COOPERATIVE SMALL CELL NETWORKS: HIGH CAPACITY FOR HOTSPOTS WITH INTERFERENCE MITIGATION

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ABSTRACT

Due to the high potential to enhance spectral efficiency and spatial reuse, small cell networks, SCNs, have emerged as a promising solution to improve the capacity of mobile communication systems so as to satisfy the ever growing demand for high data rate services. However, without proper planning, the dense deployment of SCNs may cause severe interference, resulting in limited capacity. In hotspots with a large number of users, the small cell network is challenged by the extremely high aggregated capacity requirement and may fail to guarantee the quality of service of all users. To leverage the benefits of SCNs and overcome the drawbacks, we propose a cooperative small cell network, CSCN, architecture that jointly utilizes several advanced techniques to enhance the capacity of hotspots. In this article, we first examine the existing solutions for capacity enhancement and hotspots. We then present the basic concept of the proposed CSCN architecture, and discuss the related technical aspects. The high potential of a CSCN in terms of capacity improvement and interference mitigation is demonstrated by a simulation study. Finally, we present several open problems for future research based on the CSCN architecture.

INTRODUCTION

The recent wide development of user terminals (e.g., smartphones and tablets) has triggered a drastically increasing demand for high data rate services. With limited spectrum, such demand necessitates more efficient use of the spectrum resource to improve the capacity of wireless networks. To this end, small cells have been recognized as an effective means of enhancing network capacity [1, 2].

Compared to a single macrocell base station (BS) with high power and large coverage area, a small cell network (SCN) consists of multiple low-power and spatially separated small-scale BSs with small coverage areas. With such an architecture, the distance between the transmitter and receiver is greatly reduced, resulting in high signal-to-interference-plus-noise ratio (SINR). The low power of each BS enables more efficient spatial reuse of spectrum, which in turn improves the capacity of the entire network. Moreover, compared to a traditional macrocell BS that brings high leasing and maintenance fees, a SCN can greatly reduce the cost of wireless operators.

However, the benefits of SCNs come at the price of a more complicated network architecture. The following features pose great challenges to the design and operation of an SCN.

A Large Number of Small Cell BSs — The number of SCN BSs within a given area is expected to be much larger than that of macrocell BSs. With limited backhaul capacity, it would be difficult to perform centralized control and coordination.

Vulnerability to Interference — Due to the small coverage area, small cell BSs may be close to each other in a hotspot, which may easily cause strong intercell interference. If different bands are assigned to neighboring cells, the available bandwidth for each cell is greatly reduced. Moreover, deploying a small cell tier over an existing cellular network may also cause inter-tier interference if the two tiers occupy the same spectrum band.

Irregular Coverage Area — Unlike traditional cellular networks with a hexagonal coverage area for each BS, the coverage area of a small cell BS is usually irregular. To mitigate interference as well as guarantee network connectivity, it is expected that the overlapping coverage areas of different small cell BSs are small, and there are no coverage holes. These requirements make the deployment of small cell BSs more complicated.

Limited Power Budget — Compared to a macrocell BS, the power of a small cell BS is quite limited. It is thus critical to efficiently utilize the power resource. Advanced technologies are needed to deal with the case when a large number of users are served by a small cell BS under a stringent power constraint.

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With the increasing number of mobile users, these SCN problems would be aggravated in hotspots with a heavy traffic load. When a large amount of users assemble in a certain area (e.g., a shopping mall or a football stadium), small cell BSs could be overloaded and unable to serve each user with limited spectrum resources. Under this circumstance, traffic congestion and call outage may frequently happen, resulting in degradation of user quality of service (QoS). Although the SCN is initially regarded as a solution to guarantee user QoS in hotspots, supporting high data rate services for a large number of users now becomes a new challenge.

In this article, we focus on the problem of exploiting cooperative small cells to provide high data rate services for hotspots. Since the SCN needs to provide high data rate services to a large number of users, it faces many new challenges when applied in hotspots. Although the proposed schemes in prior works [3–5] can deal with the overloading problem in hotspots, they are based on the traditional cellular network architecture, and the traffic loads mainly consist of voice services with low requirements for data rates. Therefore, these schemes cannot be directly applied in the SCN to serve hotspots. Furthermore, the inherent features of SCN mentioned before introduce new challenges in the design of SCNs. In particular, the large number of SCN BSs makes it a great challenge to adopt centralized network control strategies. Thus, decentralized strategies that allow local cooperation among the small cell BSs are highly appealing. To overcome these problems and satisfy the high capacity requirement at hotspots, we propose a cooperative small cell network (CSCN) architecture in this article. Based on the SCN architecture, the proposed CSCN leverages several existing technologies with flexible designs to improve the spectrum utilization and network capacity to provide enhanced QoS to users in hotspots. The goal of this article is to provide an insightful look into the architecture and achievable performance enhancements of the CSCN. An illustrative example and a simulation study are presented to demonstrate the high potential of the proposed CSCN approach.

