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RETHINKING CELLULAR NETWORK PLANNING AND OPTIMIZATION

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ABSTRACT

To meet the ever increasing demand of wireless services for high data rates and mobility, mobile communication systems have evolved from the first generation cellular network to the current 4G one. The core purpose of a cellular network is to provide users with guaranteed QoS and seamless coverage throughout the service area. In the early stage, this task is achieved by installing cells at candidate sites and configuring their parameters as optimally as possible. Generally, each cell is assigned a dedicated operating frequency, and its adjacent cells operate on different frequencies to avoid inter-cell interference. As the evolution of the cellular network proceeds, advanced signal processing techniques, such as coordinated multipoint transmission and reception, and inter-cell interference coordination, are rising as promising solutions to improve the system performance, which on the other hand inevitably increase the CAPEX and OPEX of the cellular system. Besides, as the deployment of cells becomes denser and denser, it is more and more difficult and expensive to obtain capacity or QoS gains with these signal processing techniques. In this article, we rethink the cellular network planning issue in the context of heterogeneous networking, which is widely accepted as a cost-efficient paradigm to enhance the performance of the cellular system. We point out that the essential objectives of designing a cellular network, coverage and capacity, can also be achieved in heterogeneous networking scenarios using a cutting-edge territory division technique, which divides a service region into multiple subregions with almost equal traffic loads. We develop a dynamic cellular network planning framework that can significantly reduce the CAPEX and OPEX of the system. The QoS for users can also be enhanced while shifting away from employing complex and costly signal processing techniques.

INTRODUCTION

The cellular mobile communication system has experienced a process of successive evolution over the past decades, driven by the ever increasing demand of wireless services for high data rates and mobility. From the first generation (1G) system to the current worldwide 4G, the mobile communication system has experienced significant variations in many aspects. For example, multiple access methods have evolved from frequency-division multiple access (FDMA), time-division multiple access (TDMA) and code-division multiple access (CDMA) to orthogonal frequency-division multiple access (OFDMA) employed by the 4G network. Particularly, the infrastructure of the 4G network and beyond is totally different from the previous ones with well planned macrocells. Low transmission power access points, also referred to as small cells, such as picocells, femtocells, and relays, are deployed within the coverage of the conventional macrocells in the 4G system and beyond. Such an infrastructure is called a heterogeneous network (HetNet), which can improve the throughput of the system and quality of service (QoS) for users. Figure 1 depicts an overview of the evolution of mobile communication networks. Specific technical directions designed to achieve cost-efficient resource provisioning, diverse applications, and augmentation of intelligence have been identified [1]. As indicated in Fig. 1, denser and smaller cells are expected in future cellular networks, along with brand new communication frequency, antenna techniques, and architectures.

Since the introduction of the concept of cells in the 1940s, the key objective of a cellular system is to provide sizable capacity and ubiquitous coverage over the service area. At an early stage, during the design process, this aim is achieved by optimum selection of sites to install cells and determining their RF parameters, like the maximal transmitting power, antenna height, and the number and orientation of sectors [2]. The selected cells form the basis of the cellular network, which must satisfy certain performance requirements, including coverage and capacity, but minimize the infrastructure cost [3]. A map of conventional cellular network planning is presented in Fig. 2. Theoretically, the analytical approach consists of three elements: radio network definition, coverage/capacity analysis, and radio network analysis, which are passed in several turns iteratively. During radio network definition, experts choose proper cell sites and configure their parameters. The capacity and coverage issues are addressed in the next step, coverage/capacity analysis, which synthesizes factors such as morphography and interference

