set of relaying routes is defined as in. To model the network traffic dynamics, we extend the notation presented in for uplink and we denote by ,1 , (,...,), *i* *i* *i n* *i* **R** the traffic that the access point *APi* is transmitting to the users on the downlink where - *a- R APr APi mr*= 1 2 2 1 3 *0=mi - mrd0 mid0* 0 *-b- APr APi* 1 2 2 1 3 -3 1 2 1 2 3 *mr*= 0 *downlink* 0 = *mi ni* is the number of rings in cell *i*. The overall network traffic on the uplink and downlink is defined as 1 2 1 (, ,...,) (,...,) *Nc N* and 1

2 (, ,...,) *Nc* □ □ □ □ □1 (,...,) *N* □□□, respectively where *c N* is the total number of cells (*c N* □I) and *N* is the total number of rings in the network obtained as 1 *c I N I N n* □□ □. For the same traffic vectors □*i*, □*i*, the base station schedule the transmission through different channels (time slots) which results in temporal and spatial MAC protocol. The base stations jointly assign an access vector 1 2 1 (, ,...,) (,...,) *Nc N* **a** □**a a a** □*a a* to the different rings to give them permission to transmit, where each component (,) *n n n a a a* □□□with , (0,1) *n n a a* □□□. With *a*□= 1 the users from ring *n* are allowed to transmit uplink otherwise not, and with *n a*□= 1 the users from ring *n* are allowed to transmit downlink otherwise not. In the two cell case 1 2 , the first half of the coefficients represent the permissions to transmit for the rings in referent cell *r* and the second half for rings in interfering cell *i*. Symmetric bidirectional transmission is considered in the sense that the access point will only transmit to the users situated in the rings activated by **a** where both components of (,) *n n n a a a* are active, or not active, simultaneously. Recall that the index pattern for **a** is presented in Fig. 7. The link notation for the bidirectional case will be address in the following sections.

2.3 Bidirectional relaying topology with physical layer network coding

In this section, network coding [147] is additionally introduced and combined with the previous results on optimum relaying to reduce the number of slots needed for the users to complete their transmissions and achieve further improvements of the system performance. Let us assume that the hops are indexed in increasing order for uplink as *h*(*up*) and for downlink as *h*(*down*) . By combining the uplink and downlink traffic from the previous hop at hop *h* as (,) ( ) ( ) 1 1 *down up down up h h h y y y* □□the number of overall time slots needed for transmission in *B* cycles can be reduced. To elaborate this concept in more detail, an example of possible topology that includes network coding is shown in Fig. 20 for two cells. The traffic between users and access point is bidirectional. So given a schedule that alternates the transmissions between the different rings, after certain number of time slots all intermediate users (,) *i m i*□ I have information frames buffered for transmission in both directions. Whenever an opportunity arises, the intermediate users combine two information frames, one for each direction, with a simple *XOR* operation and send it to its neighbors in a single omni directional transmission. Both receiving nodes already know one of the frames combined (have it stored from the previous transmission), while the other frame is new. Thus, one transmission allows two users to decode a new packet, effectively doubling the capacity of the path, reducing the power consumption of the transmitter node and reducing the number of time slots required to complete the transmission.

The transmission schedule presented in Fig. 20 defines a possible topology for two cell scenario and access vector **a** = **1**. In this case all rings have duplex connection and the topology consists of eight partial topologies representing transmissions in eight consecutive time slots. In the first time slot (the first partial topology) there are two simultaneous transmissions; packet originating from the access point *APr* (addressed to user in ring 3) is transmitted to ring 2 in cell *r* and at the same time packet originating from ring 2 (addressed to access point *APi*) of cell *i* is transmitted from ring 2 to ring 1. In the second time slot (the second partial topology), packet originating from access point *APr* (addressed to user in ring 1) is transmitted to ring 1, at the same time packet originating from ring 3 (addressed to access point *APr*) is transmitted from ring 3 to ring 2 and, packet originating at *APi* (addressed to user in ring 2) is transmitted to ring 1 in the adjacent cell. Similarly the same notation is then used for transmissions in time slots from 3 to 8. As already discussed earlier these eight partial topologies together are referred to as a *possible two dimensional* (*time and space*) *topology* and will be represented in the sequel by a given topology index (*t*).

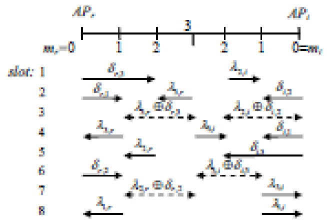

Fig. 4. Possible schedule by using network coding.

