Self-organizing Networks for 5G: Directional Cell Search in mmW Networks

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***Abstract*—We discuss the motivation and potential use-cases of self-organizing networks (SON) in 5G networks. Disruptive technologies and features of 5G networks include millimeter wave (mmW), massive multiple-input multiple output (MIMO), and cloud-radio access network (C-RAN). These have ramifications on SON aspects of the networks. We discuss several new SON use-cases and problems pertinent to emerging 5G technologies. The discussed 5G SON use-cases include spectrum management and sharing, user association, multi-radio access technology (RAT) optimization, and directional cell search for mmW networks. We then investigate directional cell search in detail, and consider a network graph based approach for self-organized beam assignment in mmW 5G networks. Simulations results in a realistic Manhattan environment demonstrate the benefits of proposed approach, in terms of improved user signal-to-interference plus noise ratios to potential handover beams, thereby resulting in better directional cell discovery.**

I. Introduction

The phenomenal growth in the popularity of wireless devices and Internet based services in recent years has spurred an exponential increase in demand for higher data rates, seamless coverage, and ubiquitous connectivity. Novel use-cases and applications are emerging rapidly, in areas such as health-care, smart living, transportation, and industrial automation. Recently, the 5G paradigm is envisaged for meeting these challenges, especially in future networks to be deployed in the 2020 time frame. The main paradigms of 5G include massive broadband, massive machine communications, and mission critical communications. Massive broadband focuses on enabling a $1000\times$ increase in aggregate data rates via extreme densification, increased spectrum, and higher spectral efficiency [1]. Massive machine communications and mission critical communications constitute the paradigm of machine type communications — a distinguishing feature of 5G. The motivation for massive machine communication is to support connectivity of massive number of devices to a common platform, whereas mission critical communications aims at providing ultra-reliability defined as 99.999% reliability and 2 millisecond latency. In order to meet the aforementioned requirements and performance targets envisioned for 5G networks, a multitude of potentially disruptive technologies are currently under consideration. For instance, emerging technologies for enabling massive broadband include small cells, massive multiple-input multiple output (MIMO), and millimeter wave (mmW) operation [2], [3].

It is worth noting that introduction of new technologies may impact different aspects of network design and operation, especially the ones that are related to CAPEX/OPEX and energy consumption. In this regard, the potential of self-organizing network (SON) functionalities in 5G networks cannot be overstated [4], [5], [6], [7]. In particular, disruptive 5G technologies motivate the need for defining new SON use-cases tailored to the needs of 5G networks. Apart from the aforementioned technologies, upcoming features such as multi-radio access technology (RAT) operation and interoperator spectrum sharing, can benefit from SON. From a 5G perspective, centralized SON is relevant for most use-cases, due to the centralized nature of cloud-radio access network (C-RAN) architecture [5]. Moreover, application of network virtualization and software defined networking (SDN) concepts will introduce a high degree of programmability and agility in the network, paving the way for an efficient network automation. In particular, SDN is inherently suitable for enabling SON functionalities in RAN [8]. The key benefit of virtualization is that it enables an efficient sharing of radio and hardware resources, whereas an SDN based architecture comprises of a logically centralized control entity, with a global view of the network. Thus, integration of these technologies can enable quick network configuration and resource optimization via dynamic automated mechanisms [5]. The programmable nature of SDN controllers can be leveraged to run self-organizing programs for managing the network and optimizing resource usage. The fine grained and centralized control of network wide resources can enhance the gains achievable by SON mechanisms, particularly for the use-cases related to resource sharing and utilization.

In this paper, we identify possible use-cases for 5G SON, and discuss their potential from a 5G perspective. Then, we focus on a use-case specific to mmW 5G networks – directional cell search. A 5G SON framework based on network graphs is discussed to address this use-case. Simulation results are presented to analyze the performance of proposed approach.

The rest of the paper is organized as follows. Section II gives an overview of different potential SON use-cases for 5G. and III discusses the cell search problem. Finally, conclusions and future research directions are given in Section IV.

II. Road to 5G SON: Use Cases and Graph Models

The main use-cases for 5G are motivated by the characteristics which differ from 4G networks, and pave the way for application of SON for an efficient network operation [9], [10]. Potential SON use-cases for 5G networks are as follows.

