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GREEN SMALL-CELL NETWORKS

A Cost- and Energy-Efficient Way of Meeting the Future Traffic Demands

The exponentially increasing demand for wireless data services requires a massive network densification that is neither economically nor ecologically viable with the current cellular system architectures. A promising solution to this problem is the concept of small-cell networks (SCNs), which is founded by the idea of a very dense deployment of self-organizing, low-cost, low-power,

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CELL-SIZE REDUCTION IS THE SIMPLEST AND MOST EFFECTIVE WAY TO INCREASE SYSTEM CAPACITY.

base stations (BSs). Although SCNs have the potential to significantly increase the capacity of cellular networks while reducing their energy consumption, they pose many new challenges to the optimal system design. We show in this article how a large system analysis based on random matrix theory (RMT) can provide tight and tractable approximations of key performance measures of SCNs.

Fast-changing communication patterns toward high-speed multimedia communications anytime, anywhere have provoked a big explosion in mobile data traffic. Some big telecommunications equipment manufacturers recently announced that wireless voice has been surpassed by wireless data traffic, and several market forecasts, e.g. [1], predict an exponential traffic growth during the years to come. The main drivers of this massive growth are wireless modems and smartphones, whose prominent usage is about data rather than voice. Additionally, expectations tend toward a local area network (LAN)-like experience not only at home but also on the move. Consequently, current networks already reach their capacity limits in highly populated metropolitan areas during peak times. Congestion problems arise not only at the wireless link but also in the backhaul network.

The interest in environmental friendly or green technologies was recently spurred by the SMART 2020 report [2], a study of the possible effects of information and communication technology (ICT) on global carbon emissions. Although ICT's contribution to the global emissions is and will remain a rather small percentage of the global figures (with 1.25% in 2002 and around 2.5% in 2020), the general trend of a 10% yearly increase in ICT-related carbon emissions is alarming. This means that, despite significant progresses in energy-efficient technologies, the growth in data traffic will outpace our ability to reduce or even maintain the overall energy consumption and related emissions. Thus, more network capacity on the one hand and less energy consumption on the other are two seemingly contradictory future requirements on ICT. This begs the question of how mobile operators can satisfy the future traffic demands, both economically and ecologically.

Although mobile data traffic is rapidly increasing, in the short term, a large percentage of home- or office-based mobile data traffic can be offloaded from the cellular networks via femto cells and/or through the usage of dual-mode phones (WiFi-3G+/4G). Short-term technology upgrades to existing standards [e.g., high-speed packet access (HSPA)] and the transition to optical fiber backhaul links can also be helpful in meeting this increasing demand. However, emerging mobile applications, e.g., (social) augmented reality, as well as the increasingly popular introduction of mobile-broadband substitution will further stress the mobile networks.

In the long term, it is thus questionable if ubiquitous wireless broadband coverage with rates on the order of Gb/s/km^2 can be realized without a radical network design change. Usually, macrocell BSs are designed for the coverage of large areas and are capable of handling low data traffic like voice. Thus they fail to provide high data rate coverage to crowded metropolitan hotspots and indoor environments. For this purpose, micro- or picocells with a reduced coverage range of ten to several hundreds of meters need to be deployed as gap fillers and for providing localized high-traffic solutions. These devices can be essentially scaled-down macrocell BSs that still require a substantial amount of costly planning, integration, management, and maintenance. Hence, these types of small cells can be seen as a necessary evil to complete the portfolio of a radio network rather than as a market in their own right.

It is well known that cell-size reduction is the simplest and most effective way to increase system capacity. Figure 1 shows the gains in spectral efficiency of wireless communication systems from 1950 to 2000, which can be attributed to the different technological advances [3]. While the development of sophisticated coding and modulation schemes and the broadening of usable radio-frequency spectrum led to significant performance gains, the lion's share of the capacity improvements, a staggering factor of 2,700, is due to the shrinking of cell sizes and universal frequency reuse. Since spectrum resources are scarce and little additional technological improvements in coding/modulation schemes are to be expected, a lot of present day research focuses on the improvements of the existing network architecture through the incorporation of interference cancellation techniques [4], cognitive radio [5], and cooperative communication schemes [6], such as network multiple-input multiple-output (MIMO).

