GRAPH THEORY AND ITS APPLICATIONS TO FUTURE NETWORK PLANNING: SOFTWARE-DEFINED ONLINE SMALL CELL MANAGEMENT

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ABSTRACT

Network planning is facing new and critical challenges due to ad hoc deployment, unbalanced and drastically varying traffic demands, as well as limited backhaul and hardware resources in emerging small cell architectures. We discuss the application of graph theory to address the challenges. A clique-based software-defined online network management approach is proposed that captures traffic imbalance and fluctuation of small cells and optimally plans frequencies, infrastructures, and network structure at any instant. Its applications to three important small cell scenarios of cloud radio, point-to-point microwave backhaul, and interoperator spectrum sharing are demonstrated. Comparison studies show that in each of the scenarios, this new approach is able to significantly outperform conventional static offline network planning schemes in terms of throughput and satisfaction levels of small cells with regard to allocated bandwidths. Specifically, the throughput can be improved by 155 percent for the cloud radio scenario and 110.95 percent for the microwave backhaul scenario. The satisfaction level can be improved by 40 percent for interoperator spectrum sharing.

INTRODUCTION

Recent decades have witnessed great advances in wireless cellular communications. User data rates have dramatically grown from 270.833 kb/s for Global System for Mobile Communications (GSM) [1] to 326 Mb/s for Third Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A) [2]. Cellular networks have evolved from extending coverage and mobility in wide areas to providing bandwidth-demanding services in high-traffic geographies (i.e., hotspots). As a result, mobile users are benefiting from equivalent data rates to wired systems, while enjoying cable-free flexibility and convenience. A key enabler for improving user experience has been the move toward smaller picocell and femtocell deployments. A small cell device is lightweight, easy to install, and plug-and-play. They can be deployed wherever there are high traffic demands.

Network planning is another critical aspect of cellular networks that has significantly contributed to improved performance and user experience. Conventional network planning approaches start by choosing site locations for seamless cellular coverage. Based on the site locations, those approaches then measure or predict radio propagation, calculate interference, and allocate non-overlapping frequencies to avoid excessive interference [3]. The approaches also estimate traffic demands of the cells based on demographic distributions, and plan bandwidths accordingly. Optimal site locations and frequency decisions can be planned offline by formulating optimization problems, such as the integer linear programming problem for disaster recovery [4] and the mixed integer programming problem with Lagrangian relaxation for energy efficiency [5]. These optimally planned sites and frequencies are static in general, where the network performance requirements (throughput and dropped call rate) are optimized on an average basis.

Critical challenges arise when the conventional static offline network planning approaches are applied to small cells. The conventional macrocells are carefully placed to guarantee coverage. Some small cells may even be owned and randomly deployed by customers. As a result, the density of small cells can be very high in some areas. To mitigate intercell interference in those areas, a large number of offline planned frequencies would be required for cells with overlapping coverage areas if conventional approaches are used.

Second, small cells exhibit high dynamic fluctuation in traffic demand due to their hotspot nature. Their traffic demands fluctuate drastically over both time and geography. Static frequency planning using conventional offline approaches would yield inefficient use of scarce spectrum when traffic is low, and cause severe congestion as traffic increases.

More challenges come from practical constraints of deploying small cells. In many cases, small cell devices will be mounted on walls, street lamps, or bus stops where there is unlikely to be high-speed cable access. Point-to-point microwave backhaul, which can achieve fiber-like link capacity, becomes a fast-to-install and cost-effective solution to connecting small cells to the core network. However, the required backhaul speed also fluctuates drastically with the varying small cell traffic. Offline frequency planning would not be able to capture the fluctuation, leading to either a waste of the allocated bandwidths or backhaul congestion.

Another practical challenge is limited hardware infrastructure for cost saving considerations. One example is cloud radio [6], where the number of available base stations (BSs) is much smaller than the number of installed antennas. Adaptively connecting the BSs and antennas can overcome the shortage of BSs [7]. Nevertheless, this cannot be implemented using conventional offline network planning.

The challenges presented rule out the possibility of optimizing small cell locations in the conventional manner. There is a clear opportunity for online frequency planning for small cells that adapts to drastic local traffic demands, potentially leveraging localized observations and decisions. Specifically, at any instant, the bandwidths of the cells where traffic load is low can be released and used by other cells experiencing high traffic load. Intercell interference can be suppressed by carefully assigning non-overlapping frequency bands to the interfering small cells.

We note that the ad hoc deployment of small cells can be characterized by a graph with a topology correlated to irregular geographical distribution of traffic demand. The interference conditions can also be captured in the graph. At any instant, the traffic demand varies across the graph, and so should the planned frequencies to meet the traffic demand, as well as mitigate the interference. From this perspective, graph theory will be an effective tool to plan the frequencies online, exploiting the graphic characteristics of small cells.