So there will be limited interference transmission for 3 users per cell in 8 channels (8 slots in Fig. 4) giving the inter cell throughput 6/8 = 3/4, as opposed to the 6/12 = 1/2 in a conventional TDMA system where each cell uses a half of available channels (slots). Although scheduling in Fig. 5b and Fig. 19b requires 7 time slots in total (for uplink and downlink) it also assumes transmissions over three rings which requires higher power. The optimization process defined by (18) now becomes

$$\{\Re_r^{(2)}\} = \max_{B,H,\varpi,\Re^{(2)}} C_{\Re^{(2)}}; \text{ where } C_{\Re^{(2)}} = \sum_r c_{\Re_r^{(2)}} \qquad (33)$$
$$\Re = \Re^{(up)} \cup \Re^{(down)},$$

Where (2) is a two dimensional relaying topology to be elaborated in more detail in the next section, *B* is the number of slots needed for the users to complete their transmission uplink/downlink (scheduling length), *H* is the number of hops and □stands for the network coding operation. For each slot *b* □ 1,...*B* , parameter (2) *r c*□is given by corresponding (15)-(16) and (2) *C*□is the network capacity.

2.4 System optimization

The extension of the optimization problem presented in by to bidirectional traffic is straight forward. An independent set of equations (23) should be written for both directions and (24) should be modified to include the overall utility function

U □*U*(*up*) *U*(*down*)

with separate set of constrains for both directions. For each direction of the traffic, *U* is given by (22) and includes data rate, power consumption and delay. TSL algorithm has been modified to search for the optimum topology for the scenario presented in Fig. 20. In a real network, where the traffic is dynamic, the network topology should be reconfigured to track the variations in the network and guarantee good network performance. In multicell MCNs with nonuniform traffic distribution, the search for the optimum topology becomes an NP-hard problem. TSL algorithm results in high complexity and for this reason in the next section we define an evolutionary sequential genetic algorithm that can be used for readjustment of the topology due to traffic variation.

2.5 SGA-TSL algorithm

In this section, a Sequential Genetic Algorithm (SGA) is presented to dynamically adjust the optimum topology to the traffic variations in the network. As result, routing and scheduling will be implicitly adjusted with the relaying topology. SGA represents a suboptimum solution which provides performance close the optimum with less complexity or with shorter computational time.

3.5.1 Encoding scheme

For simplicity of presentation we start this section by considering only uplink transmission which will be further extended to the bidirectional case. The topologies are encoded as a set of chromosomes, where each chromosome defines a partial topology. A chromosome consists of a number of gene-instances 1 (,...,) *Nc* □ □ □1 (,...,) *N* □□□where *c N* is the total number of cells and *N* is the total number of rings in the network. Each vector □*i* consists of *i n* components, where *i n* is the number of rings in cell *i*. These gene-instances in our design correspond to mobile users that are transmitting from specific rings. We use binary coding scheme and the value of the gene will be 1 if the corresponding user is transmitting in that time slot or 0 otherwise. On the other hand, the phenotype information for a genotype instance is represented by the set of active links that the corresponding users are activating in each time slot. For the two cell example, using the notation of the links shown in Fig. 7 for uplink transmission, the phenotype of gene *γ1* is 1 (link *l*1 is used), for gene *γ2* can be 2 or 4 (link *l*2 or *l*4 can be used), and so on. With this scheme the topology is given by a set of chromosomes that define the partial topologies generated in *B* time slots and are denoted by *PTb* (*t*) □, where *t* is the index of the topology, *b* is the index of the time slot *b = 1,…,B* and *γ* the index of the gene.To illustrate the encoding scheme a simple example of a possible topology (*t* = 1) is considered, for two cell case and **a** = **1**, that consists of the set of links 1 2 3 7 8 9 *T*(1) {*PTb* (1)} *l* , *l* , *l* , *l* , *l* , *l* □□□as shown in Fig. 5.

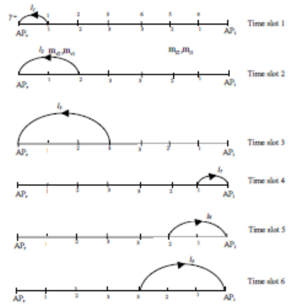

Fig. 5. The transmission pattern for topology index t = 1.