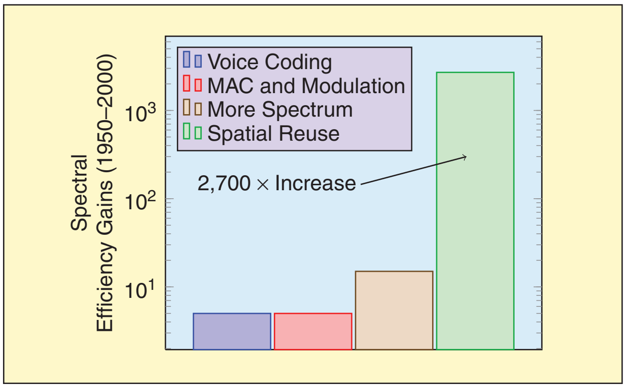

FIGURE 1 Sources of spectral efficiency gains of wireless communication systems from 1950 to 2000 [3].

However, from the discussion earlier, it is clear that none of these technological advances can carry the forecast data traffic alone without a substantial network densification. Additionally, the acquisition and planning of new sites, especially in dense urban areas, are increasingly difficult and require huge capital expenditures (CAPEXs). The deployment, operation, and maintenance of additional macro/micro/picocells cause heavy operational expenses (OPEXs).

SCNs are a novel and radically different network design concept that could provide a cost- and energy-efficient solution to cope with the forecast traffic growth. SCNs are based on the idea of a very dense deployment of low-cost, low-power BSs that are substantially smaller than the traditional macrocell equipment. Umbrella macrocells would be needed, in this architecture, to ensure area coverage, while most of the data traffic is carried by a large number of small cells. Operationally, the SCNs could share the backhaul infrastructure with the already existing wireless or wireline access points [e.g., fiber to the x (FTTx) or VDSL]. The small-cell BSs would be installed on available street furniture (e.g., lampposts, bus stops, etc.) and would rely on their self-organization functionalities for autonomous operation. SCNs would eliminate the need for costly cell site acquisition, detailed network planning, and regular maintenance. They would consequently reduce CAPEX and OPEX while providing unprecedented network capacities.

In the rest of this article, we describe our vision of green and cost-effective SCNs and provide a detailed description of the related technical challenges. We then briefly demonstrate how RMT can be used for the performance analysis and optimization of SCNs.

Green and Cost-Effective SCNs

The idea of small cells is not new. Simple physics tells us that bringing a radio transmitter and receiver closer together reduces the necessary transmit power to overcome path loss and other phenomena, such as fading and noise. What were known as small cells during the operation of cellular networks in the late 20th century can be viewed today as macro- or microcells with a range of several hundred meters. These so-called small cells are now complemented by picocells for coverage and local capacity extensions. However, the recent launch of femtocells can be seen as the first step toward an unplanned deployment of self-organizing SCNs.

While femtocells are used nowadays for traffic offloading and indoor coverage, their true potential to provide high capacity in indoor and outdoor environments in a cost- and energy-efficient way is not fully exploited yet. Today, converged mobile/fixed operators have some of the key assets for a cost-effective deployment of dense small-cell systems: Through the high FTTx penetration, operators have already established a high-capacity backhaul infrastructure, and they could use the street cabinets as shelters for new radio sites. In contrast to the conventional usage of femtocells, SCNs would be deployed by the operator and could be used to enable public access. Moreover, SCNs would avoid overprovisioning of bandwidth to certain areas by allowing an operator to add localized capacity where the demand is, by simply installing a few additional devices to the network.

SCNS ARE A NOVEL AND RADICALLY DIFFERENT NETWORK DESIGN CONCEPT THAT COULD PROVIDE A COST- AND ENERGY-EFFICIENT SOLUTION TO COPE WITH THE FORECASTED TRAFFIC GROWTH.

SCNs have the potential to realize substantial energy savings. However, a dense deployment of possibly thousands of small cells can only be more energy efficient than a traditional macrocellular architecture if operated in the right way (remember that the number of small cells needed to cover a given area scales with the square of the cell size). Since most of the small cells would only be sporadically serving users, SCNs needed to be able to reconfigure to the actual traffic situation according to an energy-follows-load principle [7]. That is, in times of low traffic, the network adopts a configuration with smaller capacity but also lesser energy consumption (e.g., by shutting down of cells/sectors or sleep modes). Further, energy- and cost savings could be realized through self-powered small-cell BSs (e.g., by solar panels), which are independent of a reliable grid.

