Femtocells: Past, Present, and Future

Jeffrey G. Andrews, Holger Claussen, Mischa Dohler, Sundeep Rangan, Mark C. Reed

***Abstract*—Femtocells, despite their name, pose a potentially large disruption to the carefully planned cellular networks that now connect a majority of the planet's citizens to the Internet and with each other. Femtocells – which by the end of 2010 already outnumbered traditional base stations and at the time of publication are being deployed at a rate of about five million a year – both enhance and interfere with this network in ways that are not yet well understood. Will femtocells be crucial for offloading data and video from the creaking traditional network? Or will femtocells prove more trouble than they are worth, undermining decades of careful base station deployment with unpredictable interference while delivering only limited gains? Or possibly neither: are femtocells just a "flash in the pan"; an exciting but short-lived stage of network evolution that will be rendered obsolete by improved WiFi offloading, new backhaul regulations and/or pricing, or other unforeseen technological developments? This tutorial article overviews the history of femtocells, demystifies their key aspects, and provides a preview of the next few years, which the authors believe will see a rapid acceleration towards small cell technology. In the course of the article, we also position and introduce the articles that headline this special issue.**

I. Introduction

The topology and architecture of cellular networks are undergoing a major paradigm shift from voice-centric, circuit switched and centrally optimized for coverage towards data-centric, packet switched and organically deployed for capacity. The principle drivers for this shift are intense consumer demand for mobile data that has exceeded even the most aggressive predictions of five years ago; enabling features of the newer wireless standards, in particular LTE; and relentless hardware and software integration that has enabled the entire functionality of a base station to be miniaturized. For example, in 2010 the amount of global mobile data traffic nearly tripled for the third year in a row, and exceeded the traffic on the entire global Internet in 2000 [1]. By 2015, nearly 1 billion people are expected to access the Internet exclusively through a mobile wireless device [1]. It is obvious that the traditional cellular network, which is already at the point of failure in many important markets, cannot keep pace with this data explosion through the expensive and incremental methods of the past: namely increasing the amount of spectrum or by deploying more macro base stations.

This rapid increase in mobile data activity has raised the stakes on developing innovative new technologies and cellular topologies that can meet these demands in an energy efficient manner. The importance of this is highlighted in Fig. 1 where the projected increase in network traffic and its contributing components for North America from 2007 to 2020 is shown [2]. The point reinforced by this figure is that traffic is set to grow exponentially over many years with wireless data increasing the most rapidly.

J. Andrews (jandrews@ece.utexas.edu) is with the University of Texas at Austin. H. Claussen (holger.claussen@alcatel-lucent.com) is with Bell Labs, Alcatel-Lucent. M. Dohler (mischa.dohler@cttc.es) is with CTTC. S. Rangan (srangan@poly.edu) is with Polytechnic Institute of New York University. M.C. Reed (mark.reed@anu.edu.au) is with the Australian National University. Article date: November 4, 2011

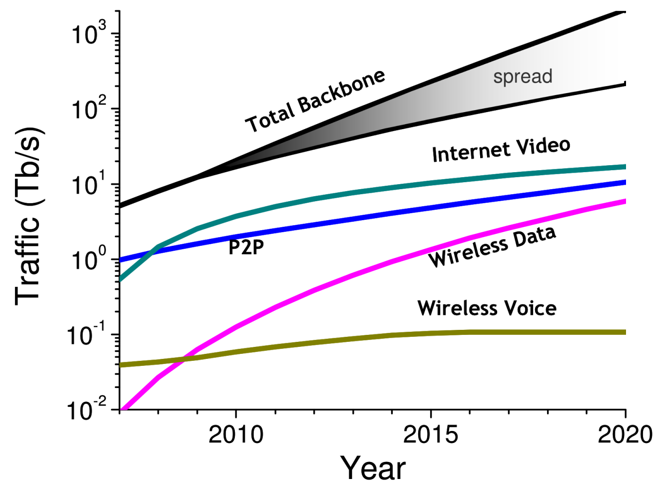


Fig. 1: Traffic demand for North America [2]

One of most interesting trends to emerge from this cellular (r)evolution are femtocells [3], [4]. Femtocells are small, inexpensive, low-power base stations that are generally consumer-deployed and connected to their own wired backhaul connection. In these respects, they resemble WiFi access points, but instead they utilize one or more commercial cellular standards and licensed spectrum. To a mobile station (MS), a femtocell appears indistinguishable from a traditional base station, as they have all the usual overhead channels and are capable of in-band handoffs. Originally envisioned as a means to provide better voice coverage in the home – many subscribers cite poor signal quality in their house when switching to a different service provider – they are now primarily viewed as a cost-effective means of offloading data traffic from the macrocell network. By the start of 2011, an estimated 2.3 million femtocells were already deployed globally, and this is expected to reach nearly 50 million by 2014 [5]. Femtocells, along with WiFi offloading, are expected to carry over 60% of all global data traffic by 2015 [6].

To make sense of this new network paradigm, we survey the history of small cell technology (Section II) and provide a broad technical, prototcol and business taxonomy for femtocells (Section III). Then, we overview plausible engineering and mathematical models for femtocell-overlaid cellular systems (Section IV). Adding this much unplanned in-band infrastructure to the network raises many questions and introduces many interesting technical, business, and regulatory challenges. We conclude by discussing all three sets of challenges (see Section V), focusing on the technical challenges, which span multiple fields: modeling and analysis, communication and information theory, network protocol design, distributed optimization, and implementation. In the course of the article, we provide a broad and detailed review of the literature, highlighting the contributions that accompany this overview article in this first IEEE special issue on femtocells.

II. A Brief History of Femtocells

A. Early Origins

The idea of small cells has been around for nearly 3 decades [7]. Initially, "small cells" was a term used to describe the cell size in a metropolitan area, where a macrocell (on the order of kilometers in diameter) would be cell split into a number of smaller cells with reduced transmit power, known today as metropolitan macrocells or microcells, and having a radius of perhaps several hundred meters.

Simultaneously, cellular repeaters or "boosters" were being investigated [8], [9] as an alternative to small base stations. These re-radiating devices were intended to help improve the signal quality in poor coverage regions, while reducing costs by not requiring a wireline backhaul. However, their reuse of the licensed spectrum for backhaul limited the achievable throughput, and hence these repeaters were neither helpful to the system capacity nor simple to deploy.

In the 1990s, a precursor to cellular picocells began to appear [10] with cell sizes ranging from tens to about one hundred meters. These "traditional" small cells were used for capacity and coverage infill, i.e. where macro penetration was insufficient to provide a reliable connection or where the macrocell was overloaded. These types of small cells were essentially a smaller version of the macro base station, and required comparable planning, management and network interfaces. More similar to the current femtocell concept was a little known industry project in the early 1990s led by Southwest Bell and Panasonic to develop an indoor femtocell-like solution that re-used the same spectrum as the macrocells [11] and used wired backhaul (T1 or PSTN). However, there was a lack at this time of ubiquitous IP backhaul, and the level of integration had not yet achieved the critical point where a base station could be truly miniaturized. Like the other small cell technologies just mentioned, they were technically a step forward but economically unsuccessful, because the cost of deploying and operating a large number of small cells outweighed the advantage they provided.