In this case every user transmits in a separate time slot directly to its access point.
The partial topologies are:

$$PT_{\gamma}^{b=1}(1)=\{l_1\}\rightarrow genotype=(100000)\rightarrow phenotype=1\text{-}0\text{-}0\text{-}0\text{-}0\text{-}0$$
$$PT_{\gamma}^{b=2}(1)=\{l_2\}\rightarrow genotype=(010000)\rightarrow phenotype=0\text{-}2\text{-}0\text{-}0\text{-}0\text{-}0$$
$$PT_{\gamma}^{b=3}(1)=\{l_3\}\rightarrow genotype=(001000)\rightarrow phenotype=0\text{-}0\text{-}3\text{-}0\text{-}0\text{-}0$$
$$PT_{\gamma}^{b=4}(1)=\{l_7\}\rightarrow genotype=(000100)\rightarrow phenotype=0\text{-}0\text{-}0\text{-}7\text{-}0\text{-}0$$
$$PT_{\gamma}^{b=5}(1)=\{l_8\}\rightarrow genotype=(000010)\rightarrow phenotype=0\text{-}0\text{-}0\text{-}0\text{-}8\text{-}0$$
$$PT_{\gamma}^{b=6}(1)=\{l_9\}\rightarrow genotype=(000001)\rightarrow phenotype=0\text{-}0\text{-}0\text{-}0\text{-}0\text{-}9$$

As we can see, the previous topology consists of a set of six chromosomes (partial topologies) that give the information of which user is transmitting in each time slot and which link is being used. To extend the previous notation to bidirectional links, the genes are duplicated. So, every partial topology is defined by two genotypes (uplink/downlink) and two phenotypes. The vector of gene-instances now should include also the access point 1 0 1 1 (,...,) (, ,...,) *Nc N Nc* □□□̃ □□ □ □□. Each vector □*i* consists now of *i n* + 1 components, where *i n* is the number of rings in cell *i* and the first entry of □*i* represents transmissions from/to the *i*th access point. To illustrate the encoding scheme with bidirectional links, we present an example where the transmission pattern presented.

2.6 Traffic cognitive topology control

After modeling our dynamic topology search problem by genetic algorithm GATSL, in this section the functioning of the network based on this approach is described. The network will be referred to as Traffic Cognitive Network (TCN).n More specifically we discuss the operation of the Traffic Cognitive Topology Control (*TC*)2 algorithm to adjust the topology to the traffic variations in the network by sequential genetic algorithm. The term cognitive refers to the awareness of the traffic variation.

To model the traffic in a TCN, we use the traffic vectors □and □described in Section 3.2. For a given spatial traffic distribution the access vector should be varied in time to provide *E*((*t*)) (*t*) □**a** □ □and *E*((*t*)) (*t*). □**a** □ □**.** The variation of the traffic in the network is defined by the vector1 1 (,...,) (,...,) *Nc N* _ □_ _ □□□where *c N* is the total number of cells and *N* is the total number of rings in the network**.** If the traffic in the network changes due to users that became inactive then the corresponding component of *n* □where the change occurs is negative. On the other hand if a new source appears in the network this component is positive. The differential access vector corresponding to the traffic variation is given by ' *I F* **a** □**a** □**a** , where **a**I is the access vector corresponding to the initial traffic and **a**F is the access vector after the traffic has changed (final). We assume that the traffic distribution is observed (cognition) in time intervals short enough to detect each change in the traffic so that traffic change only in one ring is assumed in a given observation instant. (*TC*)2 algorithm described below uses an exhaustive search (TSL) algorithm to find initial optimal topology and SGA-TSL for tracking traffic variations. Different options to initialize SGA-TSL are discussed in the following section.

The (*TC*)2 algorithm works as follows:

1) Calculate the access vector* aI *for a given traffic distribution λ and δ, by using (36).
***2) Use TSL to generate the set of feasible candidate topologies* □ (2)*for* aI.**
3) For each topology in the set* □ (2)*:
4) Calculate the aggregate powers needed for users to deliver the information.
5) Calculate the utility using (23).
6) Use CVX [126] to optimize the source rates in (34).
7) Go to 3) until the optimum topology* T* *is obtained or if the traffic distribution in the network has changed (* a' □ 0 *), use SGA-TSL to find the new optimum topology* T* *and go to 3).