Challenges

SCNs can be seen as a bridge between fully centralized (cellular) and decentralized (ad hoc) networks and require a paradigm shift from operations, administration, and maintenance (OAM) to self-organizing networks (SONs) with self-learning and intelligent decision making at the nodes. It is widely acknowledged that a massive network densification is only financially viable if the need for costly human involvement in OAM is significantly reduced. Also coverage and performance prediction, interference and mobility management, as well as security issues pose many new challenges to the design of SCNs.

Self-Organization

SCNs require self-configuration, -optimization, and -healing mechanisms. These allow for the autoconfiguration of basic radio and system parameters, the optimization of resource allocation and neighbor lists (e.g., for handover mechanisms) and the recovery from node failures. The self-optimization functionalities should also be able to realize short-term energy savings e.g., by microsleep modes and/or dynamic signaling bandwidth reduction, as well as a full network reconfiguration for long-term savings.

ONE OF THE MAIN LIMITATIONS OF SCNs IS THE SIGNIFICANT AMOUNT OF INTERCELL INTERFERENCE FROM OTHER SMALL CELLS OR MACROCELLS.

Load-balancing mechanisms for SCNs also need to minimize handovers between small cells that could otherwise create a prohibitive amount of control data exchange. To ensure the scalability of SCNs, all algorithms need to be decentralized and stable under incomplete and erroneous information. Moreover, the message exchange between the nodes needs to be kept to a minimum.

Coverage and Performance Prediction

The dense and unplanned deployment of SCNs results in unpredictable interference patterns and a possibly patchy coverage. Thus, the installation of additional macrocell sites to ensure seamless area coverage would be a desirable feature. In addition, the necessarily lower antenna heights of SCNs compared with traditional macrocells make radio propagation predictions in urban areas with possibly strong line-of-sight (LOS) components difficult. Another challenge posed by SCNs is how to guarantee quality of service for delay-sensitive traffic over an unreliable IP-backhaul network that is not owned and controlled by the operator.

Interference Management

With public access, full frequency reuse and an increasing density of small-cell deployments, the interference between small cells as well as interference between small cells and macrocells grows and needs to be managed. Intelligent power control limiting the bandwidth per user and dynamic spectrum access are some of the possible options [8]. Also idle modes and the temporary shutdown of lightly loaded sectors/cells leading to reduced power density can help to minimize interference. Other promising but complex methods comprise interference alignment [9] or multicell processing [6]. Since these techniques require reliable channel state information and/or significant message exchange between the BSs, their benefits for practical networks are still unclear.

Mobility

With a cell diameter of 10–100 m, user mobility becomes difficult to handle in SCNs. Already at a speed of 30 km/h, it is only a matter of seconds to move from one cell to the other. Traditional hard-handover mechanisms would cause, in such a scenario, far too much control signaling between the small cells, and more efficient procedures are hence required. A possible solution relies on user grouping, where static users are served by small cells while mobile users are allocated to the macrocell [8]. Another alternative is the formation of virtual cells, i.e., a cluster of cooperating small cells that appears to the user as a single distributed BS [10]. In this setting, handovers would occur only at virtual cell boundaries.

Security

On account of their hierarchical flat structure, SCNs might exhibit weak points, unknown to date in traditional cellular systems. User privacy could be at risk as most traffic passes through an IP-based backhaul network, which might not be under the full control of the operator. The small-cell equipment must also be tamper resistant to prevent hackers from getting access into the BSs and to create fake BSs gaining access to private user data.