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A. Spectrum Management and Sharing

Efficient management and sharing of available spectrum between operators is paramount to higher capacity and lower costs. In 5G a multitude of new interoperator spectrum sharing paradigms will be introduced. Examples include licenced shared access, Licenced Assisted Access (LAA), citizen broadband radio service, co-primary spectrum sharing, and pluralistic licencing. Automated management and sharing of spectrum between RANs belonging to different operators is an attractive use-case for SON. The respective spectrum controllers of the operators may interact with each other and with the spectrum database. The time scale of operation depends on the nature of spectrum sharing scheme. Similar approaches can be applied for low level spectrum sharing for interference mitigation in a single operator RAN, albeit in centralized manner with a faster time scale.

B. User Association

A common method of user association is that a user selects base station on the basis of reference signal strength indicator. This method is intrinsically sub-optimal for ultra dense and multi-tier networks, due to non-uniform user distribution and asymmetric transmit powers of base stations. In particular, interference is a key issue in reuse-1 deployments. Consequently, user association can have a profoud impact on network performance. Heuristic approaches based on the concept of biasing have been proposed for multi-tier networks. Its increasing importance in 5G motivates the use of SON based techniques. Efficient user-association can lead to significant performance improvement in massive MIMO networks [11].

C. Multi-RAT Optimization

In 5G networks, multiple RATs on both licenced and unlicenced spectrum bands will co-exist, particularly LTE/LTE-A (with LAA) and WiFi. Thus, RAT-selection in both uplink and downlink is a problem of interest for 5G networks [12], [13]. Efficient selection of RAT using SON will lead to better network performance. Both network assisted [14], and fully distributed approaches have been reported in literature [15], with promising results. Other SON problems that come under this use-case include traffic steering and inter-RAT handover optimization. Joint optimization of multi-RAT parameters is essential for an efficient overall resource usage.

D. Directional Cell Search

In existing cellular systems, cell search is done using omnidirectional antennas or sectorized antenna patterns. A defining characteristic of 5G is mmW band operation using highly directional antennas, which are to be used both during network discovery phase and for user specific transmissions. Otherwise, there may be a mismatch between the range of a cell where the network is discoverable, and the range where an acceptable service is possible [16]. However, the use of directional beams complicates the cell search procedure. The key challenge is to enable cell search using highly directional beams over a large angular domain [17], [18]. In [17], a directional cell discovery procedure is proposed, which is based on periodic transmission of synchronization signals in time-varying random directions. Context-based cell search based on user location is discussed in [19]. A comparative analysis of initial access techniques is presented in [20]. Therefore, from a perspective of 5G SON, directional cell search is an important problem for enabling mmW operation.

E. Graph Based Approaches for SON

In the rest of the paper, we discuss a directional cell search procedure based on a graph based network model. Graph based models simplify the modeling and abstraction of networks, paving the way for efficient network-wide resource allocation and management. These methods have been used for LTE/LTE-A SON problems, such as physical cell ID assignment and primary component carrier selection [21], [22]. The accuracy and information in the network graph depends on the underlying measurement and reporting mechanisms. Moreover, a hierarchy of graphs can co-exist, reflecting the information regarding the network state at different levels. The abstracted information from lower-levels can be aggregated and presented to upper control layers as different types of graphs. The upper layers can use these for high level resource allocation and spectrum management. In this regard, the importance of proper low level abstractions cannot be overemphasized, as it has a direct impact on the signaling load for measurement and reporting.

The concept of centralized coordinator in 5G can further enhance the benefits of such approach, by aggregating and abstracting the measurements and information received from low levels, and creating a network graph. It can also control the time-scale and the type of measurements being performed by the lower level entities. A centralized view of the network constructed from abstractions is an essential step towards an efficient network-wide resource allocation. Once the network graphs are created using the abstractions from the lower layers, SON programs can be run in the centralized coordinator on these graphs to optimize the network [23].

In what follows, we discuss such a framework for directional cell search in 5G networks. In this particular case, the network can be modeled as a multigraph, and resource allocation corresponds to multicoloring problem.

III. Directional Cell Search in mmW Networks

The network graph based SON framework for beam assignment is illustrated in Fig.1. The users are involved in measurement and reporting of potential handover beams to the serving base station. The base station creates a local neighborhood graph on the basis of abstractions of the measurements received from the users. Moreover, it forwards the local graph to the central coordinator, which then constructs a network graph. The SON programs are run by the central coordinator on the created network graph. A feedback loop exists via which the central coordinator controls the base stations. It can also ask base station and users for measurements and abstractions. The central coordinator has a picture of over the overall resource situation in the whole network. An alternative to centralized SON enabled by the central coordinator, is distributed SON run by the base stations. Compared to centralized method, distributed beam assignment is more scalable and easier to be implemented. Next, we discuss the system model and algorithms for the beam assignment problem.