The operation of *SGA-TSL* program can be summarized as:

***1. B1: number of time slots of the initial optimum topology* TB1 *for* aI (initial traffic)**
***2. f1: value of the fitness function (utility) associated with the initial topology* TB1**
***3. B': number of time slots of the optimum topology* TB' *for* a ' (differential access vector)**
***4. f0: value of the fitness function (utility) associated with the initialization of the new topology* TB0 (after traffic variation)**
***5. NA: number of active rings in the network after the traffic variation A n Fn N* □ □ a**
6.* procedure *Check_traffic_variation
7.* (( )) ( ); (( )) ( ) *F F E t t E t t* □ □ a □ □ a □ □ *{Assign access vector* aF *based on the existing traffic}
***8.* ' *I F* a □ a □a**
***9. If* a' □ 0**
***10. Apply TSL(*a'*) to obtain the optimum topology for* a'.**
11. Check the value of _ to initialize the new topology:
***12. - If _n*>0*, initialize the new topology as the set of chromosomes* TB0 □ {PTB1 ,PTB'} .**
13. - If _n* < 0*, the new topology is initialized as the set of the different
***14. chromosomes in both sets* TB0 □ {PTB1 - PTB'}**
15. Calculate the fitness function (f0) by using (23) and (34) with f0→U
***16. Initialize f = f0; n_m = 0;* aI = aF**
17. end
***18.* end**
19.* procedure *Calculate_fitness
20. Calculate f by using (24) and (34) with f→U
21. If (f-f0)>threshold
22. Reconfigure the system with T* = Tnew that corresponds to the fitness fopt = f
23. f0 = f;
24. end
***25.* end**
- - - - - - - - - - - - - - SGA-TSL algorithm - - - - - - - - - -
26. While (1)
27. Check_traffic_variation
28. for b = 1 to B0
29. Tnew = crossover(* PTb ,PT(b□ 1)mod B0 *);
30. Calculate_fitness
31. end
32. If (n_m < NA) {number of mutations < number of rings actived}
33. Tnew = mutation(* TB0 *,γn_m);
34. n_m++;
35. Calculate_fitness
36. end
37. end

Lines 1 to 5 define the variables used in the program. From line 6 to 18, the procedure

Check_traffic_variation is defined. In line 7, the access vector **a**F isassigned depending on the traffic variation. Line 8 calculates the differential access vector **a** ' . Line 9 examines if the traffic has changed. In line 10, TSL program is used to obtain the optimum topology associated with the traffic variation in the network, **T***B*' . This topology is needed to initialize the algorithm.

This topology has only one active source and TSL program should complete the search in few iterations. From line 11 to 14 the topology depending on the traffic variation is initialized to start the program. If a new source has appeared, the new topology **T***B*0 is initialized as the set (union) of partial topologies (chromosomes) of the initial topology **T***B*1 and the set of partial topologies corresponding to **T***B*' . On the other hand, if a source has become inactive then the new topology **T***B*0 is initialized as the difference between the two sets of partial topologies. In line 15, the fitness function *f0* for the new topology is calculated. In line 16 the instant fitness value *f*, the number of mutations *n_m* and access vector **a**I are initialized.From lines 19 to 25 the procedure *Calculate_fitness* is defined. In line 20, the fitness value *f* is calculated as result of the optimization described by (23). Line 21 checks if the new fitness value *f* is higher than the previous one *f0* plus certain threshold. The threshold can be zero or a positive value depending on how often the traffic changes in the network. If the previous condition holds, line 22 reconfigures the system with the new topology ***T****new*. From lines 26 to 37, SGA-TSL algorithm is described. Line 27 checks if the traffic in the network has changed. In line 28, the time slots of the new topology **T***B*0 are assigned to index *b*. The crossover of the partial topologies corresponding to **T***B*0 is performed in line 29 to obtain the new topology ***T****new*. In line 30, procedure Calculate_fitness is called. Lines 32 to 36 perform the mutation operation if *f* did not follow the previous requirements for the topology to be updated. As the mutation is performed gene by gene, line 32 checks if the number of mutations is less than the number of active rings in the network. Line 33 realizes the mutation operation over gene *γn_m*. Line 34 updates the number of mutations. In line 35 procedure *Calculate_fitness* is called again to check if the new fitness value *f* has improved compared to the previous one *f0* to reconfigure the network with the topology associated to *f*.

Finally, the algorithm goes back to 26 to check again the traffic or to continue with the crossover and mutation operations to find a better fitness.An extensive set of examples is given in Section 3.7 to illustrate the performance of SGA-TSL algorithm for different traffic variations.