The remainder of this article is organized as follows. We first review several existing technologies for capacity improvement and serving hotspots. The CSCN concept is presented next, followed by detailed discussions on various technical aspects of the proposed architecture. An illustrative example is provided along with a simulation study to demonstrate the performance of the CSCN. We then discuss open problems and conclude this article.

Overview of Existing Technologies

Capacity Enhancement

With the idea of reducing transmission distance, a major approach to improve capacity can be classified as deploying access points that are close to users. The main techniques include WiFi access points, femtocells [6], and distributed antenna systems [7]. With high-speed wireline connections and wireless routers as access points, WiFi technology has been widely adopted due to its salient features of low cost and easy deployment. However, it operates on unlicensed spectrum bands and adopts contention-based medium access control (MAC) protocols, making it hard to guarantee the QoS requirements of a large number of users.

The femtocell concept was proposed for QoS provisioning and capacity enhancement. Femtocells are user deployed indoor low-power access points that operate on licensed spectrum band with typical coverage range of 10–50 m. The small propagation loss and low power enable high data rates and spectrum reuse, benefiting both indoor users and wireless operators. Furthermore, the traffic burden of a cellular network is reduced since indoor users are served by femtocells. However, femtocell technology only improves indoor coverage, while adding femtocells over an existing cellular network potentially causes interference to outdoor cellular users.

The drawbacks of femtocells are largely caused by the chaotic nature of their deployment by users. Thus, effective control and coordination are necessary for overcoming such drawbacks. To this end, an operator-deployed distributed antenna system (DAS) offers an effective solution, and has been applied to improve both indoor and outdoor capacity. The basic idea of a DAS is to deploy spatially distributed antenna units that are close to users, and these antenna units are connected to BSs with dedicated wireline connections. As a femtocell, a DAS brings about benefits in improved link quality and spatial diversity. However, a potential problem for a DAS may be the limited capability of antenna units. Since the antenna units can only act as transceivers, different antenna units cannot distributively coordinate/cooperate with each other. Thus, a BS needs to perform centralized control over all the connected antenna units, which brings new challenges to the backhaul and processing units in the BS, especially when the number of antenna units is large. Besides the DAS, relay was proposed as another approach to improve coverage and capacity. In areas with poor coverage, relay nodes are deployed to receive, decode or amplify, and forward signals for users, resulting in improved SINR and network capacity [8]. However, since the relay nodes only serve as transceivers without coordination ability, a BS needs to perform centralized control for the resource allocations of all the relay nodes [9]. Thus, relay enhanced cellular networks bear similar limitations as DASs.

The essence of the above capacity improvement techniques is to improve SINR and spectral efficiency. According to Shannon's formula, increasing the total bandwidth is the most effective way to improve network capacity. However, given the limited spectrum resource, the only choice is to create spectrum reuse opportunities to improve spectrum utilization. From the spatial domain, directional antennas, multiple-input multiple-output (MIMO), and smart antennas all exploit spatial diversity to achieve spatial multiplexing gain. With proper design of antenna

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parameters, the application of directional antennas can reduce undesired signal leakage, thus creating more spatial reuse opportunities in wireless networks [10].

For a MIMO system, through adjusting beamforming parameters according to the channel conditions of different antennas, capacity can also be effectively improved. For a smart antenna system, a BS first estimates the location of a user based on the arrival direction of uplink signals. It then controls the downlink transmission beam pattern so that the desired user is served while other users do not experience interference. This way, it is unnecessary to assign different channels or time slots to users served by the same BS; each user can be allocated more resource, resulting in higher network capacity.

Furthermore, cognitive radio (CR) technology [11] allows secondary users to opportunistically access the channels that are currently not occupied by primary users. With this approach, spectrum opportunities can be utilized by secondary users; thus, higher spectrum efficiency is achievable.

Nevertheless, due to limited spectrum sensing capability, the CR system faces several problems such as misdetection, false alarms, and hidden terminals. Consequently, existing CR systems, such as IEEE 802.22 wireless regional area networks (WRANs), largely depend on a spectrum database to acquire channel state information.