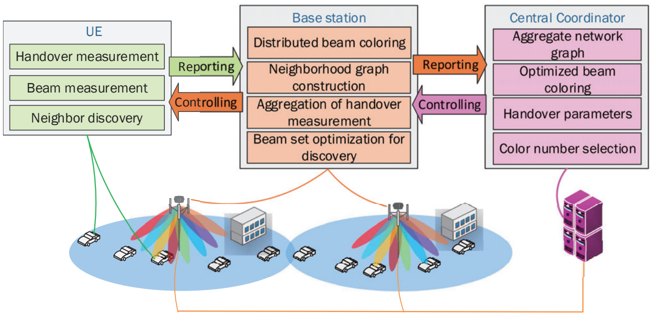

Fig. 1. Framework for self-organized directional cell search.

A. System Model

We consider a graph multicoloring formulation of the directional cell search problem in a 5G mmW MIMO cellular network. This formulation enables the application of various graph coloring algorithms based on local search metaheuristics. We model a network consisting of $I = |\mathcal{I}|$ base stations. For transmission of discovery signals, each base station has a set of fixed beams $\mathcal{B}_i$. The number of available beams is same in all the cells, i.e. $|\mathcal{B}_i| = B$, for all $i \in \mathcal{I}$. In order to cover the whole cell (or sector), time division multiplexing is used for broadcast transmissions from the beams – in a given broadcast channel resource, one beam, or a subset of beams, is used for broadcast transmission of discovery signals for cell search. These beams enable the users to discover the cells. A user is able to discover a given cell only if the beam from the base station of that particular cell is pointing in its direction, and the interference from own cell beams in under control. The spectrum allocation among base stations is based on reuse-1, thus beams may interfere with each other. Accordingly, it is important for a base station to schedule its beams in a way that not only the whole cell is covered, but the interference to the beams of other cells is minimized. For this, a graph multicoloring formulation of the problem along with different algorithmic approaches can be used.

1) Graph Multicoloring: Let $G(\mathcal{I}, \mathcal{E}, w)$ denote a multigraph representation of the network, where $\mathcal{I}$ and $\mathcal{E}$ are the sets of vertices and edges, respectively. A function w is defined on the set $\mathcal{E}$, such that $w(e)$ is weight of the edge $e \in \mathcal{E}$, and each vertex is assigned colors from a set $\mathcal{B}_i$. The aim is to minimize the net weight (interference) on the edges.

2) Weighted Directed Multigraph: The graph is constructed on the basis of user measurements by considering interference-to-carrier (I/C) ratios between the strongest beam of potential handover candidate cell, and the beams in own-cell. During network operation, a cell collects historical information from handover measurements of its users during operation, and aggregates this to a local description of the graph underlying directional cell search. A user receives multiple beams with varying powers from each base station. Let us denote the power received by user $u \in \mathcal{U}$ from its serving base station i on beam b is $p^u_{i,b}$. In cell i, there is a subset of beams $\mathcal{B}_{\mathrm{HO}\to j} \subseteq \mathcal{B}_i$ which are potential handover candidates (best other-cell beams) for at least one user in the network. Let $\mathcal{U}^b = \bigcup_{j\in\mathcal{J}} \mathcal{U}^b_j$ denote set of such users currently served by a set of base stations $j \in \mathcal{J}$ (with a set of beams $\mathcal{B}_j$), and considering a potential handover beam $b \in \mathcal{B}_{\mathrm{HO}\to j} \subseteq \mathcal{B}_i$. Thus, for each user in $\mathcal{U}^b_j$, there exists a set $\mathcal{B}_j$ of own-cell beams, and a single potential handover beam. Based on the interference a user receives from its own-cell beams $\mathcal{B}_j$, and the received power from potential handover beam b, an I/C vector is calculated for each user. It represents a coupling between user $u \in \mathcal{U}^b_j$ of cell j and beam b of cell i. The base station collects the history of these measurements, and aggregates the user I/C vectors by taking a maximum over the own-cell users $\mathcal{U}^b_j$. This gives an I/C vector $\mathbf{x}^b_{j,i} \in \mathbb{R}^B$, given as (1). It represents the worst I/C coupling between users served by cell j, which consider a beam in cell i as a potential handover beam.