In the rest of this article, we introduce graph theory and its applications to small cell network planning. Particularly, a new graph based software-defined online network planning approach is presented, which is able to address the key challenges of the ad hoc deployment of and drastically fluctuating traffic in small cells. The applications of the approach to three important small cell scenarios of cloud radio, microwave backhaul, and inter-operator spectrum sharing are demonstrated. In each of the scenarios, comparison studies confirm that the approach is able to significantly outperform conventional static offline schemes in terms of throughput and satisfaction level. Specifically, the throughput can be improved by 155 percent for the cloud radio scenario and 110.95 percent for the microwave backhaul scenario. The satisfaction level can be improved by 40 percent for inter-operator spectrum sharing.

Graph Theory in Existing Wireless Networks

Graph theory has been widely applied for allocation of radio channels or time slots in both wireless ad hoc mesh and infrastructure networks. Particularly, constructing cliques [8, 9], or equivalently coloring [10, 11], is most exploited to maximize spatial reuse. The basic idea is to generate a compatibility graph (sometimes called a complement graph [9]) of a network. Therein, every vertex represents a radio link (in other words, a transmitter), and every edge indicates that the two links associated with the edge are frequency compatible (in other words, the links can transmit at the same frequency without interfering with each other). This converts the channel allocation problem for spatial reuse maximization to a problem of searching for the subgraph with the most vertices that are mutually connected in the compatibility graph. Such a subgraph is defined as a maximum clique in graph theory. A clique in a graph defines a subgraph with all its vertices mutually connected. The maximum clique can be obtained by determining the largest cardinality (i.e., size) of all the maximal cliques of the compatibility graph, where a maximal clique defines a clique that cannot be enlarged. Each time a maximum clique is obtained, a radio channel is allocated to all the links associated with the maximum clique. The radio channel satisfies at least one of the links. As a result, the radio channel is most efficiently utilized by the largest number of concurrent links without interference. Then the compatibility graph is reduced by removing the vertices associated with bandwidth-satisfied links, followed by constructing the maximum clique of the reduced graph to allocate the next channel.

Such graph-based allocation approaches can be applied to plan the frequencies under ideal small cell settings, where there are abundant hardware infrastructures to process small cell signals and the backhaul bandwidth is unlimited. The reason is that the ideal settings have a similar ad hoc structure, and spatial reuse is important to satisfy the drastically fluctuating traffic demand of the small cells. However, in many practical deployment scenarios, hardware infrastructures and backhaul bandwidth are limited for cost consideration, so careful design and extension of the graph-based approach is required for those scenarios, as discussed later.

Graph Theory for Online Small Cell Network Planning

In this section, we discuss applications of graph theory to small cells. A new graph-based online network planning approach is presented, which instantly configures small cells in terms of access structure, backhaul topology, and inter-operator frequency sharing. The online network planning can be implemented as network maintenance software, and run in the operation and maintenance center (OMC) of a wireless network. The planning results can be disseminated throughout the network as part of network control signaling.

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An operator's management of small cells is considered, even though some small cells can be owned and randomly deployed by customers, as discussed previously. The reason for this consideration is that operators' close control of small cells is necessary to coordinate frequency channels, mitigate interference, and facilitate handover.

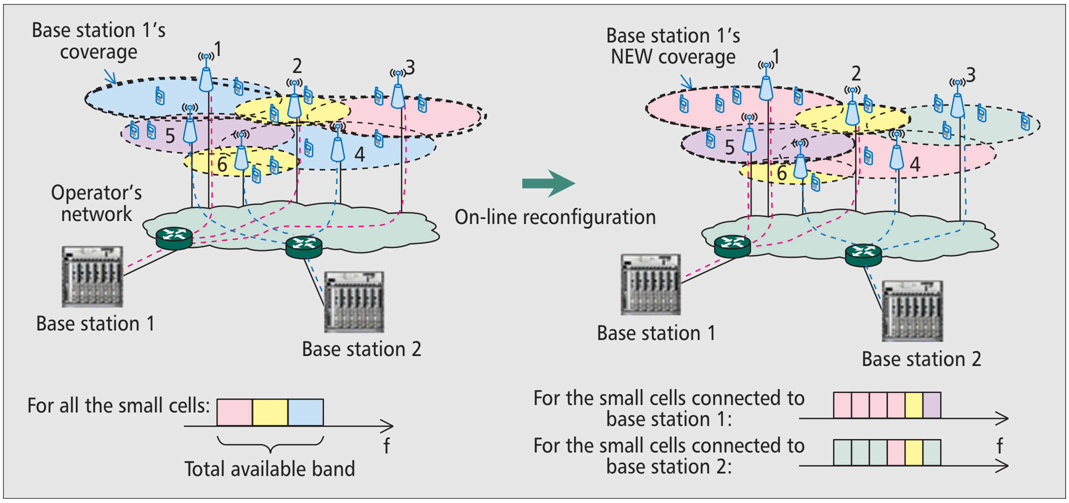

Figure 1. An example of a graph-based software-defined online network planning approach to cloud radio, where two particular distributions of users are shown. The left figure shows a scenario where there are two users within the coverage of each small cell (this is a uniform distribution). The right figure shows a scenario where the users have moved relative to the left figure. There are now four users in the coverage of small cells 1 and 3, and only one user in the coverage of the remaining cells. From the left figure to the right one, we show a reconfiguration of the connections between the BSs and small cell antennas in response to the movement of the users. We use different colors to indicate the frequency sub-bands allocated to the small cells, and highlight the coverage border of base station 1, which demonstrates the result of online structure planning.