A Large System Perspective

It is of practical and theoretical interest to study the fundamental limits of SCNs in terms of throughput, delay, and reliability, and to develop distributed resource allocation algorithms and protocols that achieve these limits. However, the theoretical performance analysis of SCNs is challenging because of the complexity of any meaningful system model that needs to account for the following aspects:

- *LOS links:* With decreasing cell sizes, the user terminals (UTs) are likely to have LOS links to one or several BSs. This means that the normally fast-fading wireless channel contains strong deterministic nonfading components.
- *Path loss:* The UTs are likely to be covered by several BSs to each of which they have a different path loss.
- *Limited backhaul capacity:* Small-cell BSs are connected via a possibly unreliable backhaul infrastructure prone to capacity limitations, errors, and delays.
- *Imperfect channel state information (CSI):* With an increasing number of transmitters and receivers, the amount of CSI to be acquired grows rapidly. Smaller cell sizes might also reduce the channel coherence time under mobility.
- *Intercell interference:* SCNs are limited by intercell interference from other small cells or macrocells. The statistical properties of this interference might not be completely known to the receivers.
- *Cooperation:* Several BSs could operate as a virtual cell to overcome the problem of frequent handovers in SCNs. The BSs of such a virtual cell can be seen as a distributed antenna system that jointly processes the signals of multiple cells.

We will consider in the sequel a general model for the uplink channel from K UTs to B small-cell BSs, as shown in Figure 2. These BSs are assumed to form a virtual cell and to be connected to a central station (CS) via backhaul links of capacity C (b/s/Hz). The BSs act as simple relay nodes that forward quantized versions of their received baseband signals to the CS that jointly processes the signals of all BSs in the virtual cell. We assume that the UTs are equipped with a single antenna while the BSs can be equipped with multiple antennas. The only number of interest here is the total number of coordinated antennas N (i.e., the total number of receiving antennas). We assume a Rician fading channel, modeled by the sum of two matrices H and A of size $N \times K$. H is a random matrix with independent elements, where the (i,j)-entry of H represents the fast-fading channel gain from UT j to the ith receiving antenna at a given time. The matrix A is deterministic and represents the LOS components of the individual links. The second moments of the matrix entries are proportional to the inverse path loss of the different links. Under these assumptions, the received N-dimensional signal vector y at the CS at a given time can be written as

$$y = (H + A)x + z,$$

where x is a K-dimensional vector of the transmitted signals by the K UTs and z is an overall noise term representing thermal noise, intercell interference, channel estimation errors, and quantization noise due to limited backhaul capacity. From a modeling perspective, the only quantity of importance is the covariance matrix of z. Albeit simple, this model can capture some of the essential features of SCNs.

Important performance measures in this context are the mutual information I and the ergodic mutual information I_{erg} between the channel input x and the channel output y. While I is a measure of how much information can be exchanged over the channel for a given realization H, I_{erg} corresponds to the average rate the channel supports. Another performance criterion is the outage probability $P = \text{Prob}[I > R]$, i.e., the probability that a desired target rate R cannot be supported by the actual channel realization. This quantity is directly related to the fluctuations of I for different channel realizations.

The exact calculation of the aforementioned quantities is intractable because of the complexity of the channel model. Remember that $H+A$ is a random matrix, whose elements have different means and variances, and the noise vector z has an arbitrary covariance matrix. However, in the large system limit, i.e., for K and N growing infinitely large at a same speed, the mutual information I normalized by the number of receive antennas N becomes almost independent of the channel realization and can be closely approximated by deterministic quantities that can be calculated in closed form [11], [12].

One may ask why these results are of practical interest. Obviously, we are not interested in virtual cells consisting of thousands of BSs serving thousands of UTs. On the contrary, realistic system dimensions are rather on the order of say three BSs, equipped with two antennas each, serving $K = 9$ UTs (i.e., $N = 3 \times 2 = 6$). One of the main motivations for the application of large RMT to wireless communications

THE NECESSARILY LOWER ANTENNA HEIGHTS OF SMALL CELLS COMPARED WITH TRADITIONAL MACROCELLS MAKE RADIO PROPAGATION PREDICTIONS IN URBAN AREAS WITH POSSIBLY STRONG LINE-OF-SIGHT COMPONENTS DIFFICULT.

is related to the rather surprising observation that it can provide close approximations of the system performance for even small system dimensions. To demonstrate this, we consider a virtual cell with three cooperative BSs serving multiple UTs, as shown in Figure 3. Each BS is assumed to have two antennas, and we consider one random snapshot of user locations.