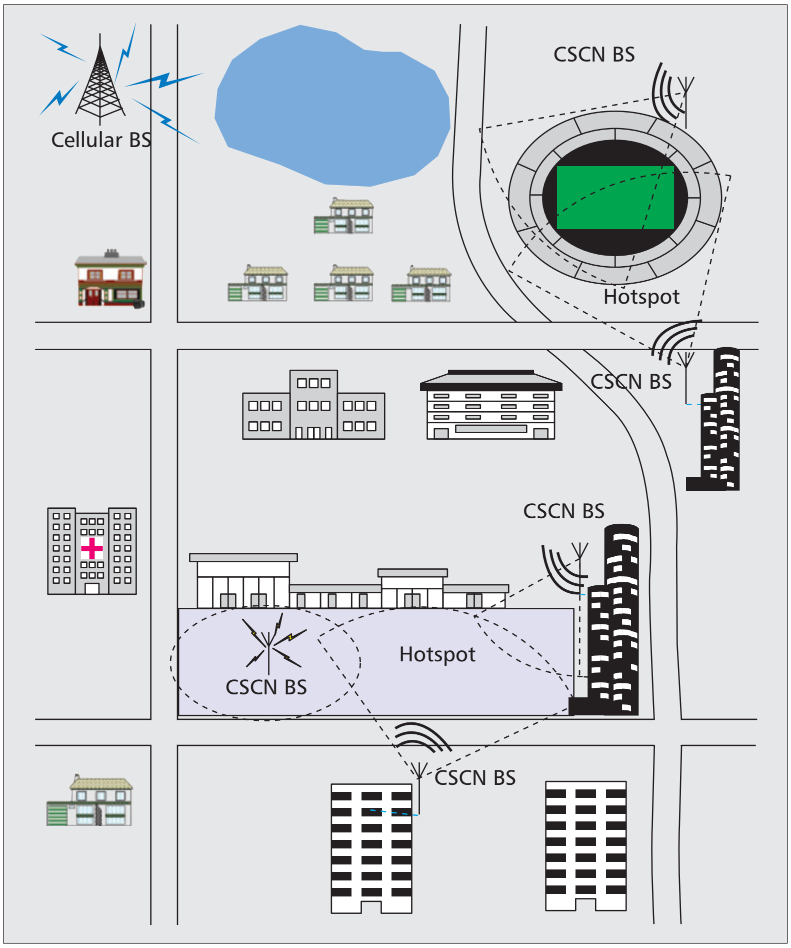

Figure 1. An example of a CSCN in a metropolitan area.

Serving Hotspots

To satisfy the high capacity requirements at hotspots, several techniques have been proposed based on the cellular network architecture, including cell splitting [12], cell sectoring [3], channel borrowing [4], and load balancing [5]. The cell splitting method is essentially similar to the small cell approach, where the original cells are split into smaller cells so that the average number of available channels within a given area is increased. The cell sectoring technique employs directional antennas at each BS, and each BS serves multiple sectors with different spectrum bands, thus reducing the co-channel interference among different cells and improving the frequency reuse efficiency.

Through channel borrowing, a cell borrows channels from adjacent cells to serve the users in a hotspot. Last but not least, load balancing provides another approach to deal with the heavy traffic load in hotspots. When a cell is overloaded due to the hotspots in its coverage area, it can hand over some of its users to adjacent cells. This way, the traffic burden in the hotspot cell can be mitigated, and the QoS of its users can be guaranteed.

The Concept of Cooperative Small Cell Networks

The CSCN is an extension of the SCN for enabling local cooperation among neighboring small cell BSs. It consists of multiple small BSs equipped with directional antenna connected to each other via a wireline backhaul through the X2 interface. The BS deployment pattern and coordination are carefully designed. The objective of the CSCN is to improve user QoS and the total network capacity in hotspots. The key components of the CSCN are BS deployment, BS-coordination-based dynamic resource management, and interference coordination.

Base Station Deployment — In the CSCN, the BSs are deployed according to the environment and average demand (with a certain amount of redundancy). Then the coverage area of each BS is adjusted to an appropriate shape to improve spatial reuse and reduce interference, which can be realized by applying directional antennas with adjustable parameters. With the development of hardware technology, BSs can be produced with much smaller size than before, and the coverage area of each BS can be flexibly controlled [13]. Therefore, flexible coverage areas and deployment patterns of antennas are feasible in the CSCN. When CSCN BSs are deployed in a hotspot, the environment information, such as the architectural layout, is utilized to determine the optimal shapes of the coverage areas.

Dynamic Resource Management — In hotspots, the user distribution and traffic load may change quickly over time. Therefore, the CSCN should dynamically allocate spectrum resources by jointly considering the instantaneous requirements and interference mitigation in order to improve capacity and accommodate the load. We propose a decentralized BS cooperation scheme that enables channel borrowing and user handover among neighboring BSs.

***Interference Coordination* —** In the CSCN, BSs can sense the spectrum occupation condition and exchange information with neighboring BSs or cellular BSs. They then coordinate with each other to mitigate interference as well as efficiently utilize spectrum resources. Since the transmission beam of a mobile device (MD) is omnidirectional, MDs served by neighboring CSCN BSs may cause uplink interference to each other. Moreover, the transmission beam of a BS cannot be perfectly controlled, which potentially causes downlink interference. Thus, coordination between the BSs is necessary to mitigate interference. We propose a cooperative and decentralized interference management scheme that employs spectrum sensing and inter-BS coordination to control the interference in real time.

To better understand the principles of the CSCN, we present an intuitive scenario in Fig. 1, where the CSCN is employed in a metropolitan area to enhance the QoS of users in hotspots. The CSCN BSs provide coverage to the desired area while the interference caused to other areas is controlled. Neighboring BSs coordinate with each other to allocate spectrum resources according to the instantaneous traffic load and reduce interference. From the perspective of both time and space, the CSCN improves the spectrum utilization, resulting in the increased network capacity.