$$\mathbf{x}^b_{j,i} = \max_{u\in\mathcal{U}_j} \left[\frac{p^1_{i,u}}{p^b_j} \cdots \frac{p^{|\mathcal{B}_i|}_{i,u}}{p^b_j} \right] \tag{1}$$

The global network graph for directional cell search can be aggregated at a central coordinator. Vectors describing the local network view at different cells can be used to populate an adjacency matrix $\mathbf{A} = [a_{k,l}]_{BI\times BI}$. The rows $k = Bi{+}1 \ldots B(i{+}1)$ denote the B potential handover beams of base station i, and the columns $l = Bj + 1 \ldots B(j + 1)$ denote the index of the beams of host base station j whose users are measuring potential handover beams. For row k, the elements of columns $l = Bj + 1 \ldots B(j + 1)$ are filled by the vector $\mathbf{x}^b_{j,i}$, in the row that corresponds to beam b of cell i. Thus, an adjacency matrix is created which characterizes the interference between own-cell beams and other-cell potential handover beams.

B. Algorithms

The beam assignment problem is a multicoloring problem. Each base station needs to select a color combination with B colors. The task is to schedule a set of beams $\mathcal{B}_i$ of each base station i in B time slots such that the interfering beams are assigned to different time slots, so that I/C the users experience to the potential handover candidate beams is reduced. Alternatively, broadcast transmissions to 2 or 4 beams simultaneously can be considered. Here, we use a local search based algorithm, given as Algorithm 1. The algorithm is executed in a centralized manner by the central coordinator. However, it is straight-forward to formulate its distributed variant, which would be run at the level of base stations.

Algorithm 1 Beam Assignment Algorithm

Cell i using a valid beam schedule c, selects a new schedule $c' = \mathrm{RandPerm}\{c\}$ for cell i. Keep the beam schedules for other cells fixed.
Find the set of UEs $\mathcal{U}_i$ which are associated with cell i. For $\mathcal{U}_i$, calculate the I/C vector V_c and $V_{c'}$ for beam schedules c and c'. Compute $\Delta = \max(V_{c'}) - \max(V_c)$,
if $\Delta < 0$ **then**
    $c \leftarrow c'$
else
    $c \leftarrow c$
end if

C. Simulation Results

The simulations are carried out using a Manhattan model shown in Fig. 2, where the number of base stations $|\mathcal{I}| = 48$. A summary of the parameters used in simulations is given in Table I. The historical collection of experiences of users in the network is collected by a uniform sampling of $|\mathcal{U}| = 2560$ user positions. Each base station serves a given sector with $|\mathcal{B}_i| = 16$ beams. A planar array model is used for beamforming broadcast. Cell discovery broadcast beams are transmitted during a number of time slots assigned by the central coordinator. The number of time slots (beam colors) is assumed to be 16 , 8, or 4. A smaller number of time slots for discovery purpose results in less overhead for neighbor cell search. When there are less colors, discovery signals are transmitted simultaneously to multiple directions. The idea is that most of the broadcast channel information, common to the cell, may be transmitted to multiple cells simultaneously. Only a small part of broadcast information would be beam specific. We have designed different kinds of beam patterns for this planar array, as depicted in Fig. 3. For a setting of 16 colors, single beams is transmitted during one slot. Paired beams and quadrupled beams are used for settings with 8 colors and 4 colors. The beam assignment SON-algorithm given as Algorithm 1 is used to improve the signal-to-interference plus noise (SINR) performance for handover users. Simulation results are shown in Fig. 4. The distribution of SINRs of the handover measurements are shown, for users that are in the handover regions, i.e. the received power from a neighboring cell beam is within 10 dB of the received power of the best serving cell beam. The initial point of each base station is a fixed permutation of beams over time slots. At an update instant, a base station creates a new random permutation c' as a potential local move, and tests it for the maximum I/C values for handover users. The result shows that, the setting of 16 colors with 16 directional single beams results in best handover discovery SINR performance. Using less colors results in less overhead in neighbor cell search, but the SINR performance will degrade due to the smaller beamforming gain and increasing interference by using paired beams or quadrupled beams. It can be seen from the results that in this setting, one iteration is almost optimal for the distributed update of color patterns for each cell.