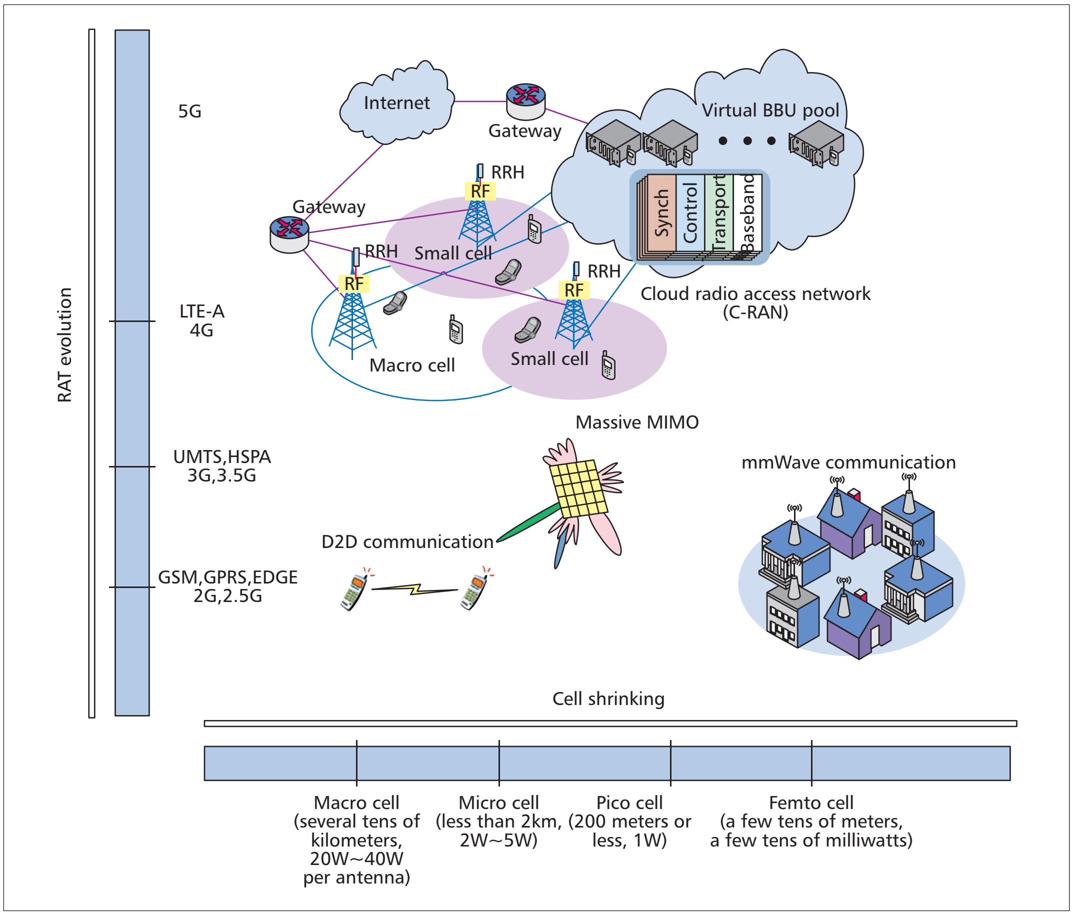

Figure 1. An overview of the evolution of cellular communication network. RAT: radio access technology. GSM: global system for mobile communications. GPRS: general packet radio service. EDGE: enhanced data rates for GSM evolution. UMTS: universal mobile telecommunications system. HSPA: high-speed packet access. D2D: device-to-device. MIMO: multiple-input multiple-output. LTE-A: long term evolution advanced. RRH: remote radio head. BBU: baseband unit.

Frequency reuse exploits the fact that signal power falls off with distance, which means that the coverage area of a cellular system can be divided into non-overlapping subregions, also referred to as cells, and the same channels can be shared between cells at spatially-separated locations.

distribution to generate the optimum resource allocation. Radio network analysis calculates the QoS values of the area considering channel characteristics and key performance indicators (KPIs) definition [2]. An early cellular system (1G) generally assigned a dedicated operating frequency to each cell, and the adjacent cells were assigned different frequencies to avoid inter-cell interference. This was the most important interference elimination strategy for radio network planning in the next decades, up to and also including the era of the worldwide deployed Global System for Mobile Communications (GSM), a representative second generation (2G) cellular system for which cell planning was intensively investigated in both academic papers and practical network deployment. In contrast to the FDMA-TDMA used by GSM, the third generation (3G) cellular system adopted CDMA technology with a frequency reuse factor of 1. The interference cancellation for 3G networks relied on careful power control and multiuser detection techniques. Cell planning for 3G networks was also fully discussed during the last decade [4].

Interference management in the HetNet, which arose in the 4G system, is totally different from those in the previous cellular networks because the wide variations of transmission powers between macrocells and small cells make inter- and intra-cell interference difficult to address. Thus, advanced signal processing techniques, such as coordinated multipoint (CoMP) transmission and reception, and inter-cell interference coordination (ICIC), are rising as promising solutions to fulfill the potential performance gains of HetNets. Naturally, the capital expenditure (CAPEX) and operating expense (OPEX) of the network inevitably increase because of employing these complex and costly interference management strategies. However, as the deployment of cells becomes denser and denser, the cellular system becomes more and more complex, and the inter- and intra-cell interference could become uncontrollable in the near future. As a result, it is more and more difficult and expensive to obtain capacity or QoS gains with signal processing techniques [5]. We need a new viewpoint to analyze the problem of improving the performance of the cellular system, as well as new methods to address the consequent technical issues. In this article, we argue that cell planning, which is not paid much attention to in HetNets compared to that in conventional cellular networks, is still an effective and efficient way to enhance system performance. We also develop a novel cell planning method and show its advantages over existing strategies in the literature.