Compared to an SCN, the spectrum utilization of a CSCN is improved due to the adoption of directional antennas and dynamic resource allocation through BS coordination. As shown in Fig. 2, two close BSs with directional antennas (i.e., BS 3 and BS 4) can simultaneously utilize the same spectrum band since there is no overlap between their coverage areas. For BS 1 and BS 2 with overlapped coverage, they can sense the spectrum environment and instantaneous traffic conditions, and exchange information with each other via backhaul signaling. After that, BS 1 and BS 2 can coordinate with each other to avoid mutual interference and traffic congestion.

Technical Aspects

Base Station Deployment

The goal of CSCN BS deployment is to improve spatial reuse as well as mitigate downlink interference through the application of directional antennas. Through careful design on the location and coverage area of each BS, spectrum utilization can be improved to satisfy the high capacity requirement of a large number of users.

The deployment of antennas in a CSCN can take advantage of the specific architectural layout. Note that the coverage area of a BS can be controlled by using a tilted antenna with adjusted tilt angle [14], as illustrated by the example given in Fig. 3. Suppose the zone between the two buildings is a hotspot, and the BSs at the top of buildings A and B provide service to users in the hotspot, with the vertical antenna transmission pattern illustrated in the figure. The specific coverage areas of the two BSs can be preset or distributively coordinated between the two BSs, depending on the technology available. This way, we can first divide a hotspot into several areas, then employ multiple BSs to serve each area with the above pattern. BSs that serve the same area can coordinate with each other to optimize the network performance and improve the QoS of users in the area.

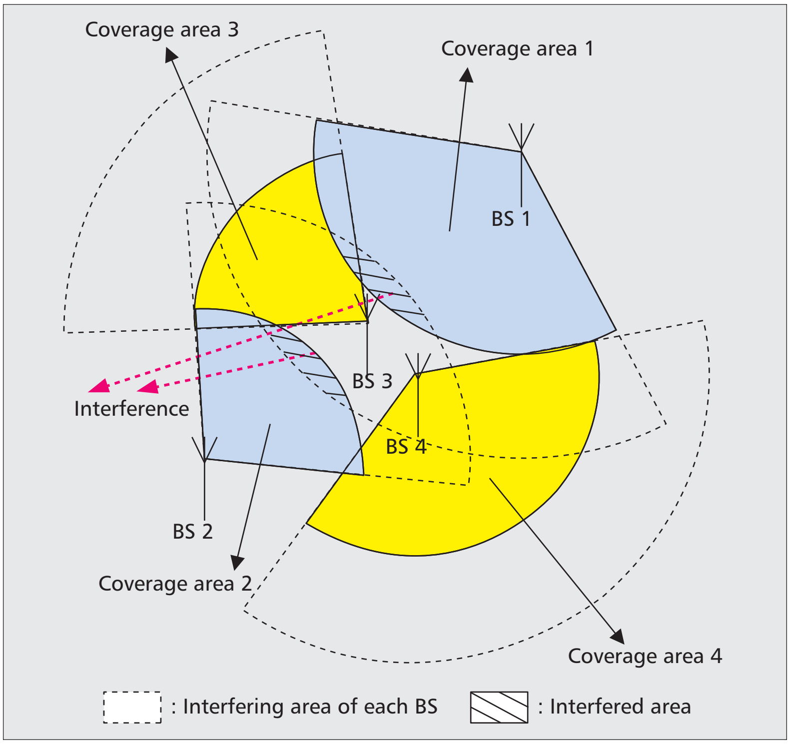

Figure 2. Application of a directional antenna for BS deployment in the CSCN.

Next, within one area, we propose a preliminary architecture of BS deployment to mitigate the downlink interference. The proposed architecture bears a decentralized feature that can reduce the control overhead. Take a rectangular area (which may be a square or a lobby in a real-world scenario) shown in Fig. 4 as an example. Suppose that with a transmission range of d m, the received signal strength from a CSCN BS is sufficiently small that it causes negligible interference. Then we divide the rectangular area into three kinds of regions with parameter d. To mitigate the interference to users outside the rectangular area, we add constraints on antenna directions for BSs located in regions 1 and 2. For a BS in region 1, the antenna azimuth is restricted within a right angle, and the radiation direction is limited to the interior zone of the rectangular area in order to guarantee that the BS does not cause interference to users outside the rectangular area. Similarly, antennas of BSs in region 2 can only direct to the inner side to avoid interference with the outside. For BSs in region 3, due to the relatively longer distance to users outside the rectangular area, there is no restriction on the directions of antennas. With such constraints, the downlink interference only occurs within users and BSs in the given area, so