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It is noted that the new online approach is substantially different from the algorithms developed for wireless ad hoc mesh networks [8–11]. This is because those algorithms are limited to channel assignment applications.

Small Cell Access Structure Planning

Figure 1 illustrates the application of graph theory to online configuration of the radio access structure of small cells. The concept of cloud radio is considered, as it has been demonstrated to be cost effective and operator friendly [6].

In this scenario, small cell antennas are installed to cover high-demand areas, while a number of small cell BSs are distributed across the operators' network. The BSs are the signal processing boards in BS racks, processing the digital signals of small cells. The concept of a clique in graph theory can be exploited to determine the best pairing of small cell antennas and BSs given changes in geographical distribution and traffic demand in coverage areas [7].

To achieve this, a *compatibility graph* of the small cell antennas is first generated to graphically describe the interference tolerance between the cells. Here, a vertex represents an antenna, and an edge connecting two vertices indicates that the interference between the two associated small cells is tolerable. Frequencies are allocated to the maximum cliques of the graph until the traffic demands of all the small cells are satisfied, as described above.

Next, we can generate another new *compatibility graph* to characterize the constraint of connecting multiple small cell antennas toward a single BS [7]. In this graph, each vertex indicates a small cell antenna, and two vertices are connected with an edge if the two corresponding small cell antennas are allocated non-overlapping frequency bands. The BSs are then paired with the *maximum cliques* of the graph one by one until no antenna is unconnected. By doing this, every BS is most efficiently used, processing the largest amount of traffic load it can. Also, the small cell antennas are all best satisfied with their allocated frequency bandwidths, as none of them is compromised by reducing their allocated bandwidths.

In the case where there are not enough BSs to connect the small cell antennas, a convex quadratic minimization problem can be formulated [12] to let the unconnected small cell antennas share the frequencies with already connected small cell antennas, hence connecting to their BSs. The frequency shares of the small cell antennas are optimized so that the satisfaction degradation of all the cells is minimized.

Such an online structure planning process is important, and often necessary, to meet the changing traffic demands of small cells. This is evident from the example of Fig. 1, where the traffic demands change from a uniform geographical distribution to an unbalanced distribution. Small cells 1 and 3 become heavily loaded due to the movement of users. To meet their traffic growth, it is necessary to let the two small cells reuse the frequency, as illustrated in the bottom right of the figure. To be specific, cell 1 uses the sub-bands indicated in pink, and cell 3 uses the sub-bands indicated in green. Some of the sub-bands overlap to satisfy the traffic demands of the two cells. As a result, the two small cell antennas must be connected to different BSs. The network structure must switch, as illustrated in the figure. If the structure did not switch, small cells 1 and 3 could by no means reuse the frequency, and their increased traffic demands could not be satisfied. In this sense, the proposed approach is suitable for densely and randomly deployed small cells. It allows for a merger of multiple adjacent low-demand small cells, thereby saving frequencies for neighboring high-demand cells. The approach also allows for cell split. With the growth of traffic, adjacent coverage-providing cells that are originally connected to the same BS are split into separate throughput-demanding cells that connect different BSs and use different frequencies.

The online structure planning process is also important for adaptively distributing computations across the system. This can avoid the congestion caused by limited computational resources of the BSs. In the example of Fig. 1, if the network structure did not adapt, one BS had to serve nine users while the other BS was only serving three users. Congestion could happen at the first BS, leading to throughput loss.

The proposed online planning process is different from the offline planning of traditional one-tier macrocell networks. Our process instantly arranges frequencies and configures topologies, adapting to the changing traffic demands and interference conditions of active small cells. It will enable the operators to adaptively and efficiently manage small cells with unplanned locations and bursty traffic. In contrast, traditional offline planning is static, and cannot adapt to these changes.

General performance of the graph-based software-defined online structure planning process is evaluated by considering a typical hotspot of 0.5 km^2 in [12], where 15 small cell antennas and up to 5 BSs are used to cover the hotspot. The system bandwidth is 20 MHz. The average physical layer spectral efficiency is assumed to be 5.0 b/s/Hz, which applies to common small cell modulation and coding based on the WINNER II B1 channel models.