B. The Birth of Modern Femtocells

New thinking on the deployment and configuration of cellular systems began to address the operational and cost aspects of small cell deployment [12], [13]. These ideas have been applied successfully to residential femtocells where cost issues are amplified. A femtocell is fundamentally different from the traditional small cells in their need to be more autonomous and self-adaptive. Additionally, the backhaul interface back to the cellular network – which is IP-based and likely supports a lower rate and higher latency than the standard X2 interface connecting macro and picocells – mandates the use of femtocell gateways and other new network infrastructure to appropriately route and serve the traffic to and from what will soon be millions of new base stations.

Perhaps more important than the need to provide cellular coverage infill for residential use, the mobile data explosion discussed in the Section I has mandated the need for a new cellular architecture with at least an order of magnitude more capacity [14]. The most viable way to meet this demand is to reduce the cell size and thereby the spatial frequency reuse [15], unless the plentiful (and inexpensive) frequencies in the tens of GHz can be harnessed for mobile broadband, which is extremely challenging [16]. In parallel to the escalating data demands, several technological and societal trends have made low-cost femtocells viable. These include the wide availability and low cost of wired broadband internet connections; the development of 4G cellular standards that are OFDMA and IP-based and provide a better platform for femtocell overlays than 3G CDMA (near-far problem) networks that are circuit switched (the femtocell backhaul is inherently IP); and relentless hardware and software integration has made it foreseeable to have a fully functional low power base station in the $100 price point range.

Small cells have recently become a hot topic for research as evidenced by a significant increase in publications in this area, and small cell technology has advanced a great deal from the simple cell splitting ideas presented in [7]. For example, the number of publications including femtocell or femtocells in the topic registered in the IEEE data base have increased from 3 in 2007 to 10 (2008), 51 (2009), 116 (2010), and continues to accelerate. In addition, the European Union has started funding research on femtocells, for example the ICT-4-248523 BeFEMTO project, which focuses on the analysis and development of LTE/LTE-A compliant femtocell technologies [17]. Today, advanced auto-configuration and self-optimization capability has enabled small cells to be deployed by the end-user in a plug-and-play manner, and they are able to automatically integrate themselves into existing macrocellular networks. This was a key step to enable large scale deployments of small cells.

As a result we have now seen successful commercial femtocell deployments. In the US, Sprint Nextel started their nationwide femtocell offering in 2008, with Verizon and AT&T following suit in 2009 and 2010, respectively. In Europe, Vodafone started their first femto deployment in 2009 in the UK, and subsequently other countries. In Asia, Softbank mobile, China Unicom, and NTT DoCoMo launched their femtocell services in 2009. According to the Femto Forum, operator deployments grew by 60% in the second quarter of 2011 to 31, including eight of the top 10 global mobile operator groups.

C. Modern Femtocell Research

There is a growing body of research on femtocells, of which we briefly summarize some notable early results here. Early simulation results for femtocells were presented by H.

Claussen and co-authors at Bell Labs (Ireland) [18]–[20], which were extended to self-optimization strategies and multiple antennas shortly afterward [21], [22]. On the academic side, early work included new mathematical models and analysis by Chandrasekhar and Andrews, specifically looking at the uplink interference problem in CDMA-based networks with closed access [23], [24]. This model and approach was adapted to the downlink and with multiple antennas in [25]. Other early work from UCLA suggested adaptive access control to mitigate the cross-tier interference problem [26], which was given further attention in [27], [28].

Das and Ramaswamy in [29], [30], investigated the reverse link (RL) capacity of femtocells, modeling inter-cell interference as a Gaussian random variable. As discussed in Section IV, such a model is probably not accurate for cellular systems with femtocells. In [31] the authors investigated user-assisted approaches to interference optimization, while in [32] the authors presented interference management techniques for both downlink and uplink of femtocells operating based on high speed packet access (HSPA); this work was extended in [33], which developed new analytical techniques to improve the optimization for WCDMA femtocell systems.

Several papers have also considered interference coordination in OFDMA based networks, including co-channel interference [34], interference management [35], and interference avoidance strategies [36]. Mobility management and access control for femtocells was discussed in [37]–[39] where access control can be viewed as an effective form of interference avoidance.

Built on these past contributions, technologies have emerged over time, the governing standards of which are discussed subsequently.

III. Femtocell Standardization

From a technology point of view, a femtocell is not only characterized by short communication range and high throughput, but also by its ability to seamlessly interact with the traditional cellular network at all layers of the network stack, performing tasks like handoffs (HOs), interference management, billing, and authentication. This necessitates substantial support by the appropriate standards bodies.

The governing body with arguably most impact onto standardization bodies is the Femto Forum. It is a not-for-profit membership organization founded in 2007 to enable and promote femtocells and femto technology worldwide. Today, it counts on more than 70 providers of femtocell technology, including mobile operators, telecommunication hardware and software vendors, content providers and start-ups. It has had a major impact in various standardization bodies, such as ETSI and 3GPP. It caters, among others, for developing a policy framework that encourages and drives the standardization of key aspects of femtocell technologies worldwide. It is active in two main areas: 1) standardization, regulation & interoperability; and 2) marketing & promotion of femtocell solutions across the industry and to journalists, analysts, regulators, special interest groups and standards bodies. We now overview how femtocells fit into 3G CDMA-based networks, and then 4G OFDMA-based networks (LTE).

1) UMTS/cdma2000 Femtocells: UMTS' three main embodiments (put forward by 3GPP) and cdma2000 (put forward by 3GPP2) have similar architectures and are based on CDMA. Being IMT-2000 compliant, they theoretically offer order of magnitude higher data rates than the GSM family, although depending on the load, the user experience may not be much different. CDMA networks are interference-limited and their performance has a fragile dependence on power control. Without accurate centralized power control, the "near-far effect" causes nearby users to overwhelm the received power of farther users, since they use the same band. With femtocells, such centralized power control is nearly impossible to accomplish because the received power levels cannot be simultaneously equalized at numerous points in space. For example, an uplink macrocell mobile user may transmit at a power level that effectively disables many nearby femtocells in that band. Therefore, adding even a small number of CDMA femtocells can have a profound impact, as seen theoretically in [24]. Two straightforward solutions to this problem exist, however. The first is to go to an open access control paradigm (discussed below in Sect. IV-B), where each mobile simply communicates with the strongest available base station: thus, strong interferers are simply handed off and subsequently lower their power. When this is not possible, and the femtocells are closed access, the mobile can switch to another 3G band (most operators have at least two paired 5 MHz channels per market) or revert to GSM.

2) LTE/LTE-A Femtocells: 3GPP is now focused on Long Term Evolution (i.e. LTE, formally 3GPP Release 8 onwards) and LTE-Adanved technologies (LTE-A, Release 10 onwards), while 3GPP2 activities are now essentially discontinued. WiMAX marches on, including femtocell standardization activities [40], but its impact in developed markets figures to be small. The physical and MAC layer impact of femtocells on LTE and WiMAX are quite similar, due to their comparable physical and MAC layer designs, which are based on orthogonal frequency division multiple access (OFDMA). Since LTE is likely to be the dominant cellular data platform for the foreseeable future, the smooth integration of femtocells into LTE is particularly important, and is the subject of a paper in the special issue [41].