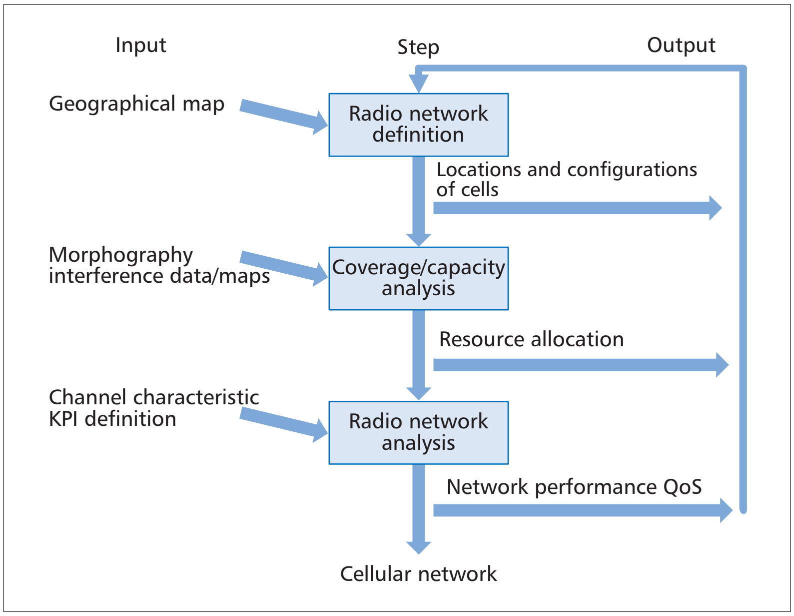

Figure 2. Conventional approach of cellular network planning.

The rest of this article is organized as follows. In the next section, we present a brief review of conventional cellular network planning. Then we point out the shortcomings of the current commercial cellular network planning scheme. Following that, we present a novel cellular network planning framework by employing a cutting-edge territory division method, which can yield a near optimum solution from the viewpoint of load balancing. Potential open questions are then discussed. Conclusions are drawn in the final section.

CONVENTIONAL CELLULAR NETWORK PLANNING

Since the radio spectrum for mobile communications is scarce, frequency reuse naturally arises at the very beginning of the commercialization of the cellular system. Frequency reuse exploits the fact that signal power falls off with distance, which means that the coverage area of a cellular system can be divided into non-overlapping subregions, also referred to as cells, and the same channels can be shared between cells at spatially separated locations. This is the premise behind early cellular system design. Conventional cell planning generally involves addressing a facility localization problem, which tries to determine the positions of cells in the service region and configure their parameters to provide acceptable system performance, such as power coverage and system capacity.

Reviewing the development of cellular systems, capacity and coverage are the two key targets in terms of cell planning. A general flow of cell planning for a cellular network starts from the analysis of a propagation model and traffic density in the target service region. The former is used to measure power coverage, of which the objective is generally that the received powers of the users in a given cell are above a threshold in the worst case in order to demodulate the expected information correctly; the latter is for capacity coverage, of which the objective is that a given cell can provide enough throughput for the users in the coverage of the cell. Both objectives should be achieved to provide users with QoS-guaranteed services. Moreover, from the viewpoint of the whole system, if the power and capacity can be optimally planned simultaneously, the deployment cost of the system would be minimized. However, compared to power coverage, which can be planned by using well-developed propagation models and field measurement, capacity coverage is more challenging because of the inherent dynamic characteristics of the traffic demand distribution, such as usage patterns and mobility of users. Especially at the beginning of designing a cellular system, only limited geographical and demographic features can be used, making the traffic density prediction in the service region very difficult, if not impossible, to determine accurately in advance. Thus, it makes sense for mobile service providers (MSPs) to pay more attention to capacity coverage than power coverage, which is relatively easy to handle.

The power coverage of a cellular system is generally achieved by selecting enough sites from the candidate ones to deploy cells and configure their parameters to meet the minimal received power requirements of the users in the cell. The candidate sites for deploying cells should be determined considering antenna height, terrain, and population density. The throughput of a cell is always designed to satisfy the maximum traffic demand among all cells that would be deployed. This design strategy is adopted by MSPs because it is reasonable for them to attach the first importance to the requirements of users, which is a prerequisite to gain profits. As a result, as long as the deployed cellular system can meet the current demands of users, extra cost should be paid as a matter of course even though it is not the optimal scheme from the viewpoint of the whole system. Moreover, such extra input can be covered by charging users served by the cellular system.

SHORTCOMINGS OF CURRENT COMMERCIAL CELLULAR NETWORK PLANNING

With the advent of 4G cellular systems, such as Long Term Evolution-Advanced (LTE-A) and beyond, the HetNet mentioned above is introduced as a promising infrastructure, where area spectral efficiency can be improved dramatically, as can be found in both academic research and field tests. However, the HetNet also faces a severe inter- and intra- cell interference management issue by which we have never been confronted [6]. Intuitively, the HetNet acts against the cornerstone of a conventional cellular system because the coexistence of macrocells and small cells would yield heavy inter- and intra- cell interference without targeted methods. Fortunately, advanced signal processing techniques, such as CoMP and ICIC, have tackled the interference issue in HetNets, at least partially. However, as noted earlier, enhancing system performance with advanced signal processing techniques is not a sustainable strategy. In other words, the capacity and QoS gains yielded in this way cannot always keep up with the increase of mobile traffic demands. The improved performance can be expected to meet its ceiling if relying on developing new interference management algorithms alone.