Simulation results in [12] show that the new software-defined online approach is substantially better than the conventional offline schemes in terms of throughput, especially when the traffic demands are geographically unbalanced and drastically fluctuating. In the case of three BSs, the approach can increase the throughput by 155 percent, given significantly unbalanced traffic. Comparison studies are also carried out in terms of the minimum ratio of the allocated and requested bandwidths of the small cells. The ratio is referred to as *minimum satisfaction factor* (MSF) [12], which indicates the satisfaction levels of the cells and subsequently the satisfaction levels of the small cell users. Simulation results show that in the case of three BSs, the online approach can improve the average MSF by 169.3 percent when the traffic demands are geographically unbalanced. In the case of five BSs, the MSF improvement grows from 47.3 to 74.8 percent as the traffic imbalance becomes more severe.

Our new simulation results are provided in Fig. 2, where throughput is plotted with the increase of small cells. It is revealed that for a given number of BSs, the new online approach is able to increasingly surpass its offline counterpart. This is because the online approach can take advantage of the increased traffic imbalance and fluctuation in a larger network. It is also revealed that for a given number of small cells, the gain of the online approach over the offline counterpart grows as the number of BSs decreases. In the case of 18 small cells, the gain increases from 10 to 24 percent when the number of BSs is reduced from 6 to 3. In this sense, the online approach makes more efficient use of limited hardware resources.

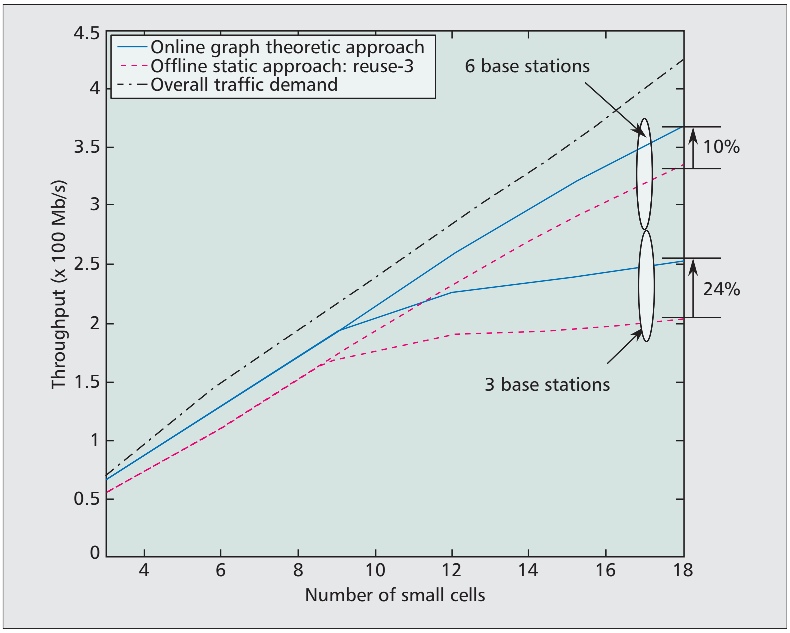

Figure 2. The growth of throughput with an increasing number of small cells, where the traffic of every cell yields an independent but identically distributed rectified Gaussian distribution with a standard deviation of 25 mb/s.

Note that further increasing the BSs beyond six would not increase the throughput of the offline approach when 18 small cells are considered. This is due to the key frequency reuse characteristic of cellular networks, if a frequency reuse factor of 3 is considered. It can be concluded that the online approach is at least 10 percent better than the offline approach, even in the case where the BSs are abundant for the offline approach.

Also, note that the new simulated gains of the online approach are not as significant as reported in [12] (e.g., 155 percent). The reason is that identically distributed traffic is simulated for every small cell in Fig. 2, while non-identically distributed traffic was considered in [12]. The online approach is able to make the most use of significant geographical imbalance of non-identically distributed traffic, resulting in large gains.

The software-defined online approach is able to outperform the conventional static offline scheme. The only exception is the case where the small cells have static traffic demands so that the two approaches perform exactly the same. The reason for this is because the online approach adapts to the changes of traffic demands and can improve performance by