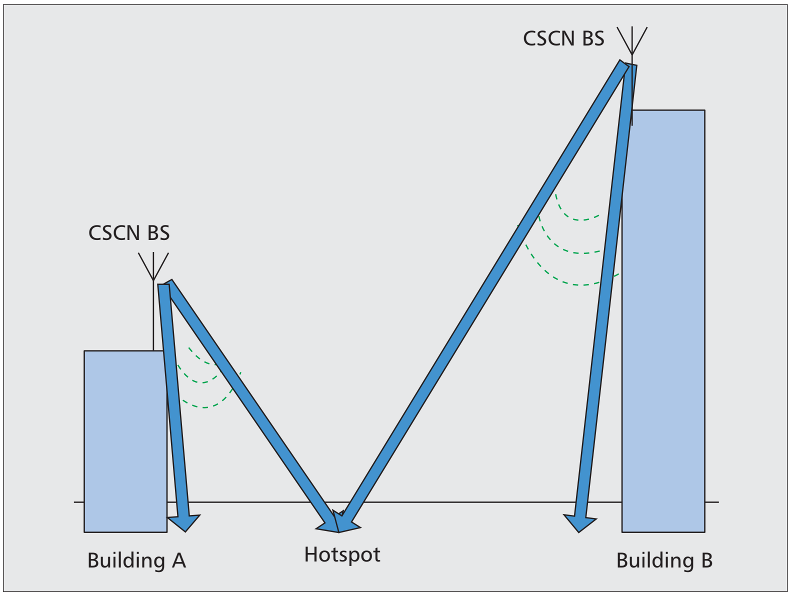

Figure 3. Application of tilted antennas to cover a hotspot in the CSCN.

local coordination among neighboring BSs is feasible.

For an area with a general shape, we first find the reference line that is d m away from the boundary of the area. Then, according to the reference line, we divide the area into three kinds of regions: corner, border, and center. A corner region is between the edges and angles on the boundary and the reference line. A border region is between the edge of the boundary and the reference line. A center region is inside the reference line. These three kinds of regions correspond to regions 1, 2, and 3 in the rectangular example, respectively. Similar to the rectangle area example, we add constraints on the antenna directions of BSs to mitigate the downlink inter-area interference. In the corner region, the antenna azimuth of a BS is restricted by the angle based on the shape of the region, and the radiation direction is limited to the interior zone of the area. In the border region, the antenna of a BS can only be directed to the inner side of the area. In the center region, there is no restriction on the antenna direction.

The proposed BS deployment architecture not only controls the interference, but also enables spectrum reuse. As the mutual downlink interference between different areas is controlled, each area can utilize all the available downlink spectrum bands, which in turn improves the network capacity.

Dynamic Resource Management

Although the BS deployment could mitigate inter-area interference, intra-area interference remains a problem. Since providing seamless coverage is the primary target, the coverage areas of different CSCN BSs in the same area may overlap, resulting in intra-area interference. Here, we propose spectrum allocation strategies to deal with this problem. We first propose an initial spectrum allocation strategy to mitigate the downlink interference among BSs in the same area. Then, based on the initial spectrum allocation, we propose a cooperative and decentralized BS coordination mechanism to improve the performance of a CSCN in the hotspot. When the instantaneous traffic load is changing, CSCN BSs can dynamically adjust the occupied spectrum resource by the antennas through backhaul signaling, and can coordinate with each other to meet the traffic demand.

Initial Spectrum Allocation — In the previous section, we divide a hotspot into several areas and consider the BS deployment pattern for each area. Within such an area, given the coverage areas of all the BSs, we propose a spectrum allocation strategy that considers both spatial reuse and interference mitigation. The objective is to maximize the total number of channels of all BSs, under constraints on interference mitigation and guaranteeing fairness among the BSs. We assume that there are M CSCN BSs and N channels in this area. As shown in Fig. 2, each CSCN BS has a coverage area and an interfering area. Define *interference list* as an $M \times M$ binary matrix with element F_{ij}, where $F_{ij} = 1$ indicates that BSs i and j interfere with each other due to overlapped coverage areas, and $F_{ij} = 0$ indicates that BSs i and j do not interfere with each other, so they can utilize the same channel.

To avoid the situation that some BSs are allocated with all the channels while some other BSs have no available channel, the number of channels allocated to each BS m should have an upper bound, denoted by A_m. Therefore, the spectrum allocation problem can be formulated as

$$\begin{aligned}
&\max_{\{\delta_m^n\}} \sum_{n=1}^{N}\sum_{m=1}^{M} \delta_m^n,\\
&\text{s.t. } \delta_i^n + \delta_j^n \le 2 - F_{ij}, \forall i, j \in \{1,\ 2, \ldots, M)\},\\
&\qquad\qquad\qquad\qquad \forall n \in \{1,\ 2, \ldots, N\}\\
&\quad \sum_{n=1}^{N} \delta_m^n \le A_m, \quad \forall m \in \{1,\ 2, \ldots, M)\},
\end{aligned} \tag{1}$$

where δ_m^n is an indicator and defined as

$$\delta_m^n = \begin{cases} 1, \text{channel } n \text{ is assigned to BS } m,\\ 0, \text{otherwise.}\end{cases} \tag{2}$$

Obviously, Eq. 1 is a 0–1 integer programming problem with linear constraints. Finding the optimal solution of Eq. 1 through exhaustive searching incurs NP-hard complexity, since the number of all possible solutions is 2^{MN}. Nevertheless, the solution to the optimization problem is an initial spectrum allocation result that does not consider the traffic load. Therefore, a suboptimal solution is still useful. To obtain a suboptimal solution with low complexity, we relax the constraint $\delta_m^n \in \{0,1\}$ to $\delta_m^n \in [0,1]$. Hence, the original problem is transformed into a linear programming problem (LP) and can be solved with existing methods such as the simplex algorithm. The solutions will be rounded up to 1 or down to 0 while satisfying the constraints in Eq. 1 to obtain a feasible suboptimal solution.