On the other hand, conventional cell planning that can suppress interference between macrocells seems unsuitable for the HetNet scenario because of the wide variation of transmission powers of different kinds of cells. Consequently, few investigations have been carried out on the systematic cell planning of the HetNet. Has cell planning also reached the end in terms of improving the performance of the cellular system, just as what happened to the single-link capacity for which the gap between theory and practice has been bridged [7]? We analyze the limitations of current cellular system design and point out that there is considerable room to improve system performance by employing more sophisticated cell planning techniques.

In most cases, traffic distribution is always unbalanced for a given service region in practical cellular systems. If each cell is designed with the same capacity, for example, the maximum traffic demand among all cells, it is inevitable that many of the cells are equipped with too much redundant capacity even though some capacity margins are necessary to address the variations of traffic demands in the service area. There is much capacity waste resulting from the current cellular network planning. Moreover, the MSPs have to deploy new cells when any of the deployed cells cannot meet the traffic demands of users served by it. The introduction of the microcell, picocell, and femtocell can be seen as the immediate output for such a cell planning strategy. Although it does not seem wise to meet the users' ever increasing traffic demands by deploying more cells, MSPs are usually willing to make such a choice because it mostly yields enough profit to compensate for the cost.

However, interference management among different cells becomes harder and harder to address, leading to introducing more and more complex signal processing and cell collaboration techniques, which increases the CAPEX and OPEX of the cellular system dramatically. As discussed above, it is uncertain that the advances of interference management algorithms can keep up with the increase of mobile traffic demands. Moreover, the site acquisition for a cellular system becomes more and more difficult, even impossible when the deployment of cells is dense enough in the foreseeable future. Recall that currently there is considerable capacity waste in almost all cellular systems. It is naturally desirable to develop new methods to plan the whole system in a more advisable way without changing the existing infrastructure of the cellular system. Motivated by these observations, we describe a novel cell planning scheme in the following sections.

CELLULAR NETWORK PLANNING: BALANCED TRAFFIC

As discussed earlier, not only can cell planning in a traffic-balanced way improve the performance of cellular networks, but it also decreases the waste of capacity provided by MSPs as well as decreasing the CAPEX and OPEX. Intuitively, for a given service region, if each cell serves a subregion with almost equal throughput requirement, the number of cells required to cover the whole service region could be the least. That is to say, if we could divide the service region into subregions with almost equal traffic demand, the total deployment cost would be the lowest. We highlight *almost* here because complete balance is not only unrealistic but also unnecessary in a practical mobile communication environment. Ideally, such a planning scheme achieves much better performance than that of the current cellular networks with unevenly distributed traffic. These analyses give insights on how to plan cellular networks in a cost-efficient way.

Theoretically, we can implement this planning scheme as follows. Given a region and the distribution of traffic demand points (TDPs) in the service region, we first roughly estimate how many macrocells are required to cover the region by considering the practical capacity supported by a macrocell and reserving sufficient margin to address the repeated traffic variations in a practical cellular network. Then we divide the region into the required number of subregions. Each subregion covers a (nearly) equal number of TDPs. At the same time, we should guarantee that at least one cell can be deployed in each subregion. Third, as we have not taken into account whether every TDP can be provided with QoS-guaranteed service, it is necessary that we figure out the effective coverage of each cell, considering propagation model and spectrum allocation. Finally, we deploy low-power cells in areas where reliable service is not promised with macro BSs alone in a traffic-balanced way as we do in the first two steps. It sounds good since each tier of the target cellular network is planned in a traffic-balanced way, which is cost-effective, and every TDP is provided with robust QoS guarantee. However, is it possible to plan a service region in this way? We present the details of our proposal in the following.

ESTIMATE THE NUMBER OF MACROCELLS REQUIRED TO SUPPORT THE TRAFFIC DEMANDS OF USERS

We have a geographic region S served by a cellular system, and a set of TDPs $N = \{1, 2, \dots, N\}$. The TDPs represent the traffic requirements of users in the service region, and each TDP corresponds to a unit of traffic demand for simplifying analysis [8]. The number of TDPs can be discovered from the database of the MSP that supplies services for the users, as well as the distribution of the TDPs, which is generally recorded by the mobile switch center of the MSP to figure out which cell provides access to an originating call. Additionally, the necessary margin for each cell should be reserved to cope with repeated traffic variation in the coverage of each cell. Denoting the total capacity required by all TDPs in S as T, the number of macrocells needed to serve the whole region is $K = (1 + m)*T/C$, where C is the average capacity supplied by a macrocell and m is the ratio of conserved margin to C.