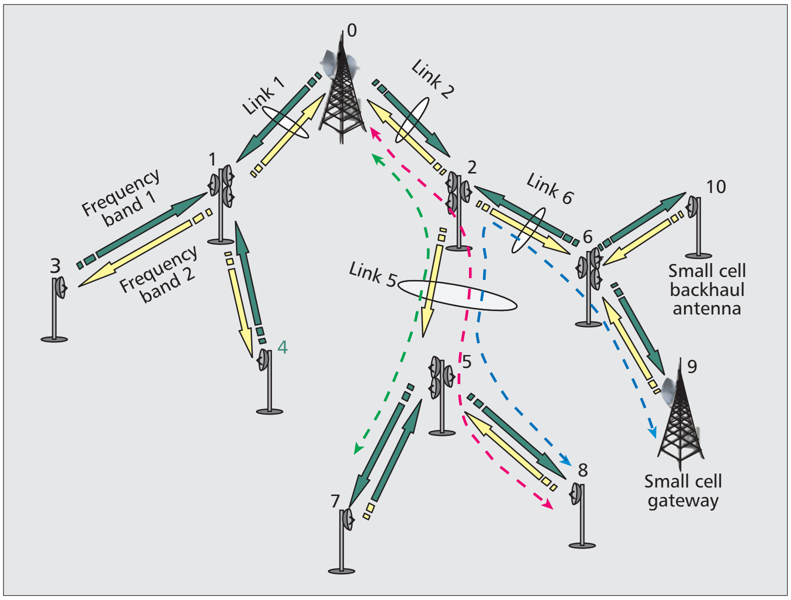

Figure 3. An example of the graph-based software-defined online approach to point-to-point FDD microwave backhaul for small cells, where the green arrows indicate band 1 and the yellow arrows indicate band 2. The small cells and their superordinate point-to-point links (which connect the cells from the gateway direction) have the same labels (e.g., small cell 1 and link 1). There are two gateways: nodes 0 and 9.

reconfiguring unused resources of low-demand cells for high-demand cells to use. Only in the exceptional case of static small cells will the online approach generate a one-off configuration and provide the same performance as the static offline approach. However, the exceptional case is rare in practice.

Note that routing/pairing and frequency allocation are two key issues in the cloud radio that have not been well addressed in the literature. The proposed graph theoretic approach is able to address the issues in a structured way. It can be implemented in the OMC, monitoring and planning the network in a centralized fashion for the best adaptive effect over the entire network. The centralized implementation is feasible, operating at much longer intervals (e.g., on an hourly basis) than other real-time operations, such as link adaptation and power control (on milliseconds bases). One reason for this is that network management addresses relatively slow changes in the network, including the changes of network topology and traffic demand. Another reason is that more frequent management, including frequency and topology reconfigurations, would be detrimental to user mobility.

Decentralization of the proposed approach is also tractable. It can be achieved by dividing the network into areas, each area consisting of a tractable number of small cells with a closed border. The BSs are assigned evenly to the areas. Our approach can be sequentially carried out to the areas. When processing an area, the small cells along the border of the area from outside are taken into account. The already allocated bandwidths of the small cells are reduced if they interfere with those within the area. Of course, the performance of this decentralized algorithm will not be as good as the globally centralized algorithm. However, its complexity grows only linearly with the number of areas. Signaling overhead will be reduced.

Other decentralized operations that can be carried out in densely and randomly deployed small cells include power control, following an online reconfiguration of the topology and frequencies. Distributed power control games can be carried out. Each cell independently adjusts its transmit power based on the interference that its users have measured and reported, as well as predefined utility and penalty functions of the power. The functions can be judiciously designed such that the whole system will be stabilized with fast convergence.

Note that decentralization of power control is necessary in densely and randomly deployed small cells (as opposed to online network management). This is because a number of users can be scheduled within milliseconds to transmit/receive with different powers at different locations of every cell. Interference changes frequently. Power control at short intervals of milliseconds is critical, which cannot be effectively addressed using a centralized approach.

Small Cell Microwave Backhaul Configuration

Figure 3 illustrates the application of graph theory to point-to-point microwave backhaul, which is cost effective for many practical small cell deployment scenarios, as discussed previously. Frequency-division duplex (FDD) is considered on each backhaul link. Therefore, two frequency bands are required. On the point-to-point backhaul links, every backhaul antenna transmits in one band and receives in the other. Adjacent backhaul antennas along a backhaul branch exploit the two bands in an alternating manner so that the backhaul can be scaled up to multiple hops, as demonstrated in the figure. Small cell traffic travels along the backhaul links to and from the gateways, where the core network is connected.

In this application, the use of cliques in graph theory can be extended to capture the drastically varying traffic on the backhaul links, allocate bandwidths, and avoid collisions between the links with co-located receivers. The clique idea can also be extended to decide the best backhaul paths for the small cells so that the traffic can be evenly distributed across the backhaul networks, eliminating bottlenecks. The clique idea can further be extended to arrange guard bands, which are crucial to mitigate excessive adjacent-frequency interference (between co-located receivers) resulting from inaccurate synchronization of practical backhaul links. These enable the backhaul routes to be adaptively configured, hence relieving a critical problem of backhaul congestion [13].

Given the two-gateway topology shown in Fig. 3, the software-defined online approach based on the extended clique idea starts by identifying the links that can be connected to the two gateways (e.g., link 5). The approach sets up a ratio of the link's traffic through the two gateways (i.e., the red and blue dashed curves) and calculates the traffic demands on all the links. For each of the two FDD frequency bands, a compatibility graph can be generated for the links, as described above. Sub-bands will be sequentially allocated to the maximum cliques of the compatibility graph, which reduces all the way until the traffic demands are satisfied (i.e., the graph becomes empty).