A key difference in OFDMA (both LTE and WiMAX) is the large quantity of dynamically allocated time and frequency slots [42]. This considerable increase in the flexibility of resource allocation is both a blessing and a curse. Because femtocells can be allocated orthogonal resources to nearby pico and macrocells, the possibility for fine-tuned interference management exists, whereas it did not in GSM or CDMA. That is, in theory, a complex network-wide optimization could be done whereby femtocells claim just as much resources as they "need", with the macrocells then avoiding using those time and frequency slots. And therein lies the curse: potentially a large amount of coordination is necessary. A popular compromise is fractional frequency reuse [43], whereby frequency (or time) resources can be semi-statically allocated to interior, edge, or small cell users, with power control on top to lower the throughput disparities experienced in each of these scenarios. Alternatively, a semi-static partition could simply be made between femtocells and macrocells. The results in [44] indicate that even with dense femtocell deployments, most resources should go to the macrocell, since each femtocell only needs a small number of resource blocks to provide comparably high throughput to their user(s).

IV. Uplink and Downlink Femtocell Models

Accurate wireless channel and network models are fundamental to the development of standards and to evaluating possible solutions to the difficulties posed in wireless systems. In this section we first briefly overview traditional cellular models, before moving onto modeling such systems with femtocells, i.e. two-tiered cellular networks. We conclude by discussing the most general (and practically important) case of multi-tiered cellular systems consisting of macrocells, femtocells, picocells and possibly further radiating elements (like relays, distributed antennas, or future infrastructure).

A. Macrocellular Modeling

1) Link Level Modeling: Cellular models start with the modeling of a single link, or wireless channel. Such channels depend on a large number of factors including the propagation environment, range, carrier frequency, antenna placement, and antenna type. Typically all of these factors are abstracted into either theoretical – e.g. path loss, shadowing, fading – and more accurate but less elegant empirical models, such as those used by 3GPP [45]. Since femtocells typically differ significantly from standard cellular systems in all the above categories except carrier frequency, it can be assumed that their channel behavior will be more similar to WiFi channels than cellular channels. Nevertheless, such "indoor" channels are for the most part well understood at a variety of frequencies [46], with current general models such as the Winner II channel models including indoor as a special case.

2) System-Level Modeling: The more challenging and unique aspects of cellular systems emerge when multiple simultaneous users are considered. Although sophisticated theoretical results and techniques have been developed for downlink (aka "broadcast") channels and uplink ("multiple access") channels [47], [48], these models and the associated "optimal" techniques have the significant shortcoming that they generally do not consider the role of (non-Gaussian) interference or highly disparate (30-50 dB) gains between the various users.

Developing analytically tractable models for cellular systems is very difficult. This fact is clearly demonstrated by the persistence of the extremely simple "Wyner model", that adopts a deterministic (or fixed average) SINR for users in a cell, regardless of whether they are interior or edge users [49]. Such an approach, unsurprisingly, is not particularly accurate in most cases [50]. Given the paucity of analytically tractable models, industry and most academics have stuck to the well-accepted hexagonal grid model for evaluating candidate system design features. The grid model is easy enough to simulate and is thought to closely approximate well-planned cellular deployments, which has allowed it to withstand the test of time.

An alternate but currently less popular philosophy is to model the base stations as randomly located. Perhaps counter-intuitively, making the base stations randomly located leads to an analytically tractable model (assuming the placements are iid) and ultimately fairly simple precise expressions can be developed for the SINR distribution (and its daughter metrics like outage and throughput) [51]. One can see in Fig. 2 that subjectively at least, a real-world macrocell deployment lies roughly between a fully deterministic grid a fully random (i.e. iid) placement. We will see below that one further advantage of this model is that it more naturally integrates femtocells and other heterogeneous elements.

B. Femtocell Access Control

One important classification for femtocells that strongly affects the model is the type access control. For a *Closed Subscriber Group* (CSG), only pre-registered mobile users can use a certain femtocell. This would typically be a tiny fraction of the mobile population. At the other extreme, in an *Open Subscriber Group* (OSG), any mobile can use any femtocell, or at least one that is "open". Naturally, hybrid approaches are possible: for example a femtocell might allow up to N non-registered mobile users to access it, but afterwards not admit new users. This would limit the load on the femtocell and its backhaul connection.

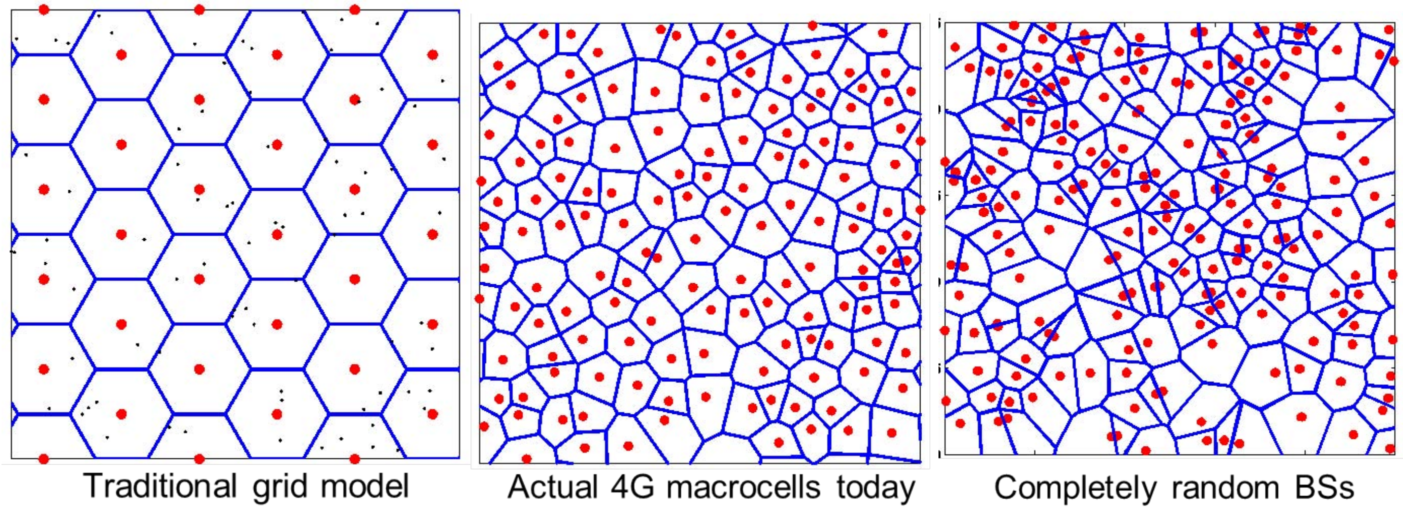
Generally speaking, open access is a superior approach from a network capacity point of view, and from the mobile users point of view. A particular femtocell owner might expect to see degraded QoS by opening it up to all mobiles in the network, but in fact this generally does not happen, and in the CDMA uplink in particular the femtocell performance is much better even for the home user with open access, since strong interferers are handed off, mitigating the near-far problem [27]. In any case, the type of access control is one of the key features in any cellular model that includes femtocells.

C. Femtocell Network Modeling

The addition of femtocells obviously requires an evolution of the traditional cellular model. There appear to be four high-level approaches to modeling femtocells in cellular networks, although the details can vary quite a bit from paper to paper. And of course some papers may use and even compare several of the below models [52].

The first approach is to keep the familiar grid model for macro base stations (including the special case of a single macro BS), and to drop femtocells "on top" of it, either randomly [41], [53]–[55] or in a deterministic fashion [56]–[58]. One BS (usually the closest and/or strongest) would connect to the mobile user, with all other macrocell and femtocell BSs (downlink) or mobile users (uplink) acting as interference. In closed access, it may not be possible to connect to the preferred base station, in which case the interference from even a single interferer can be stronger than the desired signal, which is an important distinction from a traditional cellular network.