Figure 4 shows the normalized ergodic mutual information I_{erg}/N versus the transmit signal-to-noise ratio (SNR), as computed by Monte Carlo simulations and the deterministic approximations provided in [12]. Obviously, the approximations match the simulation results very closely over the full range of SNR.

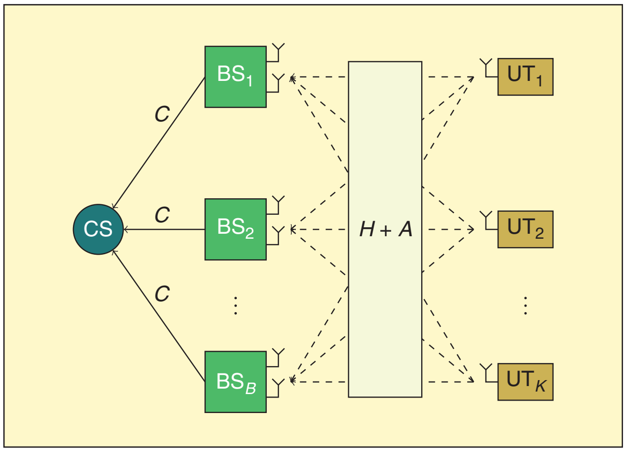

FIGURE 2 Virtual cell uplink channel.

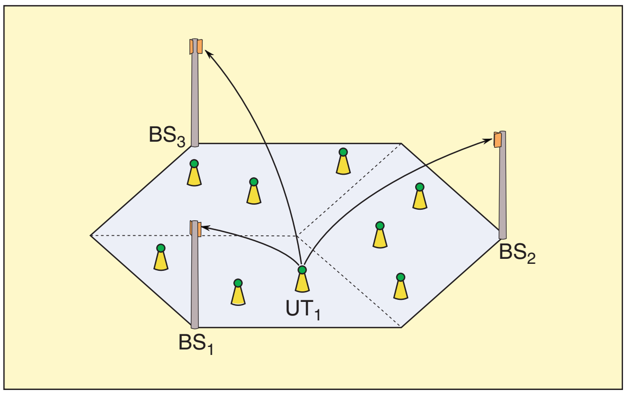

FIGURE 3 Virtual cell with three BSs serving nine UTs.

GREEN NETWORK ARCHITECTURES COULD RECONFIGURE TO THE ACTUAL TRAFFIC NEEDS ACCORDING TO AN ENERGY-FOLLOWS-LOAD PRINCIPLE.

As mentioned earlier, the fluctuations of the mutual information I are related to the the outage probability for a given target rate. Under the assumption that the channel dimensions N and K grow infinitely large, it can be shown that I, if correctly centered and scaled, behaves as a standard Gaussian random variable [11], [12]. Figure 5 compares the standard normal distribution against a histogram of the scaled and centered mutual information for the system model, as described earlier, with nine UTs. Also in this setting, the asymptotic results provide a close performance approximation for small system dimensions.

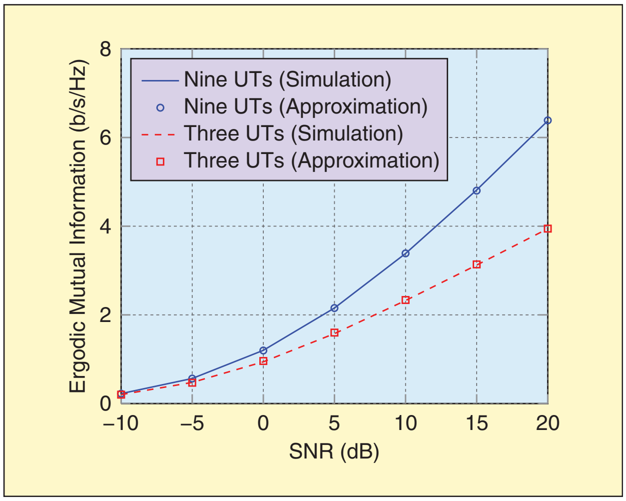

FIGURE 4 Normalized ergodic mutual information versus transmit SNR for different numbers of UTs.