A new approach is used to reduce the compatibility graph. Links that would suffer adjacent-frequency interference from already allocated links will be temporarily precluded, in addition to those satisfied and permanently removed in a conventional way (as described earlier). The preclusion can be implemented by assessing if the frequency gap between the links meets a guard band requirement. After a sub-band is allocated, the temporarily precluded links are restored in the reduced compatibility graph for allocating the next sub-band.

It is possible that the available backhaul spectrum is insufficient to satisfy all the links. In this case, the software-defined online approach adjusts the widths of the allocated sub-bands proportionally, until the satisfaction factor — the ratio of the allocated and requested bandwidths — of the links cannot be improved. This can be achieved by repeating the sub-band allocation for a given satisfaction factor, calculating the required spectrum, and adjusting the factor bisectionally until the required and actual available spectrum are equal.

The new approach can further bisectionally adjust the ratio that was set between the red and blue routes, and iterate the above operations until the satisfaction factor is maximized.

Monte Carlo simulations are carried out to evaluate the software-defined online approach in the backhaul application of Fig. 3. The overall backhaul bandwidth is 100 MHz. The guard band is 1 MHz, which is able to suppress adjacent frequency interference to a negligible level [14]. We assume an average backhaul spectrum efficiency of 5 b/s/Hz on the backhaul links, which is achievable when the adjacent frequency interference is suppressed. We also assume that every small cell has independent but identically distributed traffic demands in both uplink and downlink.

Figure 4 demonstrates the trade-off between the throughput and the MSF of the backhaul network. It shows that the software-defined online approach is far closer to the upper right corner of the figure than a conventional static offline scheme. This indicates that the online approach is able to better leverage the throughput and the satisfaction level compared to its offline counterpart. Given an average MSF of 0.8, the online approach is able to outstrip the offline counterpart by 110.9 percent, increasing the throughput from 320 Mb/s to 675 Mb/s.

Note that the offline counterpart we consider here is the one that can statically distribute backhaul resources across the network in the fairest fashion (wherever possible). There are three steps. In the first step, the backhaul bandwidths are planned such that every small cell has an equal share of the total system capacity in both uplink and downlink. The traffic on link 5 diverges to the two routes with a ratio designed to maximize the share. The ratio results in congestion at cell 6. In the second step, more bandwidths are allocated to links 2, 5, 7, and 8, until cell 2 is congested and prevents further allocations to the links. In the last step, the remaining unallocated bandwidths of GW 0 are evenly distributed between cells 1, 3, and 4. As a result, the throughput and the satisfaction level are leveraged in a static manner. In this sense, comparisons between the new online approach and the offline approach are of practical interest.

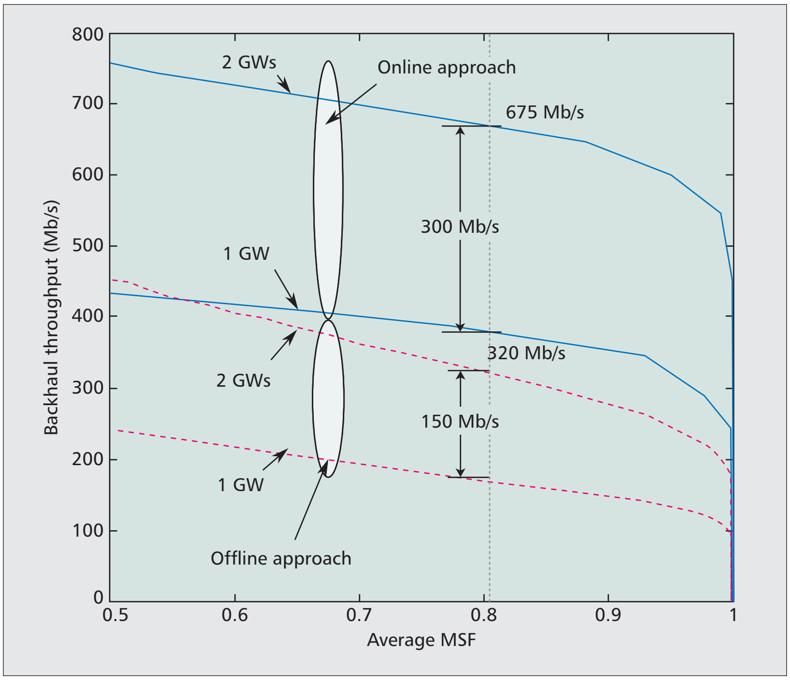

Figure 4. The trade-off between the backhaul throughput (i.e., the total throughput of the small cell system) vs. the average MSF, where the curves are plotted by increasing traffic demands of the small cells from right to left along the horizontal axis, such that the MSF decreases while the throughput grows. Two cases are considered in the figure. In the first case, there are two gateways (GWs), as shown in Fig. 3. In the second case, there is a single gateway, GW 0, and GW 9 is replaced by small cell 9.