Obviously, A_m directly affects the spectrum allocation result. Note that neighboring BSs cannot simultaneously utilize the same channel, while the objective function of the optimization problem is the total number of channels of all BSs. Therefore, a BS with more neighboring BSs will be allocated fewer channels to leverage spatial reuse and achieve a large objective value. With the constraint of A_m, even the BS with the most neighboring BSs is expected to be allocated a certain amount of channels. There is a tradeoff between fairness and overall network performance. When A_m is so small that it approaches $N/2$, the total number of channels allocated to all BSs is small. When A_m is large, the fairness among the BSs will become poor.

The derivation of the channel allocation constraint is based on the downlink scenario, since it is based on the analysis of BS coverage areas. Due to the mobility of users and the omnidirectional transmission pattern of uplink signals, the uplink interference cannot be perfectly controlled. To this end, a cooperative interference avoidance scheme will be proposed to address this problem. The goal of adding the channel allocation constraints is to reduce the expected overhead for interference management in the operating process, since neighboring BSs have already been allocated exclusive channels, and the ratio of users that require interference coordination is small.

Load Balancing through Base Station Coordination — In this part, we consider the instantaneous traffic for spectrum allocation. To deal with the potential overloading problem in a hotspot, we propose two cooperative and decentralized BS coordination strategies.

Channel Borrowing — When a CSCN BS is overloaded, it sends a request for more channels to all neighboring BSs. Upon receiving the request, the neighboring BSs with idle channels feed back the idle channel information. Then the overloaded BS utilizes the channels all its neighboring BSs reported as idle. These additional channels can assist the overloaded BS in dealing with heavy traffic. With this mechanism, BSs with heavy traffic could borrow channels from neighboring BSs, and neighboring BSs utilize the same channel at different time instants.

User Handover — Although the channel borrowing mechanism can offer additional channels to an overloaded BS, another problem emerges when the traffic load of a BS keeps increasing. Since a CSCN BS needs to allocate limited power among all the channels, with the limited power budget, the power allocated to each channel may not be enough to guarantee the QoS of users. User handover could be an effective solution to this problem. When a CSCN BS detects that the number of users within its coverage area is too high and a handover is necessary, it sends a request for handover to all neighboring BSs. Then the neighboring BSs with available power and spectrum resource respond to the request. With the feedback information, the overloaded BS reduces the pilot signal strength, and some of the users will switch to some neighboring BSs.

Interference Coordination

The proposed deployment and spectrum allocation methods can only deal with downlink interference. Due to omnidirectional uplink transmissions, uplink interference, and interference between the cellular users and the CSCN, should also be managed. Furthermore, although the directional antennas can be used to control interference, the potential interference caused by undesired sidelobes should also be mitigated.

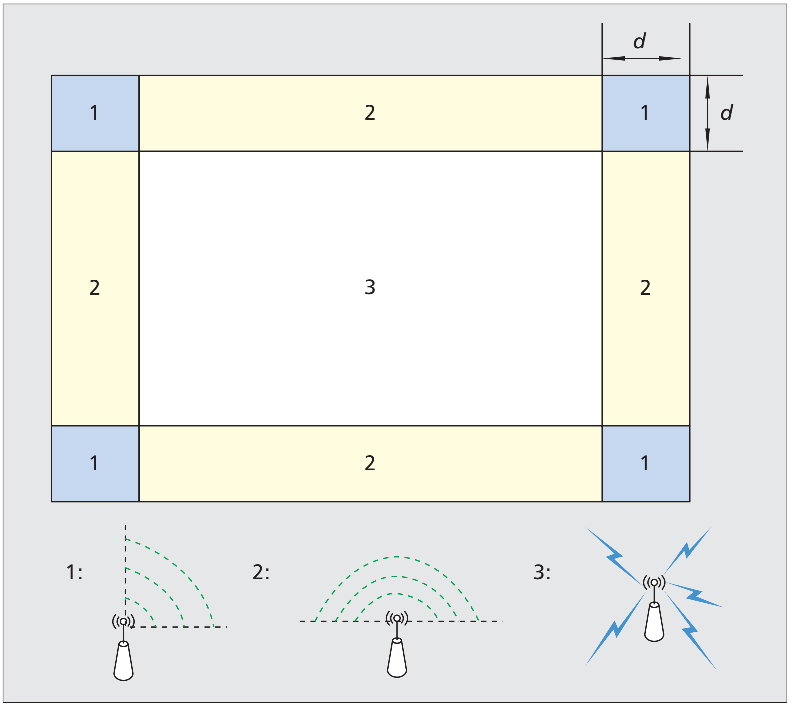

Figure 4. Area division for BS deployment in the CSCN.

We develop a cooperative interference avoidance scheme to mitigate the uplink interference between CSCN BSs. This scheme can also be applied to control the interference between the CSCN and the cellular network with minor modifications. Through spectrum sensing and channel scheduling, interference can be effectively controlled. In particular, the following procedures are adopted by CSCNs to achieve uplink interference avoidance.