Intuitively, for a given service region, if each cell serves a subregion with almost equal throughput requirement, the number of cells required to cover the whole service region could be the least. That is to say, if we could divide the service region into subregions with almost equal traffic demand, the total deployment cost would be lowest.

DIVIDE THE REGION INTO SUBREGIONS WITH EQUAL TRAFFIC

We aim to partition S into K subregions, where each subregion contains an almost equal number of TDPs with a total capacity of C. Since each subregion will be served by a cell, we should guarantee that at least one candidate site for BSs falls into each subregion to make the partition feasible for practical cell deployment. That is to say, we have to select K sites from all candidate ones to initialize our division procedure. For a given list of candidate sites supplied by the MSP, we can select K sites uniformly at the beginning. To be more specific, there are many initialization methods available. For instance, the initial positions for cells can be selected randomly from all candidate sites. A method named Rectangle Center to determine initial facility locations is proposed in [9]. On the other hand, if we dynamically plan a cellular network, which is more practical, the positions for the cells should be placed based on their former sites. One effective alternative scheme for determining the sites of the cells is that if the number of cells is larger than before, we can select extra cells from the candidate sites in traffic hot zones. Traffic hot zones here mean areas that have larger density of TDPs. If the number of cells is smaller than before, it is recommended that we remove the cells that serve the fewest TDPs. Otherwise, the sites for the cells remain the same as before. To divide the region S into K subregions with almost equal numbers of TDPs, advanced linear programming techniques are required. The algorithms proposed in [10, 11] are suitable for our purpose, where the objective function of the problem is minimizing the sum of distances between the TDPs and their corresponding cells, under the consideration that each subregion should be as connected as possible and that the TDPs tend to communicate with the nearest cells. The constraints of the problem could be listed as below. First, the number of TDPs served in each subregion should be as balanced as possible. Second, there should not be any coverage holes. Third, we assume that each subregion should not overlap any other without considering the offloading effect for simplification. The problem can be solved either with standard algorithms like cutting plane method or by using existing software such as CVX [12, 13].

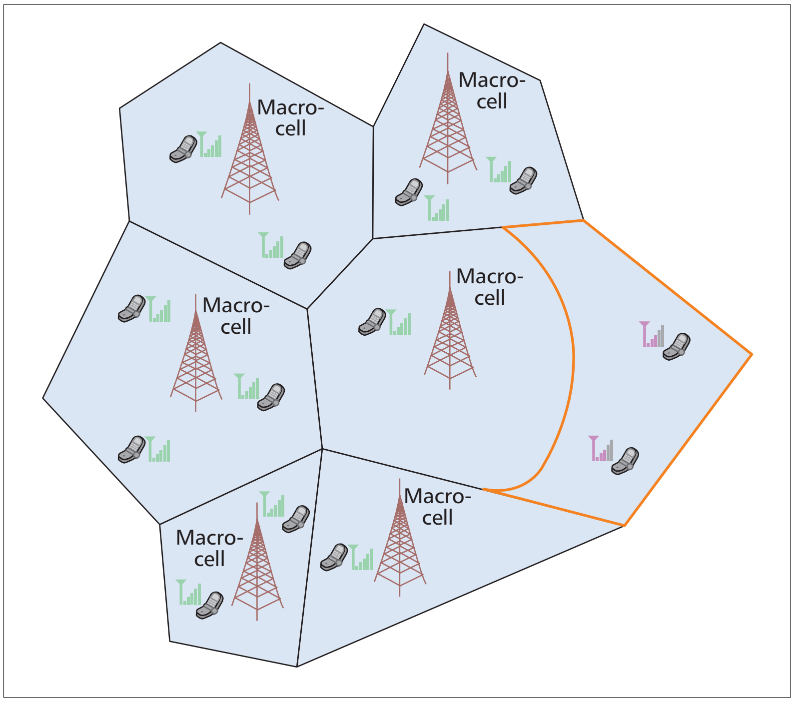

Figure 3. Some TDPs cannot get QoS-guaranteed service.