Figure 4 also compares the case where there are two GWs to the case where there is only a single GW. In the single-gateway case, GW 9 is replaced by small cell 9 in Fig. 3, while the bandwidth allocation follows the same process as described for the two-GW case. The only exception is that in the single-GW case, the backhaul routes are fixed, and there is no need to adjust the ratio of the red and blue routes.

Comparing the two cases, we can see that the increased throughput of using the second GW the online approach can achieve is double that of the offline counterpart. Specifically, the increased throughput is 300 Mb/s for the online approach, while it is only 150 Mb/s for the offline counterpart given an average MSF of 0.8. This is the result of adaptively determining the backhaul routes, balancing traffic between the GWs, and alleviating congestion at the backhaul bottlenecks in the new software-defined online network management approach.

Inter-Operator Small Cell Spectrum Sharing

Spectrum sharing is important to small cells. It can meet their unbalanced and drastically varying traffic to a greater extent by liaising multiple

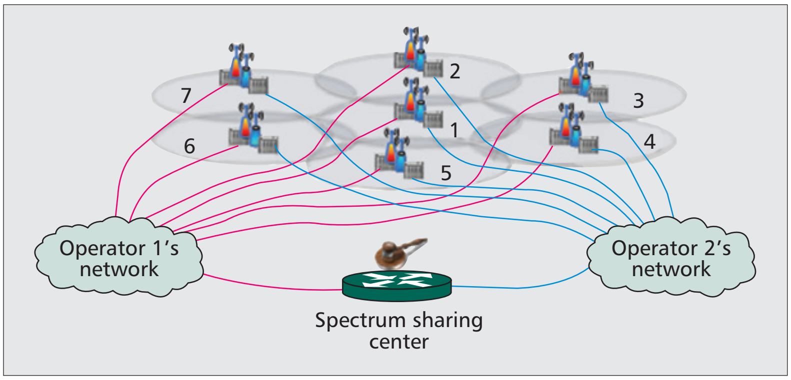

Figure 5. An example of the graph-based software-defined online approach to dynamically sharing the spectrum between two small cell operators, where red BSs belong to operator 1 and blue BSs belong to operator 2. The red and blue cables connect operators 1's and 2's BSs to their respective networks. A spectrum sharing center is an entity connecting the two operators and carrying out the approach to share the spectrum.

operators and efficiently utilizing broader bandwidths. Spectrum sharing can also save operators' spectrum costs by only charging them for what they use. In contrast, current operators need to pay for what they are statically allocated, no matter if they use it or not.

In this application, the clique idea of graph theory can be extended to dynamically release unused spectrum of one operator for another operator to use, adapting to changing traffic of the operators. The clique idea can also be extended to adaptively isolate the frequencies of different operators in overlapping coverage areas, hence eliminating adjacent frequency interference between the operators

Figure 5 illustrates the application of graph theory to sharing spectrum between two small cell operators that have overlapping coverage service areas [15]. The small cells of the two operators are co-located. This is reasonable, because operators often reuse cell sites due to practical limitations, such as site availability, Internet accessibility, and power supply. A single broad frequency spectrum is considered to be adaptively shared between the two operators. The spectrum sharing decisions are made by a government authority, denoted by spectrum sharing center (SSC).

To share the spectrum, the new software-defined online graph theoretic approach can start with each operator assigning sub-bands to meet the instant traffic demands of its cells. Compatibility graphs can be generated, and sub-bands can be allocated based on the maximum cliques of the graphs, as described earlier. The operators then send their allocated sub-bands and the corresponding maximum cliques to the SSC.

In the SSC, the maximum cliques are categorized into two groups. Group 1 consists of those that can reuse frequencies with some of the maximum cliques of the other operator. Group 2 consists of the maximum cliques that are unable to reuse frequencies with any maximum cliques of the other operator. This categorization can be achieved by evaluating the compatibility graph generated earlier. If every pair of vertices of two maximum cliques from different operators are connected, the two maximum cliques belong to Group 1. Otherwise, they belong to Group 2.

The new online approach can make an arrangement of the allocated sub-bands in such a way that the sub-bands of the two operators are placed from left and right, respectively, both starting with those associated with Group 2 followed by Group 1. The approach also aligns these two arranged sub-band sequences such that there is a guard band between the Group 2 sub-bands of the left sequence and the left end of the right sequence. As a result, adjacent frequency interference is eliminated for the Group 2 sub-bands of the left sequence.

To completely eliminate inter-operator interference, the method the online approach can use is to assess the correct sequence from right to left. If any pair of spectrally overlapped sub-bands of the two operators cannot reuse the same frequency, the entire right sub-band sequence is moved right until there is a guard band between the two sub-bands. Such assessment repeats until no inter-operator interference remains. It also keeps the spectrum of each operator continuous, thereby facilitating hardware operations and scheduling.

