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# Green, Cost-effective, Flexible, Small Cell Networks

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## 1. Introduction

During the last century, the amount of information that can be exchanged within a given area over a slice of the useful radio spectrum has doubled every 30 months [1]. Without doubt, this tremendous increase in spectral efficiency was rendered possible through the development of sophisticated coding and modulation schemes, efficient channel access protocols and the broadening of the usable radio frequency spectrum. However, the by far biggest capacity gains in personal communications are due to an increasing network densification, i.e., universal frequency reuse and the shrinking of cell sizes.

The almost ubiquitous high-bandwidth coverage and the advent of smart-phones and other portable devices have led to mobile data traffic surpassing voice on a global basis [2]. Several market forecasts, e.g. [3], predict an exponential increase in mobile data traffic during the years to come. This development will be driven mainly by new, uniquely mobile applications (navigation, social networking, video telephony, etc.) being rich in multimedia content and increasing mobile-broadband substitution through smart phones and USB-dongles.

In the light of this rapid change, it is justified to ask how operators will satisfy the exploding demand for more and more bandwidth. Mobile networks are a mature technology with little technological breakthroughs in coding/modulation schemes to be expected in the near future. Moreover, there are hardly any additional spectrum resources with desirable propagation characteristics available. Therefore, interference cancellation techniques [4], cooperative communications schemes (network MIMO) [5] and cognitive radio [6] are subject of current research seeking to further improve the way the available spectrum is utilized. However, none of these techniques can carry the forecast traffic increase alone without a further network densification. While the acquisition and the planning of new macro cell sites, especially in dense urban areas, become increasingly difficult and expensive (CAPEX), the deployment, operation and maintenance of additional macro cells cause heavy operational expenses (OPEX). Thus, operators are likely to face a "wall" in the future where a further network capacity-increase through additional macro cell deployments causes prohibitive costs.

"Small cell networks" (SCN) are founded on the idea of massive network densification by using base stations (BSs) that are substantially smaller than traditional macro cell site equipment. The deployment and profitable operation of SCNs is rendered possible by sharing already existing sites and backhaul infrastructure with other wireline/less access points (e.g., FTTN/H or VDSL street cabinets, DSL backbone) and by relying on autonomous operation and self-configuration. Eliminating the need for further cell site acquisition and detailed network planning, SCNs can thus drastically reduce CAPEX and OPEX while ensuring high data-rates, uniformly delivered over the coverage area.

## 2. Small Cells

The general term "small cell networks" covers a range of radio network design concepts which are all based on the idea of deploying BSs much smaller than typical macro cell devices to offer public or open access to mobile terminals. In essence, a small cell BS can be seen as a cellular BS designed to serve a limited coverage area, around a factor 100 smaller than a traditional macro cell. A small cell BS is a small, humanly-portable, low-cost and low-power device. It can be deployed in a plug-and-play fashion, self-configures all necessary parameters and does not require any regular maintenance. Small cells (SCs) target a coverage radius of 50−150m and radiate at low power (0.1-10W). Possible deployment scenarios are public indoor and outdoor with open or closed access, e.g. in small boxes on existing street furniture, metro hotspots, etc., but also residential and enterprise environments. In this regard, SCNs also comprise low-power micro, pico and femto cells. The main benefits of SCNs are:

- SCNs allow to offload traffic from the macro cell and to provide dedicated capacity to homes, enterprises or urban hotspots, i.e., where most data usage occurs. SCNs can be seen as a low-cost coverage extension under umbrella macro cells, but might also replace them gradually.
- Dense SCNs allow for unprecedented mobile system capacities (in terms of Gbit/s/km$^2$) and higher data-rates for each user since less devices share the bandwidth of a single cell.
- SCNs have the potential to reduce the ecological footprint of cellular networks. Bringing mobiles and BSs closer together leads to less required transmit power and enhances the terminal's battery duration. Moreover, owing to their reduced transmit power, small cells minimize the threat to human health compared to macro BSs.
- SCNs make cell site rental and dedicated backhaul provisioning superfluous since they rely on already existing backhaul infrastructure (FTTN/H, DSL) and are integrated in the street furniture, enterprise buildings or people's homes.

- Self-organization and optimization of the devices allows for plug-and-play deployment, requires no network planning and reduces maintenance costs.