2.7 Performance evaluation

2.7.1 Numerical examples

In this section, we provide some examples to evaluate the performance of the proposed SGA-TSL algorithm. The link capacities 1 2 1 2 (, , ,) *r r r i i c m m* **m m** are calculated as specified in Section 3.2. The channel gains *mi*1,*mr* 2 *G* and *mi*1,*mi* 2 *G* depend on the distance between the transmitter and receiver, and fading. For simplicity, we adopt the same model as in Section 2.8 where only propagation losses are considered. The channel gains are defined as 1, 2 1, 2 1/*mi mr mi mr G* ~ *d* where *mi*1,*mr* 2 *d* is the distance between the interfering transmitter in ring *i*1 *m* and reference receiver in ring *r*2 *m* , and is the propagation constant. The calculation of *mi*1,*mr* 2 *d* is straightforward from the geometry presented in Fig. 6.

In Fig. 5, the utility function versus the topology index *t* for access vector **a** = [010010] is shown. With this access vector user in ring 2, in both, cell *r* and *I* have permission to transmit. As the number of possible topologies obtained for this access vector is very high, we plot the segment of topologies close to the optimum topology. With no coding the maximum utility is *u* = 0.5826 while with network coding maximum utility is increased up to *u* = 0.6991. We can see that different topology indexes can provide the same value of utility. This is due to the fact that those topologies consist of different combination of the same active links in different slots.

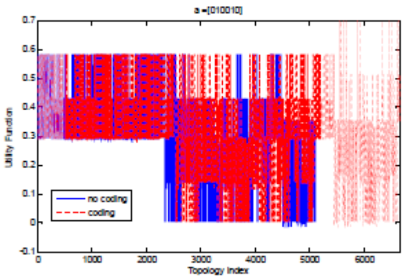

Fig.5. Utility function for access vector a = [010010].

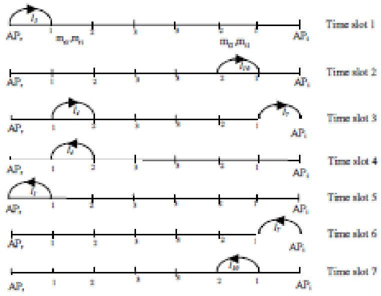

Fig. 6a. Representation of the transmission pattern defined by the topology index t = 7.

In Fig. 6a the transmission pattern is shown for one of the optimum topologies (topology index *t* = 7) in the case with no coding, for the previous access vector, defined by the set of links ( ) ( ) ( ) ( ) ( ) ( )

( ) ( ) 7 1 10 4 7 4 1 7 10 *T* {*l down* },{*l up* },{*l down* ,*l up* },{*l up* },{*l up* },{*l down* },{*l down* } . We can see that isolated short range transmissions are favored which can simultaneously reduce the inter cell interference and power consumption. In Figs. 25a and 25b the transmission patterns for two topology indices that correspond to the maximum utility with coding (t = 5571 and t = 5621) for the previous access vector are presented. The optimum topologies for the two cases are given by ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) 5571 1 10 4 7 1 4 7 10*T* {*l down* },{*l up* },{*l up* },{*l down* },{*l up* *l down* ,*l up* *l down* } and ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) 5621 1 4 7 1 4 10 7 10*T* {*l down* },{*l up* },{*l down* },{*l up* *l down* ,*l up* },{*l up* *l down* } .

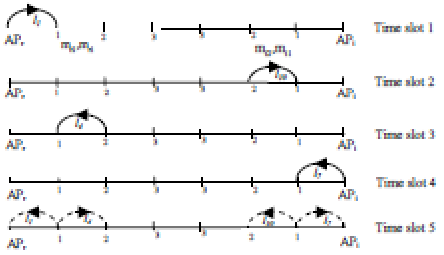

Fig. 7a. Representation of the transmission pattern defined by the topology index t = 5571.

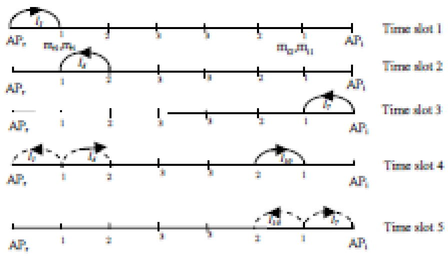

Fig. 8b. Representation of the transmission pattern defined by the topology index t = 5621.

We can see an improvement in the number of slots needed when network coding is used (5 slots) compared to 7 slots in the case with no coding. So, for the same type of isolated and short range transmissions the utility function is improved with network coding by reducing the number of slots. In Fig. 8 the overall capacity for the previous access vector **a** is presented. We can see that the overall capacity of the system obtained for the optimum topologies is improved by a factor 1.5 when network coding is used compared with the case with no coding. The overall capacity obtained for optimum topologies is 4 times higher than for non optimum solutions.