It is possible that the total required bandwidth is larger than what is actually shared, because the rightward shift increases the requirement. In this case, we can bisectionally adjust the widths of the sub-bands and repeat the above assessments until the bandwidths are equal. The satisfaction factor of the cells with regard to their allocated bandwidths (as described above) is reduced to fit in the shared spectrum. It is also possible that the arrangement of sub-bands, based on which the assessment process is described, is poorly chosen, resulting in a low satisfaction factor. To address this issue, thousands of arrangements can be generated and assessed with the arrangement providing the best satisfaction factor selected.

Figure 6 compares the operators' satisfaction factor between the new software-defined online approach and a conventional offline scheme, where the example of Fig. 5 is simulated. The shared spectrum is 10 MHz wide, and the required guard band is 1 MHz. The average physical layer spectral efficiency is 5.0 b/s/Hz, as assumed above. For the online approach, 1000 arrangements are evaluated. For the offline scheme, a guard band is statically reserved to isolate the frequencies of the two operators, and the frequency band of each operator is statically divided into three sub-bands, applying a frequency-reuse-3 technique [14].

Figure 6 reveals that the satisfaction level of the software-defined online approach declines far more slowly with the growth of traffic than that of the offline approach. In particular, when the overall traffic demand is 80 Mb/s for the two operators, the online approach is able to provide a satisfaction factor of 92 percent on average. In contrast, the conventional offline method can only provide a satisfaction factor of 52 percent.

To determine the 40 percent satisfaction improvement, we plot two reduced versions of the online approach. The first is that a guard band is statically reserved in the middle of the shared spectrum. Each operator independently allocates the frequencies in its own band to maximize its satisfaction factor, exploiting the clique idea, as described above. The second enhances the first by enabling the guard band to shift after the independent frequency allocation so that the satisfaction factors of the two operators can be balanced.

Comparing the full online approach to its first reduced version, we can see that in the 40 percent improvement, 25 percent is contributed by the clique-based frequency allocation, which adapts to the drastically varying traffic demands of small cells. The remaining 15 percent is contributed by allowing different operators to reuse the same frequencies.

Comparing the full online approach to its second reduced version, we can see that an improvement of 5 percent can be achieved by adaptively arranging guard bands during the assessment approach described earlier. Guard bands are only reserved for the overlapped small cells of different operators. Other small cells are allowed to use the guard bands for data transmission. It is worth mentioning that the 5 percent improvement is significant, given that the width of a guard band is 10 percent of the shared spectrum.

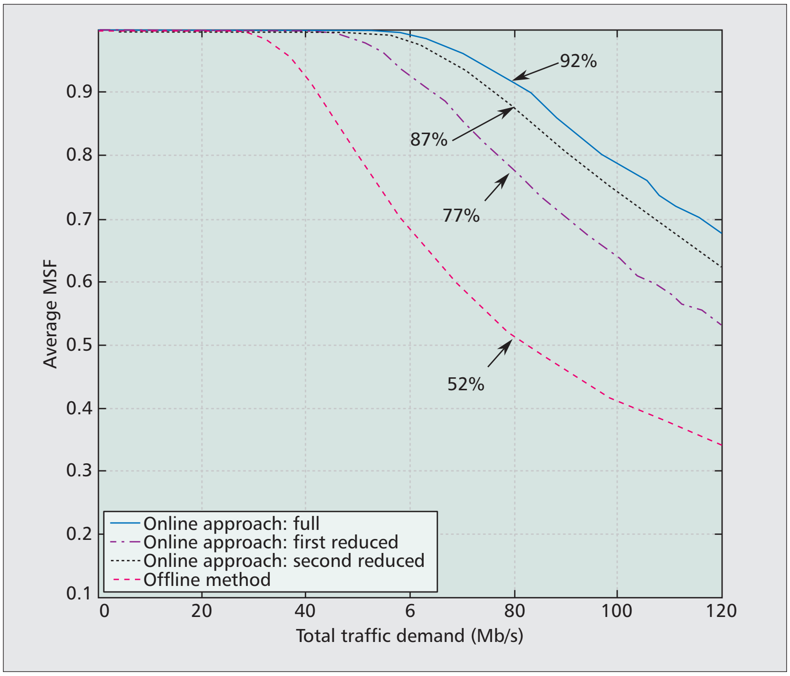

Figure 6. Comparison in terms of the average MSF between the software-defined online approach and the conventional static offline method.

Conclusions

In this article, we introduce a new software-defined online network management approach to address the challenges of the ad hoc deployment, unbalanced and drastically varying traffic demands, as well as limited backhaul and hardware resources in future small cell network planning. Extended from the concept of a clique in graph theory, this approach is able to capture traffic imbalance and fluctuation of small cells, and adaptively plan the network structures and resources. Comparison studies show that the online graph theoretic approach is able to significantly outperform conventional offline network planning in terms of throughput and satisfaction level. Specifically, the throughput can be improved by 155 percent for the cloud radio scenario and 110.95 percent for the microwave backhaul scenario. The satisfaction can be improved by 40 percent for inter-operator spectrum sharing.

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