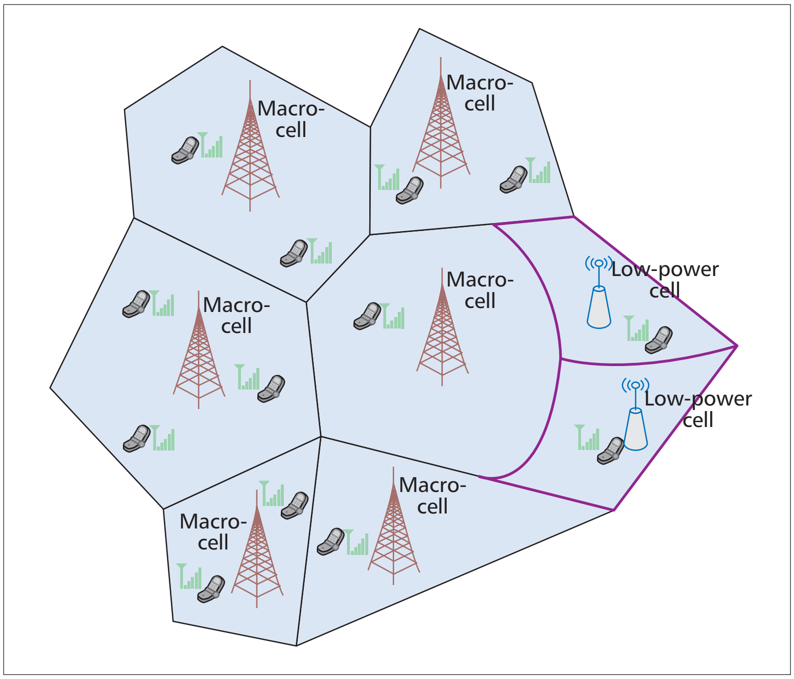

Figure 4. A map of network planning with low-power cells.

CALCULATE THE EFFECTIVE SERVICE AREA IN EACH SUBREGION

After the steps above, subregions with balanced traffic demand can be obtained. However, a new question arises: Does the cell in each subregion have the ability to provide all the TDPs in this subregion QoS-guaranteed service? It can easily be seen that as the first two steps have not taken into account factors such as propagation model and spectrum allocation, some TDPs such as those far away from their associated cells may not get reliable service, as shown in Fig. 3. The region marked by orange lines represents an area that cannot rely on macrocells alone for robust communication quality. It is necessary that we calculate the effective service area in each subregion to make sure that the QoS of every TDP is guaranteed.

PLAN LOW-POWER BSS FOR QOS-GUARANTEED SERVICE

Now that we have figured out the areas which cannot be provided with QoS-guaranteed service, some measures need to be taken to improve the QoS of the users in those areas. It is natural to consider deploying low-power cells in those areas to serve the TDPs without QoS guarantee. However, how we deploy low-power cells in these areas remains a question. Recalling the benefits of workload balancing and today's urgent need for improving the resource utilization rate, we can also plan low-power cells in a traffic-balanced way as we do in the first two steps. To be more specific, we fist estimate the number of low-power cells needed to provide services to the users in areas that cannot rely on high-power cells alone for robust communication. Second, we divide these areas into subregions with almost equal traffic demand. Third, as deploying two layers of BSs may not guarantee every TDP with robust service, it makes sense that we calculate the effective service area up to now. If all areas have been provided with reliable QoS, the scheme is completed. However, if there are still some areas that cannot obtain high-quality service, a higher layer of BSs should be deployed in the same way. A map of this step is presented in Fig. 4. It can be seen that in order to provide each TDP with satisfying communication quality, two low-power BSs are deployed in the area that cannot rely on macrocells alone, and low-power cells are also deployed in a traffic-balanced method. Under the consideration of practicability, we test our proposal with a practical traffic demand distribution in Fig. 5. Traffic demand points are marked in blue. Macrocells are marked by green triangles surrounded by black borders. For clarity, we connect low-power cells, which are presented as yellow squares, with the traffic demand points served by them with red lines.

WHEN SHOULD WE TRIGGER THE PLANNING SCHEME

It can easily be figured out that the proposed cellular planning scheme can greatly improve the performance of cellular networks and enhance resource utilization efficiency. However, as the distribution of traffic demand varies with time, the plan results of the last hour may not be suitable for this moment. On the other hand, it is not necessary that we adjust cells frequently, not only because the margin we reserve when determining the number of cells required can absorb tiny variations of the distribution of traffic demand, but also because it is infeasible for cellular networks to change frequently as it can create vast handoff, which results in unbearable signaling load in the core network. Considering all these factors, we propose to introduce a parameter called fairness index ϕ, which can measure the balance degree of traffic demand among cells quantificationally. Without much investigation, the fairness index ϕ here can be quantized as $\phi = STD/Mean$, where *STD* and *Mean* denote the standard deviation and the mean of the loads of cells, respectively. As long as the fairness index ϕ is within the acceptable range ($\phi \le Threshold$, $Threshold \in (0,1)$), it is not necessary for us to adjust the network. Of course, the loads of some cells may be slightly higher than before, but it is still at an acceptable level and the quality of experience of users would not deteriorate. Whenever the fairness index is abnormal, the planning scheme is triggered to adjust the current network to a more balanced state. For example, we can add/remove some macro or low-power cells to/from the cellular network. The procedure is further presented in Fig. 6.