A second simpler but less complete model is to focus on a single femtocell (and its associated user) dropped in the cellular network [27], [59], [60]. In the downlink, the interference



(a) (b) (c)

Fig. 2: Example of different macrocell only models. Traditional grid networks remain the most popular, but 4G systems have smaller and more irregular cell sizes, and perhaps are just as well modeled by a totally random BS placement.

to the femtocell user is assumed to be only from the various macrocells, which in a fairly sparse femtocell deployment, is probably accurate. In the uplink as well, the strong interference is bound to come from nearby mobiles transmitting at high power up to the macro base station, so the model may be reasonable. The main limitation of this model vs. Model 1 is that the performance of downlink macrocell users – who may experience strong femtocell interference depending on their position – cannot be accurately characterized.

The third model, which appears to be the most recent, is to allow both the macrocells and femtocells to be randomly placed. This is the approach of three papers in this special issue [61]–[63], and to the best of our knowledge, these are the first full-length works to propose such an approach (earlier versions being [64], [65]. Both of these papers are for the downlink only and an extension to the uplink would be desirable. An appealing aspect of this approach is that the randomness actually allows significantly improved tractability and the SINR distribution can be found explicitly. This may allow the fundamental impact of different PHY and MAC designs to be evaluated theoretically in the future.

A fourth model is simply to keep all the channel gains (including interfering channels) and possibly even the various per-user capacities general, without specifying the precise spatial model for the various base stations, e.g. [66], [67]. This can be used in many higher-level formulations, e.g. for game theory [59], power control, and resource allocation, although ultimately some distribution of these channel gains must be assumed in order to do any simulation, and the gains are to a first order determined by the locations of the various transmitting sources. So ultimately, this fourth model typically will conform to one of the above three models.

V. Overview of Key Challenges

Building on the models developed in last section, as well as the preceding discussions on standards and historical trends, in this section we turn our attention to some of the new challenges that arise in femtocell deployments. To motivate future research and an appreciation for the disruptive potential of femtocells, we now overview the broader challenges of femtocells, focusing on both technical and economic/regulatory issues.

A. Technical Challenges

1) Interference Coordination: Perhaps the most significant and widely-discussed challenge for femtocell deployments is the possibility of stronger, less predictable, and more varied interference, as shown in Fig 3. This occurs predominantly when femtocells are deployed in the same spectrum as the legacy (outdoor) wireless network, but can also occur even when femtocells are in a different but adjacent frequency band due to out-of-band radiation, particularly in dense deployments. As discussed in the previous section, the introduction of femtocells fundamentally alters the cellular topology by creating an underlay of small cells, with largely random placements and possible restrictions on access to certain BSs. Precise characterizations of the interference conditions in such heterogeneous and multi-tier networks has been the subject of extensive study [68], [69]. One of the important and perhaps surprising results shown in [61] is that in principle, with open-access and strongest cell selection, heterogeneous, multi-tier deployments do not worsen the overall interference conditions or even change the SINR statistics. This “invariance property” has also been observed in real-world systems by Nokia Siemens [70] and Qualcomm [71], and provides optimism that femtocell deployments need not compromise the integrity of the existing macrocell network.

However, in practice, at least two aspects of femtocell networks can degrade the interference significantly. First, under closed access, unregistered mobiles cannot connect to a femtocell even if they are close by. As noted in Section

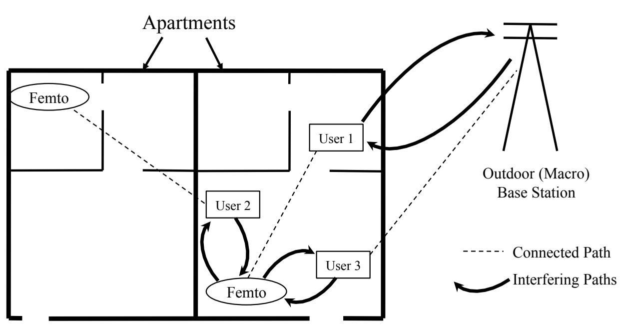


Fig. 3: Cross-Tier Intererence for the Downlink and Uplink

IV-B, this can cause significant degradation to the femtocell (in the uplink) or the cell-edge macrocell user in the downlink, which is near to a femtocell [72]. Second, the signaling for coordinating cross-tier interference may be logistically difficult in both open and closed access. Over-the-air control signaling for interference coordination can be difficult due to the large disparities in power. Also, backhaul-based signaling with femtocells is often not supported or comes with much higher delays since femtocells are typically not directly connected to the operator's core network – an issue also for mobility and soft handover as discussed below.

Recognizing these challenges, standards bodies have initiated several study efforts on femtocell interference management including those by the Femto Forum [73] and 3GPP [74], [75]. In addition, advanced methods for intercell interference coordination (ICIC) specifically for femtocell networks has been a major motivation for the 3GPP LTE-Advanced standardization effort [70], [76]. For 3G CDMA femtos, the dominant method for interference coordination has been power control strategies [77]–[79] and/or reserving a "femto-free" band where macrocell users can go to escape cross-tier interference when it arises. 4G LTE femtocells offer more tools for interference coordination including backhaul-based coordination, dynamic orthogonalization, subband scheduling, and adaptive fractional frequency reuse. How to best exploit these techniques is an active area of research [28], [80]–[83] and is the subject of two papers in this special issue [41], [84].

Going forward, more advanced techniques for interference control including interference cancelation, and cooperative communication between multiple base stations are also being researched [43], [56], [85]. A combining scheme from signals across multiple femtocell base stations is also discussed in this issue [66].

2) Cell Association and Biasing: A key challenge in a heterogenous network with a wide variety of cell sizes is to assign users to appropriate base stations. The most obvious way, which does in fact maximize the SINR of each user [86], is to simply assign each user to the strongest base station signal it receives. This results in coverage areas much like those observed in Fig. 4. However, simulations and field trials have shown that such an approach does not increase the overall throughput as much as hoped, because many of the small cells will typically have few active users.