## 3. Technical Challenges

There are several technical challenges related to the large scale deployment of small cells which we will outline in this section. First of all, today's wireless cellular networks require an extensive involvement of human operators for planning, configuration, operation, management, monitoring and maintenance, which causes huge operational costs that amount easily to more than 75% of the total expenses. Therefore, any massive network densification necessitates a significant degree of autonomy, self-configuration and optimization of its components to keep the operational expenses low. Ideally, similar to femto cell equipment, small cell BSs could be installed in a plug-and-play fashion without requiring any further initialization steps and maintenance. Experiences from existing femto cell deployments could provide valuable insights in this regard. Among the most important issues related to self-configuration and self-optimization are:

- (dynamic) configuration of radio parameters
- resource allocation (time, frequency, power)
- interaction/coexistence between small cell BSs and the macro cell layer
- optimization of joint area coverage
- authentication, registration and access permission
- automatic discovery of neighbors and composition of optimal neighbor lists
- intelligent handoff (SC-SC, SC-macro cell)
- self-protection and network recovery
- scalability (to possibly 100k's of devices)

Second, since a SCN is by definition not planned and the BSs are likely to be installed at sub-optimal locations, it is difficult to ensure full coverage without the help of some macro cells. Also indoor coverage from outdoor SCs might be difficult to achieve. Moreover, the low BS antenna heights make it difficult to model the radio propagation in urban areas with possibly strong line-of-sight (LOS) components. Thus, coverage prediction and the calculation of optimal cell sizes require extensive ray-tracing simulations based on 3D building shape data bases.

Third, regular hard handover (HO) mechanisms are not suited for SCNs due to their small coverage range. For fast moving terminals, HOs would occur far too often to allow for enough time for network scanning, ranging, etc. Location management techniques and routing algorithms for highly mobile SCNs also pose an important technical challenge.

Fourth, due to security aspects it is of utmost importance to identify vulnerabilities of SCNs. On account of its hierarchical flat structure, a SCN might exhibit weak points unknown to date in traditional cellular systems. For example, user privacy is at risk since most of the user traffic passes through an IP-based backhaul network which might be not under full control of the operator. The small cell equipment must also be tamper-resistant to prevent hackers from getting access into the small cell BS. Also self-healing mechanisms in case of BS failures need to be developed.



**Figure 1: Deployment scenario of a small cell network**

## 4. Vision & Tools

SCNs are a promising concept to cater for the future needs of mobile communication systems. However, to tap their full potential, the way we build and think about wireless networks needs to be radically changed. Our vision is green, cost-effective, flexible and cooperative SCNs (see Fig. 1):

SCNs could become a green technology which reduces the carbon footprint of wireless networks. This is because small cell BSs require less transmit power and could be made independent from external power supplies, for example through energy harvesting mechanisms like solar panels. In addition, if equipped with satellite backhaul links, SCNs could also be deployed in remote areas or developing countries where a lack of reliable power supply and infrastructure renders a classical macro cell deployment impossible. However, the large scale deployment of SCNs is only ecologically worthwhile if new energy efficient protocols and power saving mechanisms are adopted. Given the large number of devices in a SCN, it is likely that many small cells are not actively serving users but rather wasting energy due to a lack of stand-by or sleep modes.

We see SCNs as dense, self-organizing, self-healing and secure networks where mobiles and BSs interact and self-adapt in an intelligent manner with only a limited amount of human intervention. They can be seen as a bridge between fully centralized and fully decentralized networks, differing from ad-hoc networks through a static "infrastructure" of small cell BSs. By supporting a multitude of different standards (W-CDMA, WiMAX, LTE, Wi-Fi, Bluetooth, etc.) and by being able to transmit/receive on different frequency bands, a SCN could schedule data traffic according to the most favorable technology and also support legacy devices.

Cooperation between the small cell BSs is mandatory for any form of self-organization and mobility management. Due to their small coverage range, HOs between small cells would occur far too frequent in highly mobile environments and new forms of handovers must be considered. A possible solution consists in the formation of "virtual cells", i.e., clusters of cooperating cells. A virtual cell is a group of BSs seen by the mobile as a single distributed BS. Inside a virtual cell, a mobile can move without performing regular HOs. Only at the virtual cell boundaries a HO is performed.

Making SCNs a reality requires interdisciplinary research which comprises many different tools of which we will mention a few:

- **Large random matrix theory (RMT):** The study of SCNs involves both a large number of communicating/interfering devices and wireless channels with a different path loss between different devices and possibly strong LOS components. Since these channel models are hard to tackle analytically for finite dimensions, the study of asymptotic limits provides useful bounds and insight into the most crucial performance parameters.
- **Game theory (GT):** Ideally, the small cell BSs act as autonomously as possible with limited feedback and control. Thus, there is a need for decentralized optimization algorithms. Open questions are, e.g., the optimal size and grouping of virtual cells. Coalition games [7] provide a useful framework for this setting.
- **Interference alignment (IA) and VFDM:** The co-existence of SCNs, macro cells and possibly other (un-)licensed networks requires novel strategies for interference mitigation. Promising candidates are interference alignment [8] and Vandermonde frequency division multiplexing (VFDM) techniques [9].
- **Stochastic geometry:** An often neglected aspect in the study of wireless networks is the impact of the distribution of the terminals and BSs. The rather novel field of stochastic geometry [10] might provide answers to the questions of the optimal small cell density and the impact of (clustered) random versus regular (e.g., hexagonal grid) network topologies.

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