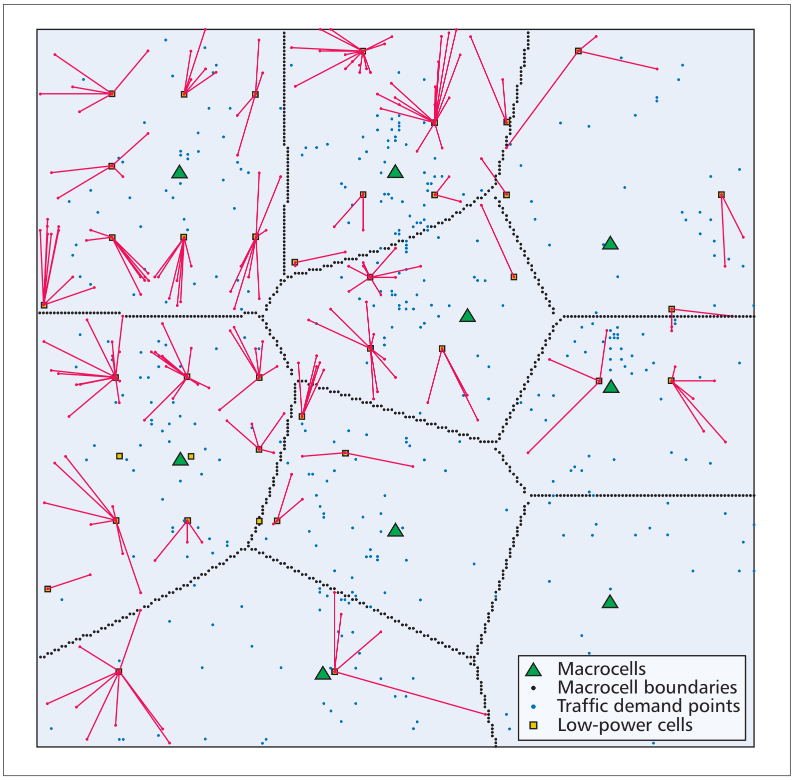

Figure 5. A map of network planning with low-power cells.

DISCUSSIONS OF REASONABILITY

With deep comprehension of the scheme proposed above, we may come up with new questions. First, is it reasonable for us to plan heterogeneous cellular networks hierarchically? Intuitively, when we conduct cell planning on one layer, other layers may have influence on the planning results or even ruin them. The tiers of cells are ordered by transmit power with the first tier having the highest power configuration. Due to differences in deployment, they have diverse path loss exponents and spatial density. Low-power BSs together with macrocells not only cooperate with each other to provide service but also cause mutual interference, which makes it difficult to analyze the characteristics of each tier and then balance the workload among districts. However, if we simplify the system as the model that characterizes the *P* tiers of a cellular network by transmit power, cell spatial density, path loss exponent, and bias factor, it has been proved that the outage probability of each tier is the same for all tiers, and is even the same as the outage probability of the overall network [14, 15]. This implies that adding low-power cells to a high-power cell network does not change the signal-to-interference-plus-noise ratio (SINR) distribution of each tier, because the increase in interference power is counter-balanced by the increase in signal power, which indicates that we can balance the workload among high-power cells without being concerned that adding low-power cells would greatly influence the planned effect of the high-power tier. This really helps simplify the job and makes our planning scheme practicable.

The second question: Is such a dynamic planning scheme feasible for practical cellular systems? Recall that conventional cell planning is always accomplished before an MSP provides services to users. Once the infrastructure of the cellular system is built, the optimization of the system generally focuses on slightly adjusting some parameters of the existing cells. Adding/removing cells seems difficult if not impossible from the viewpoint of conventional cellular network planning. However, for current cellular systems and beyond, there are/would be densely deployed cells in the service areas, which can be dynamically switched on/off according to the variation in the traffic distribution of the service area. Our proposed planning scheme could be effective and efficient for these scenarios, which happen frequently in practical cellular networks. Without doubt, our proposal is particularly applicable to the case of adding cells to serve users with QoS guarantee in an unexploited region.