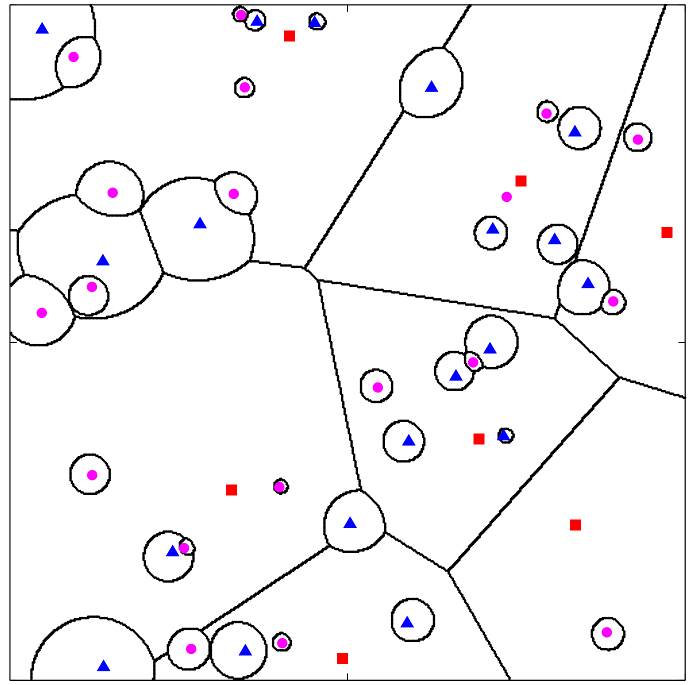


Fig. 4: Unbiased Cell Association in a 3-tier Heterogenous Network

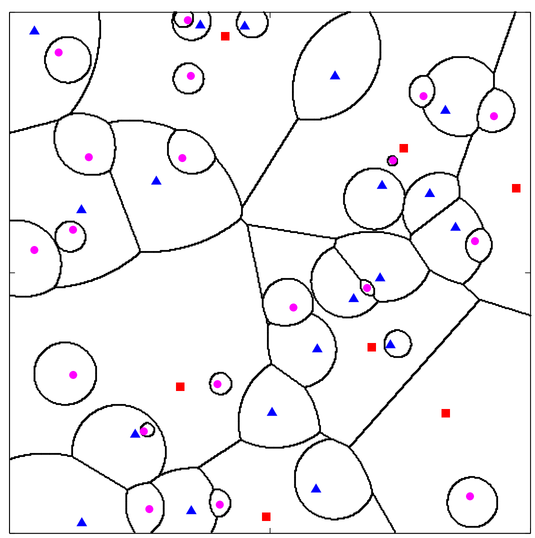


Fig. 5: Biased Cell Association in a 3-tier Heterogenous Network. Picos and femtos have a 10 dB bias.

This motivates *biasing*, whereby users are actively pushed onto small cells. Despite a potentially significant SINR hit for that mobile station, this has the potential for a win-win because the mobile gains access to much larger fraction of the small cell time and frequency slots. Furthermore, the macrocell reclaims the time and frequency slots that user would have occupied. Biasing is particularly attractive in OFDMA networks since the biased user can be assigned orthogonal resources to the macrocell, so the interference is tolerable.

An immediate practical challenge introduced by biasing include the use of overhead channels, which are typically common to all BSs in time and frequency and so a biased user would not be able to even hear its channel assignment, for example. This can been solved by introducing time-slotting for the control channels [87] or interference cancellation [41]. From a research perspective, a multi-tier network including femtocells provides an exciting opportunity to revisit cell association and load balancing rules developed for macro-only networks. In particular, it is currently unclear how much biasing is "optimal": it clearly depends heavily on (i) the throughput/QoS metric of interest, (ii) how users and the various base stations are distributed in space, (iii) traffic patterns in space-time, and (iv) the amount of adaptivity and side information the mobiles and small cell base stations are able to exploit.

3) Mobility and Soft Handover: Since the coverage area of an individual femtocell is small, it is essential to support seamless handovers to and from femtocells to provide continuous connectivity within any wide-area network. Handover scenarios include femto-to-macro (outbound mobility), macro-to-femto (inbound mobility) and possibly femto-to-femto; the latter occurring in enterprise deployments or dense femtocell coverage in larger public areas.

In principle, femtocells act as other base stations and can therefore utilize existing mobility procedures. However, femtocell mobility presents a number of unique challenges that require special consideration. Standards bodies such as 3GPP have devoted considerable attention to these mobility issues. See, for example, the specifications [75], [88]. Procedures are also being developed for vertical handovers between femtocells and non-cellular access technologies such as WiFi, for example, under the Generic Access Network framework [89], [90].

Perhaps the most difficult aspect of femtocell mobility is that femtocells are not typically directly connected into the core network where mobility procedures are usually coordinated. The lack of a low delay connection to the core network can result in significant handover signaling delays. Moreover, for similar architectural reasons, CDMA femtocells suffer from a further limitation that they are typically unable to share a Radio Network Controller (RNC) with a macrocell or other femtocell for coordinating soft handovers. Several works have begun considering architectural changes in the core network and femtocell gateway functions to address these mobility issues [91], [92], although the subject remains an active area of research.

Femto and picocells also result in much more dense deployments, which complicates base station discovery – a key initial step in any handover. Considerable research, particularly in the standard bodies, have considered improved methods for cell identification and discovery signaling [93], [94].

An additional complicating factor for femtocell mobility is the support for features such as Selected IP Traffic Offload (SIPTO) [95]. In typical macrocellular deployments, data is routed through a fixed gateway that provides a mobility anchor and constant IP point of attachment to the public Internet. However, with SIPTO, IP traffic may be routed directly to the femtocell, offloading traffic from the operator's core network. In such cases, however, each connection to a femtocell results in a different network point of attachment, possibly with a different IP addresses. Mobility must then be managed elsewhere [17].

4) Self-Organizing Networks: Femtocell networks are unique in that they are largely installed by customers or private enterprises often in an *ad hoc* manner without traditional RF planning, site selection, deployment and maintenance by the operator. Moreover, as the number of femtocells is expected to be orders of magnitude greater than macrocells, manual network deployment and maintenance is simply not scalable in a cost-effective manner for large femtocell deployments. Femtocells must therefore support an essentially plug-and-play operation, with automatic configuration and network adaptation. Due to these features, femtocells are sometimes referred to as a *self-organizing network* (SON).

The 3GPP standards body has placed considerable attention on SON features [96]–[99] defining procedures for automatic registration and authentication of femtocells, management and provisioning, neighbor discovery, synchronization, cell ID selection and network optimization.

One aspect of SON that has attracted considerable research attention is automatic channel selection, power adjustment and frequency assignment for autonomous interference coordination and coverage optimization. Such problems are often formulated as a mathematical optimization problems for which a number of algorithms have been considered [100], [101]. This special issue, in particular, contains two articles on adaptive interference coordination – one on power control [63] and a second on adaptive carrier selection [58]. Also, although femtocells are often deployed in an unplanned manner, femtocell placement may be optimized for interference and coverage, particularly in enterprise settings. An optimization method for such deployments is considered in a third paper in this special issue [57].

The adaptive and autonomous nature of interference management in SONs also bears some similarities to the cognitive radio concept, where spectrum is allocated in a distributed manner by devices operating with a significant degree of autonomy. Indeed, research has begun considering so-called cognitive femtocells that can dynamically sense spectrum usage by the macrocell and adapt their transmissions to optimize the overall usage of the spectrum [102], [103]. Two articles in this special issue [60] and [52] explore this cognitive femtocell concept; the latter considering an application for video delivery. However, purely cognitive approaches are known from poor convergence speeds and precision; to this end, the emerging concept of docitive networking [104] seems to be a viable answer, with many issues still remaining unsolved.

A quite different SON feature is the autonomous shutting down and waking up of base stations for power savings, addressed in this special issue in [55]. Currently several initiatives are focusing on reducing the energy consumption of networks. The most promenent one is "GreenTouch", a consortium founded by leading industry, academia, government and non profit research institutions around the world with the mission to deliver the architecture, specifications and roadmap to demonstrate the key components needed to increase network energy efficiency by a factor of 1000 from current levels by 2015. Small cells can play a prominent role in achieving this goal [105]–[108].

B. Economic and Regulatory Issues

Although the uptake of femtocells has not been as large as predicted by the most optimistic early market studies (e.g. [109]), the initial femtocell sales have nevertheless been impressive, as outlined in Section I. Even with this expected success, femtocells will represent only a very small fraction of the overall cellular market. Whether femtocells can ever play a dominant role in the network itself depends not only on the technical challenges discussed above, but on a number of basic economic and market questions, which are now surveyed.