Spectrum Sensing — We assume that CSCN BSs periodically sense the spectrum occupation of the radio environment. If a CSCN BS (denoted BS A) detects the uplink signal of a user that is served by another BS, and the signal of this user causes interference to the uplink transmission of BS A, it records the time-frequency usage patterns of this user, and sends the information in a control message to the neighboring BSs. The control message also contains the channel availability information, which indicates the number of remaining channels at the BS.

Confirming the ID of Interfering Users — Once a neighboring BS (denoted BS B) receives the time-frequency usage patterns from BS A, it compares this information with its uplink scheduling information. If the channel usage pattern coincides with the scheduling information of a user, it indicates that this user interferes with BS A. This way, for each CSCN BS, nearby interfering users can be identified.

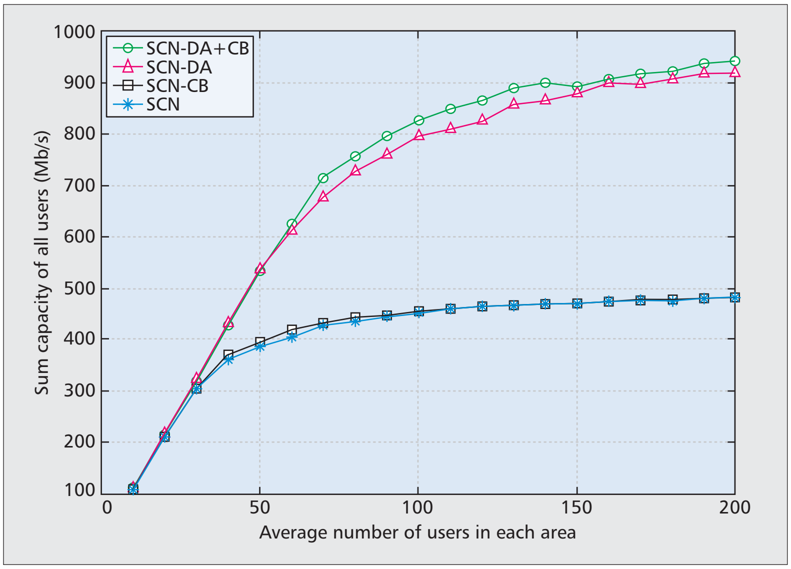

Figure 5. Network capacity vs. average number of users (μ) under different scenarios.

Interference Scheduling — With the channel availability information contained in the control message, BS B compares the numbers of remaining channels of BS A and BS B. If BS A has more remaining channels, BS B informs BS A not to schedule the channel used by the interfering user for uplink transmission to avoid interference. If BS B has more remaining channels, BS B will reschedule the uplink channel for the user that causes interference to BS A.

To avoid the downlink interference caused by BS A to the interfering user, BS B sends the downlink channel scheduling information of the user to BS A. Thus, BS A avoids allocating the channel used by this user for downlink transmission.

Illustrative Example and Simulation Results

To demonstrate the high potential of the proposed approach for capacity improvement and interference mitigation, we present selected simulation results with different schemes applied. Consider a rectangular hotspot with size 200 m × 400 m, and divide this hotspot into 8 areas with size 100 m × 100 m. In each area, the number of users is uniformly distributed with mean value μ. The network capacity and outage probability are two criteria for performance evaluation, and we assume that an outage event happens when the capacity of a user falls below a predefined threshold. In this simulation, we focus on the effects of applying deployment pattern and channel borrowing. Downlink transmission is considered since most high data rate services are provided via the downlink. In the simulations, the BS transmission power is 20 dBm and the noise power density is –174 dBm/Hz; the channel bandwidth is 200 kHz, and there are 100 channels; the outage threshold is set to 100 kb/s; the channel has path loss $15.3 + 37.6\log_{10}(R)$ in dB [15] and experiences Rayleigh fading, where R is the transmission distance in meters.

In the first scenario, we consider the original SCN without any modifications. Each area is served by one BS located at the center, and the BS adopts an omnidirectional antenna. The neighboring BSs use different sets of channels to mitigate interference, and the spectrum usage of each BS is static. In the second scenario, BSs are equipped with directional antennas (DAs), and one area is served by multiple BSs with the proposed deployment architecture. For simplicity, we consider that in each area served by two BSs with directional antennas, a user is served by the BS with the strongest received signal strength. In the third scenario, we enable channel borrowing (CB) between neighboring BSs, and the BSs employ omnidirectional antennas. In the last scenario, both DA and CB are employed. We assume that when the number of users is lower than the number of channels allocated to the serving BS, each user is allocated one channel. When the number of users is greater than the number of channels, one channel is shared by multiple users in a time-division multiple access (TDMA) pattern. In detail, suppose the number of users is U and the number of channels is N. When $N < U < 2N$, the BS randomly selects $U – T$ user pairs and assigns one channel for each user pair. When $2N < U < 3N$, the BS randomly selects $U – 2N$ groups of users, each group consists of 3 users, and these 3 users share one channel in different time slots. This process can be repeated as U further increases.