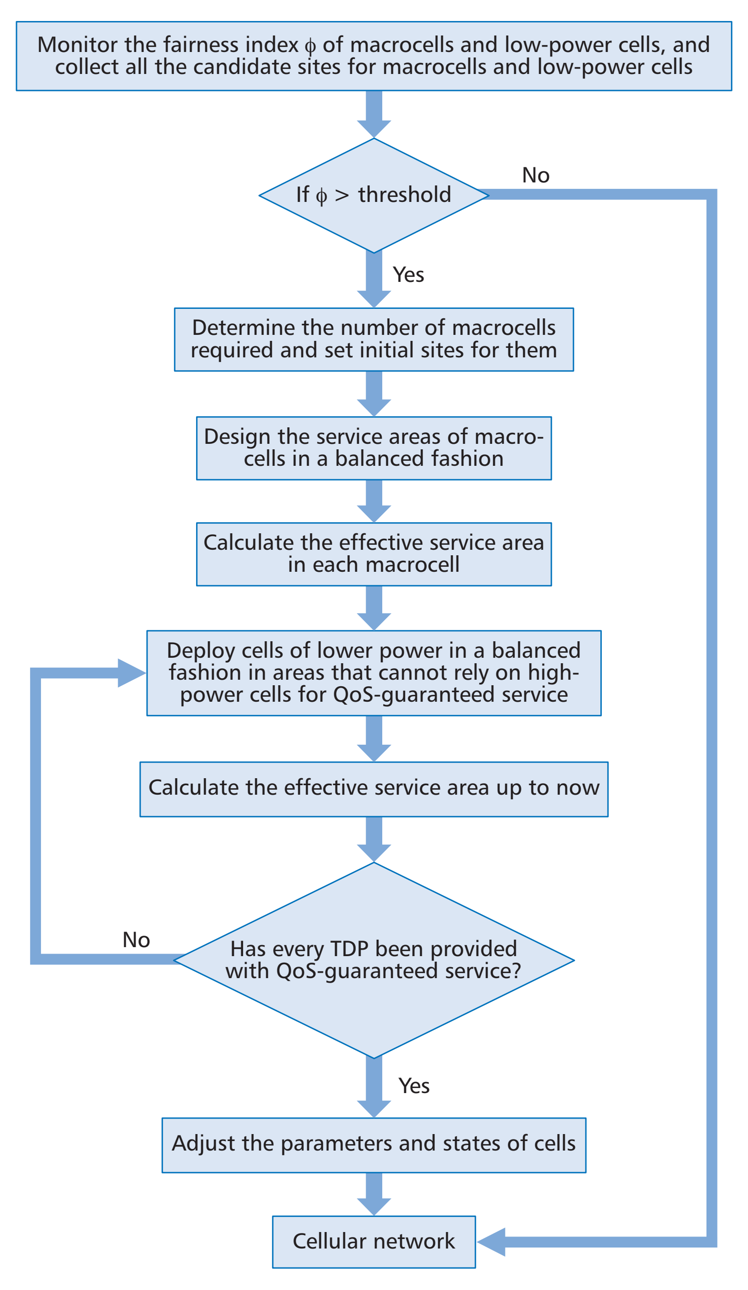

Figure 6. Flow chart of our proposal.

Another question is about the computational complexity. Obviously, our proposed planning scheme should be completed in an online manner so that the planning results can meet the requirement of the traffic changing on time in the whole service area. The main computation load lies in the division procedure, which always yields a complexity of $O(K^3)$ [10], where K is the number of cells for a practical cellular system and generally on the order of thousands even for a city. Hence, we can conservatively conclude that the computation load is acceptable for current cellular systems and beyond where cloud computing has been or would be employed to enhance the computational capabilities of the cellular systems.

RESEARCH DIRECTIONS

It has been proposed as a prominent method to improve the experience of users to decouple the data layer and the control layer in cellular networks. There are two potential development directions in the coming 5G, considering the whole architecture of the network: cloud radio access network (C-RAN)-based architecture and hyper dense small-cell-based architecture. In the C-RAN-based architecture, conventional high-power nodes could be responsible for delivering control signals, while remote radio heads (RRHs) act as the data layer. In the hyper dense small-cell-based architecture, macrocells could act as the control layer, while small cells are mainly deployed in traffic hot zones to provide high data rate. It can be seen without much effort that our core planning idea of load balancing also applies to C-RAN and hyper dense small-cell-based architecture. With the idea of load balancing among cells, the number of high power BSs, RRHs, and small cells required can be greatly reduced, as mentioned earlier, in the control and data layers, which not only decreases the total power consumption, but also restrains the inter- and intra-layer interference level. In future work, it is promising to apply our idea to the possible architecture in the coming 5G to improve both the energy and spectral efficiency of the network.

CONCLUSIONS

In this article, we recall the evolution of wireless communication networks from the first generation to the current worldwide 4G. To handle the explosive growth of mobile data consumption, the architecture of the cellular system has changed from the original homogeneous network to today's heterogeneous network. Cellular networks have become more and more dense and complex because of the crazily increasing traffic demand, which also incurs more and more unbearable interference. As a result, advanced signal processing techniques have been introduced to improve the performance of the cellular networks. On the other hand, the actual capacity utilization rate is not as high as expected because every cell is usually designed with the maximum traffic demand required among all cells. It is a common phenomenon that some cells suffer from overload while their adjacent cells only need to support very light traffic demand. Considering this, we propose to conduct cellular network planning in a traffic-balanced way. The balance degree of the network is monitored, and the planning scheme is triggered when the original balance is broken. The key idea is to divide a region into subregions with almost equal traffic based on an infinite optimization formulation. The reasonability of our proposal is supported by preliminary results. It provides insight into a brand new way to improve the performance of a cellular network and also caters to the concept of a green network, which are most significant goals for 5G deployment.

The reasonability of our proposal is supported by preliminary results. It throws insight into a brand new way to improve the performance of cellular network and also caters to the concept of green network, which are the most significant goals for 5G deployment.

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BIOGRAPHIES

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