1) Operator Business Case: The business case for femtocells has been made by a number of studies [110], [111]. The basic value proposition is that the cost of the femtocell itself is greatly outweighed by the savings from offloading traffic from the macrocellular networks [112]. These findings appear to be true across a range of market segments from residential to enterprise users. By some models, operators can realize as much as a 10x return from femtocells. In addition, new entrant operators or operators deploying new 4G technologies, can leverage femtocells to delay costly initial capital costs on macrocellular network.

2) Subscriber and ISP Incentives: With femtocells, the operator is not the only player with an economic stake in the network: subscribers and enterprises become responsible for installing the femtocells while private ISPs provide the backhaul. Unlike the operator, the economic incentives for these parties are less clear.

Private ISPs that supply the backhaul connection to femtocells will be forced to carry additional traffic, particularly if the femtocells are open access. If femtocells become the dominant cellular technology, these ISPs will end up responsible for a large portion of all mobile traffic. How ISPs would respond remains to be seen. Will ISPs enforce bandwidth or data limits, will they increase charges to subscribers, or perhaps enter arrangements with the cellular operators? How would such maneuvers affect the overall cost and business case for femtocells?

End users also face economic questions since they are the ones to purchase and install the femtocells. Femtocells provide a value for the overall network capacity by offloading traffic from the macrocells and increasing the overall number of cells. But, an individual subscriber is not directly concerned with the overall network capacity, only his or her quality of experience. These objectives may not be aligned, particularly in questions on whether femtocells should be open access and how the femtocells allocate resources between the owners and public users.

Developing an economic framework in which these diverse participants can both derive individual value while encouraging efficient use of the overall system resources will be a central research problem for femtocells going forward. An interesting line of academic work has considered various pricing and game theoretic approaches [113], [114]. This theme is explored in three articles in this special issue [54], [59], [67], that reveal interesting interplay between the economic aspects of pricing and the physical layer aspects of wireless network interactions.

3) Femto vs. WiFi and Whitespace: Femtocells offer a very different approach to that of WiFi and especially whitespace. Femtocells are provided by wireless operators as a *managed* service compared to the *best-effort* service offered by WiFi and possibly whitespace. Although today many people accept this best effort approach to mobile broadband, it is our view that users will want a mobile broadband experience with the level of reliability they have come to expect from wired broadband. As WiFi networks become ever more dense, their performance will continue to degrade since the 802.11 standards do not support coordination across different access points. In addition, subscribers want a single number to call for customer service, which is typically difficult with WiFi today. The seamless integration with the cellular network is a unique selling point for femtocells and provides value that users are likely willing to pay for. These managed services include the ability for the wireless operator to provide comprehensive end-to-end management, including data on where you are, what hardware you are using, how you are connected and various other management parameters.

Whitespace and WiFi are competing for the home wireless spectrum and thus with devices that are streaming high definition video on multiple bands, as well as wireless speakers, remote controls and baby monitors. All this makes the home of the future rather congested in the WiFi bands at least. Whitespace is even considerably more speculative, and some studies suggest that there is very little – if any – whitespace in many key US markets. Further, whitespace approaches are still not even approved outside of the US, with only the UK seriously considering their use, and then primarily for rural broadband.

Having above described femtocells as a competitor to WiFi it is interesting to note that recent trials using a converged gateway architecture that combined WiFi and 3G wireless modems demonstrated how the technologies could be combined to take advantage of both forms of connectivity to further enhance data throughput and overall reliability. Several companies are likely to simultaneously push both technologies for offloading. In short, we see WiFi and femtocells as complementary approaches to moving data off the cellular network and expect both to be very successful in the years to come.

4) Regulatory Aspects: Femtocells present several unique regulatory challenges, particularly since the operator loses some of the direct control of the access point relative to its control of base stations in traditional operator-managed networks. Of course, operators will retain a considerable degree of control, since femtocells are generally remotely configured and managed from the operator's core network. However, reliable procedures must be in place to ensure authentication, location verification and compliance to standards and spectral emission requirements. Some of the issues though are similar to those for handsets that operate in the provider's network while being manufactured and owned by third parties. A summary of these challenges can be found in [115].

Other regulatory issues concern spectrum. Since femtocells can co-exist in the same spectrum as macrocells, there is no need for specific femtocell spectral allocations. Although initial deployments have used separate or partially separate bands for femtocell deployment there is significant pressure on operators to move to shared carrier deployments. This is driven by the demand and lack of spectrum that operators have. Operators also have a need for an approach that seamlessly works across countries and regions, minimizing configuration and special settings, thus minimizing operational costs. Nevertheless, there has been some interest in femtocell specific allocations. For example, the UK regulator OfCom has proposed to allocate a portion (as much as 2 x 20 MHz) of the 2.6 GHz band specifically for low-power use [116]. Given the nature of cross-tier interference, spectrum allocation and co-channel deployments for femtocells remains an on-going challenge for wireless operators.

VI. Conclusions

The cellular industry has rarely seen more exciting times: as the demand for cellular data services skyrockets and the network topology undergoes the most significant changes since the birth of cellular, researchers and industry alike will not often be bored. Femtocells typify this renaissance with their organic plug-and-play deployment, highly democratic cost, and the possible chaos they introduce to the network. This article – and special issue – argue though that fears about femtocells negative effects are overblown. Whether or not they live up to the hype and help move the data avalanche to being a backhaul problem is as yet unclear; but it seems to the authors that there is nothing fundamental preventing very dense femtocell deployments, and that the economic and capacity benefits femtocells provide appear to justify the optimistic sales forecasts.

VII. Acknowledgements

A large number of people generously contributed to this special issue, including the authors, reviewers, and JSAC editorial staff. The guest editors appreciate the enthusiastic response from both academia and industry to this special issue.

References

[1] Cisco, "Cisco visual networking index: Global mobile data traffic forecast update, 20102015," Whitepaper, Feb. 2011.

[2] D. Kilper, G. Atkinson, S. Korotky, S. Goyal, P. Vetter, D. Suvakovic, and O. Blume, "Power trends in communication networks," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 17, no. 2, pp. 275 –284, Mar.-Apr. 2011.

[3] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: a survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59–67, September 2008.

[4] H. Claussen, L. T. W. Ho, and L. G. Samuel, "An overview of the femtocell concept," *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221–245, May 2008.

[5] Informa Telecoms & Media, "Femtocell Market Status," Femtoforum whitepaper, 2011.

[6] "Wifi and femtocell integration strategies 2011-2015," Juniper Research Whitepaper, http://www.juniperresearch.com/, Mar. 2011.

[7] A. Stocker, "Small-cell mobile phone systems," *IEEE Trans. on Vehicular Technology*, vol. 33, no. 4, pp. 269 – 275, Nov. 1984.

[8] E. Quinn, "The cell enhancer," in *Proc. IEEE Vehicular Technology Conference*, vol. 36, May 1986, pp. 77 – 83.

[9] E. Drucker, "Development and application of a cellular repeater," in *Proc. IEEE Vehicular Technology Conference*, Jun. 1988, pp. 321 – 325.

[10] R. Iyer, J. Parker, and P. Sood, "Intelligent networking for digital cellular systems and the wireless world," in *Proc. IEEE Globecom*, Dec. 1990, pp. 475 –479 vol.1.

[11] R. Brickhouse and T. Rappaport, "Urban in-building cellular frequency reuse," in *IEEE Global Telecommunications Conference*, vol. 2, nov 1996, pp. 1192 –1196.

[12] L. Ho, "Self-organising algorithms for fourth generation wireless networks and its analysis using complexity metrics," Ph.D. dissertation, Queen Mary College, University of London, 2003.