Figure 5 shows the aggregated capacity of all users in the hotspot as a function of different average numbers of users (μ). The incorporation of both deployment designs with DA and CB between neighboring BSs improves the capacity compared to the original SCN. The deployment of BSs with DAs creates more spatial spectrum reuse opportunities; thus, the number of channels allocated to each user is increased, which in turn improves the sum capacity. CB offers some capacity gain when the average number of users is larger than the number of pre-allocated channels. This is because the borrowed channels from neighboring BSs could assist an overloaded BS to provide better service to users and improve the sum capacity. When the average number of users keeps on increasing, the capacity gain offered by CB becomes limited, since the neighboring BSs are less likely to have any unused channels. When both CB and deployment design with DA are applied, the network capacity is further improved. Therefore, we conclude that the enhancements adopted in CSCN over SCN can effectively improve network capacity.

Figure 6 shows the outage probability vs. different average number of users (μ). Due to the capability for capacity improvement, the deployment design and CB also contribute to outage reduction. Note that the performance gain of CB decreases when the average number of users is large, since neighboring BSs are also likely to be overloaded, and there is no channel to borrow. From the perspectives of space and time, both schemes create spectrum opportunities and improve spectrum utilization, resulting in less traffic congestion. As expected, the combination of the two schemes could achieve the lowest outage probability. Similarly, we can conclude that the CSCN is effective in serving hotspots with proper design of the technical aspects, as discussed.

Future Research Directions

Based on the CSCN architecture, the following problems are open issues that should be further investigated to fully harvest the high potential of the CSCN.

Optimal Base Station Deployment

In the proposed BS deployment scheme, the downlink interference between different areas is controlled through adding constraints on antenna directions. Each area can thus reuse more spectrum resource, leading to improved capacity. However, one open yet challenging problem is how to optimize the placement of BSs, as well as the azimuth and range of antennas, so that the sum capacity can be maximized while the QoS requirements of all users in the hotspot are satisfied. We can employ cooperation between BSs to optimize performance, but the technical details require further research.

Optimal Handover Strategy

Due to the relatively small coverage area of a CSCN BS, multiple neighboring BSs can be candidates for load balancing when a CSCN BS is overloaded. The handover decisions determine the capacities of users and interference patterns. Furthermore, the available power and spectrum resources and traffic loads of these neighboring BSs are different. It is thus desirable to develop the optimal handover strategy for the best CSCN performance.

Power Control

It is well known that power control is a fundamental approach for capacity improvement and interference mitigation. This article does not discuss power control problem due to the lack of space. In future work, cooperative joint power and spectrum allocation algorithms should be developed with easy implementation and low complexity.

In addition, it would also be interesting to develop a CSCN testbed such that the system performance can be demonstrated in a realistic wireless environment. Such a CSCN testbed can not only validate the theoretical results, but also reveal new practical constraints that should be considered in the modeling and analysis, as well as identify new research problems.

Conclusions

In this article, we present a CSCN architecture to meet the high capacity demand in hotspots. The proposed architecture adopts sectorized base station deployment, dynamic resource management based on dynamic traffic load, and interference coordination to achieve enhanced capacity and reduced outage probability. The key is to leverage the cooperation of neighboring BSs for better spectrum reuse, interference mitigation, and capacity enhancement. The proposed approach has distributed operation, which is amenable to practical systems. The high potential of the proposed architecture is demonstrated with an illustrative example and simulation results. We conclude this article with a discussion of open problems for future research.

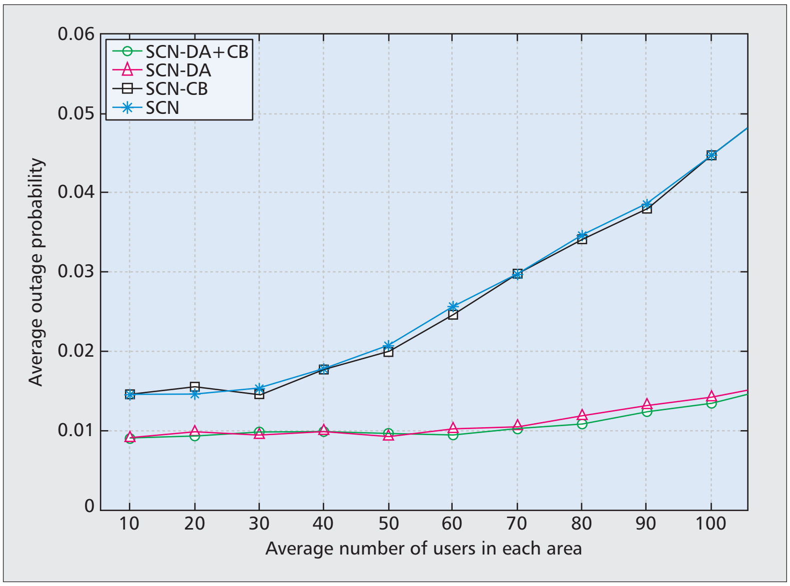

Figure 6. User outage probability vs. average number of users (μ) under different scenarios.

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