Lastly, we discuss the application of the asymptotic results presented earlier to a system design problem. An important aspect of the performance analysis of SCNs is the question of how many resources should be used for channel estimation and data transmission, given a finite channel coherence time of T channel uses. Since the CS, BSs, and UTs are unaware of the exact channel realization, we assume that the UTs broadcast pilot sequences of length $t < T$, which allows the CS to estimate the channel matrix H. It is intuitively clear that longer pilot sequences allow for better channel estimates but reduce the time for data transmission. Thus, it is natural to ask what is the optimal training length for a given coherence time T. In more mathematical terms, we would like to solve the following optimization problem:

$$\hat{t} = \operatorname{argmax}(1 - t/T)R(t),$$

where $R(t)$ is the average rate that can be achieved if the CS estimates the channel based on pilot sequences of length t, and $(1 - t/T)$ represents the fraction of the coherence time available for data transmission. To solve this optimization problem, we need to compute $R(t)$, which is, in general, intractable for finite system dimensions. It was recently shown [13] that we can replace $R(t)$ by an asymptotic approximation that is available in closed form, to find an approximate value of $\hat{t}$. Figure 6 shows $\hat{t}$ as a function of SNR for our example system with three UTs and a coherence time of $T = 100$ channel uses. The optimal values are obtained by an exhaustive search based on Monte Carlo simulations while the asymptotic approximation requires only a simple line search. We see again in this setting, the asymptotic results provide a close performance approximation for small system dimensions.

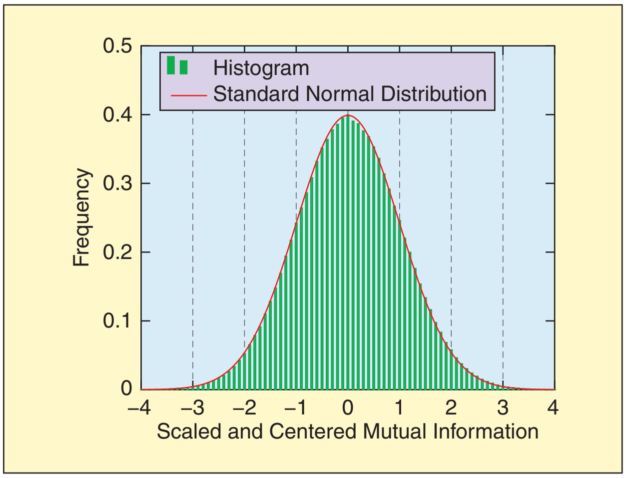

FIGURE 5 Histogram of the mutual information versus standard normal distribution.

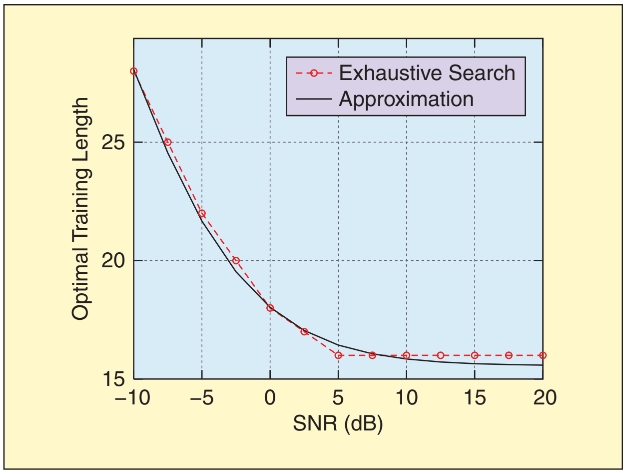

FIGURE 6 Optimal training length versus transmit SNR for a coherence time of 100 channel uses.

Conclusions

The rapidly increasing demand for wireless data traffic poses the challenge of how to increase the capacity of cellular networks in an economical and ecological way. We have presented SCNs as a potential solution to this problem and discussed possible benefits and technical challenges related to their deployment. We then showed how a large system analysis based on RMT is useful for the performance prediction of SCNs. We believe that SCNs offer many possibilities for interdisciplinary research and hope that this article stimulates further work in this direction.

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THE RAPIDLY INCREASING DEMAND FOR WIRELESS DATA TRAFFIC POSES THE CHALLENGE OF HOW TO INCREASE THE CAPACITY OF CELLULAR NETWORKS IN AN ECONOMICAL AND ECOLOGICAL WAY.

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