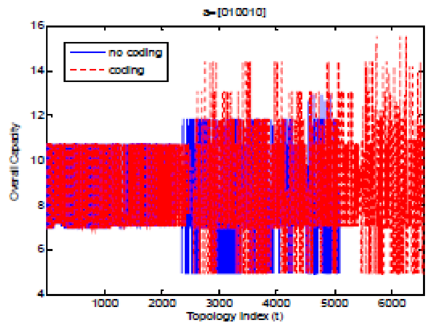

Fig. 9. Overall capacity for a = [010010].

In Fig. 10, the utility function is shown for **a** = [010100]. With this access vector user from ring 2 in cell r and user from ring 1 in cell i have permission to transmit. The maximum utility is obtained for topology index t = 478 (u478 = 0.8739) by using network coding. We can see a significant improvement compared with the maximum utility with no coding, obtained for topology index t = 215 (u215 = 0.6640). Both utilities are higher than in the previous case due to lower interference level.

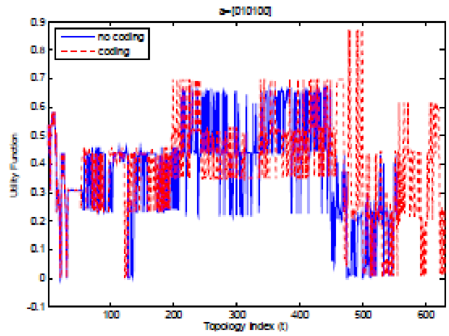

Fig. 10. Utility function for access vector a = [010100].

2.7.2 Comparisons

We compare the results obtained by SGA-TSL algorithm in, with the conventional routing protocols, used in ad hoc networks, which are based on collecting the information from the nearest neighbor. In this case, the topology is reconfigured in such a way that the users relay to their nearest neighbor. The results of this comparison are shown in Fig. 30. The fitness function obtained by nearest neighbor heuristic is significantly lower than the optimum value obtained by SGA-TSL. In some cases the value obtained by nearest neighbor heuristic can reach up to 50%.

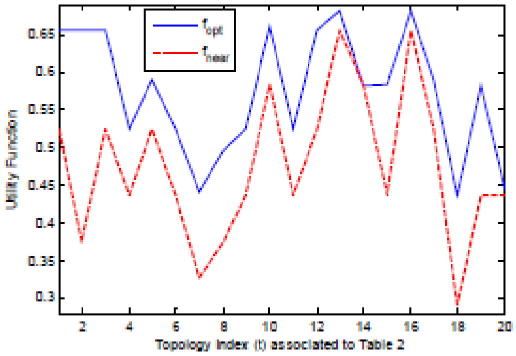

Fig. 11. Utility function for topologies *t* associated to Table 2 by SGA-TSL and nearest neighbor heuristics.

III. Conclusion

In this chapter, we have presented a dynamic joint optimization of relaying topology, routing (power) and inter relay scheduling in MCNs. As a result we have developed a specific encoding and fitness control in a sequential genetic algorithm for relaying topology update. Depending on the traffic load, there may be situations where searching for the new optimum topology will be NP-hard. Through numerical simulations we have shown that by using SGA the number of operations required to reconfigure the optimum topology is significantly reduced independently of the initial topology of the network. The utility function used in the optimization process drives the solution towards the topology favoring simultaneously isolated and short range transmissions.

As expected, within these solutions further improvements are obtained by using network coding to reduce the number of slots needed for transmission. In addition to optimum performance in terms of network utility, numerical results demonstrate also significant improvements in the convergence rate of the new algorithm. The number of generated topologies in the search for the optimum one by using SGA-TSL is at least one order of magnitude less than by exhaustive search. The same order of improvement is obtained independently of the initialization of SGA-TSL. We also have compared the performance of SGA-TSL with nearest neighbor heuristic and the value of the fitness obtained is about 50% lower than with SGA-TSL. SGA may be implemented in one of the base stations. Cooperating base stations must exchange information about the traffic distribution, and the coordinating base station should pass the information about the resulting access vector **a**F back to the cooperating base stations. This level of coordination between the base stations seems to be already considered in practice *i.e.*, coordinated multipoint transmission, where a cluster of base stations jointly perform beam forming in order to reduce inter cell interference.

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