[13] H. Claussen, L. Ho, H. Karimi, F. Mullany, and L. Samuel, "I, base station: Cognisant robots and future wireless access networks," in *Proc. IEEE Consumer Communications and Networking Conference*, vol. 1, Jan. 2006, pp. 595 – 599.

[14] Z. Roth, M. Goldhamer, N. Chayat, A. Burr, M. Dohler, N. Bartzoudis, C. Walker, Y. Leibe, C. Oestges, M. Brzozowy, and I. Bucaille, "Vision and Architecture Supporting Wireless GBit/sec/km2 Capacity Density Deployments," in *Future Network and Mobile Summit*, June 2010.

[15] M. Dohler, R. Heath, A. Lozano, C. Papadias, and R. Valenzuela, "Is the phy layer dead?" *IEEE Communications Magazine*, vol. 49, no. 4, pp. 159 –165, april 2011.

[16] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101 –107, jun 2011.

[17] BeFEMTO - broadband evolved femto networks. [Online]. Available: http://www.ict-befemto.eu/

[18] H. Claussen, "Performance of macro- and co-channel femtocells in a hierarchical cell structure," in *Proc. IEEE 18th Int'l Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC'07)*, Sep. 2007, pp. 1–5.

[19] ——, "Co-channel operation of macro- and femtocells in a hierarchical cell structure," *Int'l. J. Wireless Inform. Networks*, vol. 15, no. 3-4, pp. 137–147, 2008.

[20] L. Ho and H. Claussen, "Effects of user-deployed, co-channel femtocells on the call drop probability in a residential scenario," in *Proc. IEEE Int'l Symp. on Personal, Indoor and Mobile Radio Commun.*, Sep. 2007, pp. 1–5.

[21] H. Claussen, L. Ho, and L. Samuel, "Self-optimization of coverage for femtocell deployments," in *Proc. Wireless Telecommunications Symp.*, Apr. 2008, pp. 278–285.

[22] H. Claussen and F. Pivit, "Femtocell coverage optimization using switched multi-element antennas," in *Proc. IEEE Int'l Conf. on Commun.*, Jun. 2009, pp. 1–6.

[23] V. Chandrasekhar and J. Andrews, "Uplink capacity and interference avoidance for two-tier cellular networks," in *Proc. IEEE Globecom*, Nov. 2007, pp. 3322–3326.

[24] ——, "Uplink capacity and interference avoidance for two-tier femtocell networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3498–3509, Jul. 2009.

[25] V. Chandrasekhar, M. Kountouris, and J. Andrews, "Coverage in multi-antenna two-tier networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5314–5327, Oct. 2009.

[26] D. Choi, P. Monajemi, S. Kang, and J. Villasenor, "Dealing with loud neighbors: The benefits and tradeoffs of adaptive femtocell access," in *IEEE Globecom*, Dec. 2008, pp. 1 –5.

[27] P. Xia, V. Chandrasekhar, and J. G. Andrews, "Open vs. closed access femtocells in the uplink," *IEEE Transactions on Wireless Communications*, vol. 9, no. 10, pp. 3798 – 3809, Dec. 2010.

[28] D. López-Pérez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA femtocells: A roadmap on interference avoidance," *IEEE Comm. Mag.*, vol. 47, no. 9, pp. 41–48, Sep. 2009.

[29] D. Das and V. Ramaswamy, "On the reverse link capacity of a CDMA network of femto-cells," in *Proc. IEEE Sarnoff Symp.*, Apr. 2008, pp. 1–5.

[30] V. Ramaswamy and D. Das, "Multi-carrier macrocell femtocell deployment-a reverse link capacity analysis," in *Proc. IEEE Vehic. Tech. Conf.*, Sep. 2009, pp. 1–6.

[31] A. Schroder, H. Lundqvist, G. Nunzi, and M. Brunner, "User-assisted coverage and interference optimization for broadband femtocells," in *Proc. IFIP/IEEE Int'l Symp. on Integrated Network Management-Workshops*, Jun. 2009, pp. 199–204.

[32] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman, and A. Richardson, "Interference management and

performance analysis of UMTS/HSPA+ femtocells," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 102–109, Sep. 2009.

[33] H. Wang, M. Zhao, and M. C. Reed, "Outage analysis for WCDMA femtocell with uplink attenuation," in *IEEE Globecom 2010 Workshop on Femtocell Networks (FEMNet 2010)*, Miami, U.S.A, Dec. 2010.

[34] M. Sahin, I. Guvenc, M.-R. Jeong, and H. Arslan, "Handling CCI and ICI in OFDMA femtocell networks through frequency scheduling," *IEEE Trans. Consumer Electron.*, vol. 55, no. 4, pp. 1936–1944, Nov. 2009.

[35] L. Garcia, K. Pedersen, and P. Mogensen, "Autonomous component carrier selection: interference management in local area environments for LTE-advanced," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 110–116, Sep. 2009.

[36] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA femtocells: a roadmap on interference avoidance," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 41–48, Sep. 2009.

[37] A. Golaup, M. Mustapha, and L. Patanapongpibul, "Femtocell access control strategy in UMTS and LTE," *IEEE Commun. Mag.*, vol. 47, no. 9, pp. 117–123, Sep. 2009.

[38] S. Joshi, R. Cheung, P. Monajemi, and J. Villasenor, "Traffic-based study of femtocell access policy impacts on HSPA service quality," in *Proc. IEEE Globecom*, Dec. 2009, pp. 1–6.

[39] O. Simeone, E. Erkip, and S. Shamai, "Robust communication against femtocell access failures," in *Proc. IEEE Info. Theory Workshop*, Oct. 2009, pp. 263–267.

[40] R. Kim, J. S. Kwak, and K. Etemad, "WiMAX femtocell: requirements, challenges, and solutions," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 84 –91,, Sep. 2009.

[41] A. Barbieri, A. Damnjanovic, T. Ji, J. Montojo, Y. Wei, D. P. Malladi, O. Song, and G. Horn, "The Downlink Inter-Cell Interference Problem in Rel-10 LTE Femtocell Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[42] A. Ghosh, J. Zhang, J. G. Andrews, and R. Muhamed, *Fundamentals of LTE*. Prentice-Hall, 2010.

[43] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference Coordination and Cancellation for 4G Networks," *IEEE Comm. Mag.*, vol. 47, no. 4, pp. 74–81, Apr. 2009.

[44] V. Chandrasekhar and J. G. Andrews, "Spectrum allocation in two-tier networks," *IEEE Trans. on Communications*, vol. 57, no. 10, pp. 3059–3068, Oct. 2009.

[45] I.-R. M.1225, "Guidelines for evaluation of radio transmission," Tech. Rep., 1997.

[46] H. Hashemi, "The indoor radio propagation channel," *Proceedings of the IEEE*, vol. 81, no. 7, pp. 943–68, Jul. 1993.

[47] T. Cover, "Broadcast channels," *IEEE Trans. on Info. Theory*, vol. 18, no. 1, pp. 2 – 14, Jan. 1972.

[48] R. Gallager, "A perspective on multiaccess channels," *IEEE Trans. on Info. Theory*, vol. 31, no. 2, pp. 124–42, Mar. 1985.

[49] A. Wyner, "Shannon-theoretic approach to a gaussian cellular multiple-access channel," *Information Theory, IEEE Transactions on*, vol. 40, no. 6, pp. 1713 –1727, nov 1994.