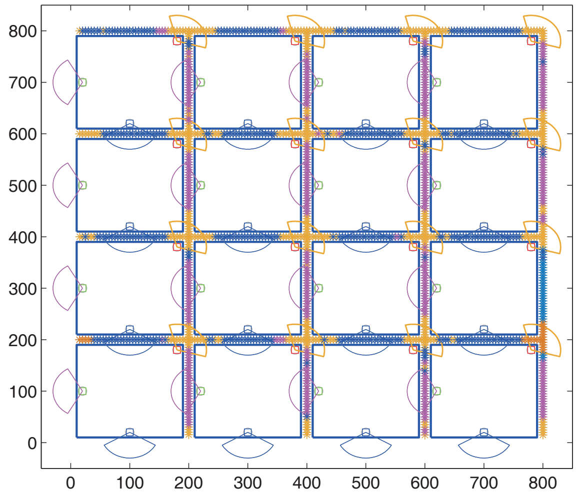

Fig. 2. Manhattan scenario and base stations with planar array

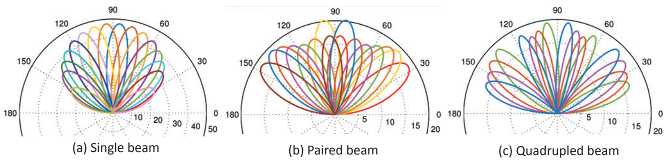

Fig. 3. Beam pattern for $|\mathcal{B}_i|$ = 16,8,4

IV. Conclusion and Future Work

This paper gives an overview of SON in the context of 5G, and discuss several potential use-cases related to disruptive technology directions in 5G networks. The use-case related to directional cell search was investigated in detail. Transmissions

TABLE I
Simulation Parameters

Simulation Configuration	
Scenario	Manhattan grid, 800 × 800m
Boundary conditions	Wrap-around in all directions
Average Inter-site Distance	100m
Number of BSs	48
Number of UE positions	2560
mmW carrier frequency	28 GHz
LOS PL model for mmW	$61.4 + 20\log_{10}(d)$
NLOS PL model for mmW	$72.0 + 30\log_{10}(d)$
LOS probability model	$\left(\min\left(\frac{d_1}{d},1\right)\left(1-\exp\left(\frac{-d}{d_2}\right)\right)+\exp\left(\frac{-d}{d_2}\right)\right)^2$
LOS correlation distance	10 m
Maximum mmW TX power	24 dBm
mmW antenna for BS	8 × 8 planar array
Beamforming setting	Analog beamforming with simple precoding
Number of beams	16, 8 or 4
Number of colors	16, 8 or 4
Handover margin(HOM)	10dB

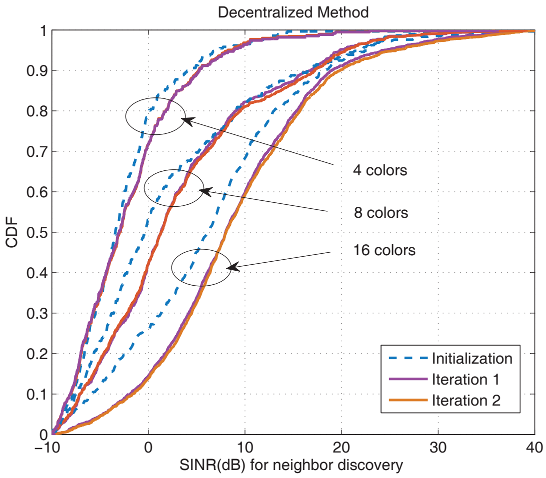

Fig. 4. SINR performance for cell search with different number of colors

of broadcast signals to multiple beams simultaneously can be used to reduce the amount of resources needed for cell search, or to reduce the latency in finding neighboring cells. The cost of this is reduced SINR in handover measurements, as there are more beams transmitting broadcast signals simultaneously with the potential handover beam in a neighbor cell, and the broadcast signals have smaller coverage. This leads to an increased number of Radio Link Failures (RLFs). Moreover, a centralized coordinator may use more involved SON-algorithms to improve the most precarious combinations of beams from two cells, to reduce RLFs, and to trade-off handover reliability against the amount of broadcast resources.

The potential ideas for future work include extending the proposed self-organization framework to model other relevant aspects of 5G SON, most notably energy efficiency. This may be enabled by transmitting beams only in the directions in which they are required, leading to reduction in energy consumption as well as probability of collision between the beams. Moreover, investigating the use of narrower beams, multiple beams per base station, and joint self-optimization of multiple parameters such as beam direction and transmission power, are other promising research directions.

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