[50] J. Xu, J. Zhang, and J. G. Andrews, "On the accuracy of the Wyner model in cellular networks," *IEEE Trans. on Wireless Communications*, vol. 10, no. 9, pp. 3098 –3109, Sep. 2011.

[51] J. G. Andrews, F. Baccelli, and R. K. Ganti, "A tractable approach to coverage and rate in cellular networks," *IEEE Trans. on Communications*, Nov. 2011.

[52] D. Hu and S. Mao, "On Medium Grain Scalable Video Streaming over Femtocell Cognitive Radio Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[53] V. Chandrasekhar and J. G. Andrews, "Uplink capacity and interference avoidance for two-tier femtocell networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 7, pp. 3498–3509, July 2009.

[54] F. Pantisano, M. Bennis, W. Saad, and M. Debbah, "Spectrum Leasing as an Incentive towards Uplink Macrocell and Femtocell Cooperation," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[55] L. Saker, S. E. Elayoubi, R. Combes, and T. Chahed, "Optimal control of wake up mechanisms of femtocells in heterogeneous networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[56] Z. Shi, M. C. Reed, and M. Zhao, "On uplink interference scenarios in two-tier macro and femto co-existing UMTS networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, no. 240745, pp. 1–8, 2010.

[57] J. Liu, T. Kou, H. Sherali, and Q. Chen, "Optimal Femtocell Base Station Placement in Commercial Buildings: A Global Optimization Approach," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[58] L. G. U. Garcia, I. Z. Kovacs, K. Pedersen, G. W. O. Costa, and P. Mogensen, "Autonomous Component Carrier Selection for 4G Femtocells - A fresh look at an old problem," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[59] X. Kang, R. Zhang, and M. Motani, "Price-Based Resource Allocation for Spectrum-Sharing Femtocell Networks: A Stackelberg Game Approach," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[60] R. Urgaonkar and M. J. Neely, "Opportunistic Cooperation in Cognitive Femtocell Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[61] H. S. Dhillon, R. K. Ganti, F. Baccelli, and J. G. Andrews, "Modeling and Analysis of K-Tier Downlink Heterogeneous Cellular Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[62] S. Mukherjee, "Distribution of Downlink SINR in Heterogeneous Cellular Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[63] W. C. Cheung, T. Q. S. Quek, and M. Kountouris, "Throughput Optimization in Two-Tier Femtocell Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[64] H. S. Dhillon, R. K. Ganti, and J. G. Andrews, "A tractable framework for coverage and outage in heterogeneous cellular networks," in *in Proc. Information Theory adn Applications Workshop (ITA '11)*, San Diego, U.S.A, Feb. 2011.

[65] S. Mukherjee, "Analysis of UE outage probability and macrocellular traffic offloading for WCDMA macro network with femto overlay under closed and open access," in *IEEE Intl. Conf. on Communications*, Jun. 2011, pp. 1 –6.

[66] Y. Jeong, H. Shin, and M. Win, "Superanalysis of Optimum Combining in Femtocell Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[67] S.-Y. Yun, Y. Yi, D.-H. Cho, and J. Mo, "On Economic Effects of Sharing of Femtocells," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.

[68] M. Haenggi and R. Ganti, "Interference in Large Wireless Networks," *Foundations and Trends in Networking*, vol. 3, no. 2, pp. 127–248, 2008.

[69] S. Kishore, L. J. Greenstein, H. V. Poor, and S. C. Schwartz, "Soft handoff and uplink capacity in a two-tier CDMA system," *IEEE Trans. Wireless Comm.*, vol. 4, no. 4, pp. 1297–1301, Jul. 2005.

[70] A. Ghosh, J. G. Andrews, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. A. Thomas, P. Xia, H. S. Jo, H. S. Dhillon, and T. D. Novlan, "Heterogeneous cellular networks: From theory to practice," *IEEE Communications Magazine*, Mar. 2012.

[71] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 10 –21, Jun. 2011.

[72] H. S. Jo, P. Xia, , and J. G. Andrews, "Downlink femtocell networks: Open or closed?" *IEEE International Conference on Communications*, Jun. 2011.

[73] Femto Forum, "Interference Management in OFDMA Femtocells," Whitepaper available at www.femtoforum.org, Mar. 2010.

[74] 3GPP, "3G Home NodeB Study Item Technical Report," TR 25.820 (release 11), 2011.

[75] ——, "UTRAN Architecture for Home NodeB Stage 2," TS 25.467 (release 11), 2011.

[76] ——, "New Work Item Proposal: Enhanced ICIC for non-CA based deployments of heterogeneous networks for LTE," RP-100372, 2010.

[77] V. Chandrasekhar, J. Andrews, Z. Shen, T. Muharemovic, and A. Gatherer, "Power control in two-tier femtocell networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 8, pp. 4316–28, August 2009.

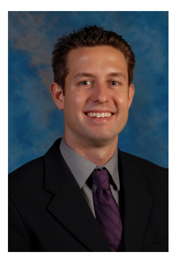
[78] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman, and A. Richardson, "Interference management and performance analysis of UMTS/HSPA+ femtocells," *IEEE Comm. Mag.*, vol. 47, no. 9, pp. 102–109, Sep. 2009.

[79] H.-S. Jo, C. Mun, J. Moon, and J.-G. Yook, "Interference mitigation using uplink power control for two-tier femtocell networks," *IEEE Trans. on Wireless Communications*, vol. 8, no. 10, pp. 4906–4910, Oct. 2009.

[80] G. Fodor, C. Koutsimanis, A. Rácz, N. Reider, A. Simonsson, and W. Müller, "Intercell interference coordination in ofdma networks and in the 3gpp long term evolution system," *J. Comm.*, vol. 4, no. 7, pp. 445–453, Aug. 2009.

[81] S. B. Kang, Y. M. Seo, Y. K. Lee, M. Z. Chowdhury, W. S. Ko, S. W. C. M. N. Irlam, and Y. M. Jang, "Soft QoS-based CAC scheme for WCDMA femtocell networks," *Adv. Commun. Tech.*, 2008.

[82] K. Sundaresan and S. Rangarajan, "Efficient resource management in OFDMA femto cells," *ACM MobiHoc*, 2009.
[83] T. D. Novlan, R. K. Ganti, A. Ghosh, and J. G. Andrews, "Analytical evaluation of fractional frequency reuse for OFDMA cellular networks," *To Appear, IEEE Trans. on Wireless Communications*, 2012.
[84] S. Rangan and R. Madan, "Belief Propagation Methods for Inter-Cellular Interference Coordination in Femtocell Networks," *IEEE JSAC Special Issue on Femtocell Networks*, Apr. 2012.
[85] S. Rangan, "Femto-macro cellular interference control with subband scheduling and interference cancelation," in *Proc. Globecomm*, Miami, FL, Dec. 2010.
[86] H.-S. Jo, Y. J. Sang, P. Xia, and J. G. Andrews, "Outage probability for heterogeneous cellular networks with biased cell association," *IEEE Globecom*, Dec. 2011.
[87] R. Bendlin, V. Chandrasekhar, R. Chen, A. Ekpenyong, and E. Onggosanusi, "From homogeneous to heterogeneous networks: A 3GPP long term evolution rel. 8/9 case study," in *CISS*, Baltimore, MD, Mar. 2011.
[88] 3GPP, "Mobility Procedures for Home NodeB; Overall Description Stage 2," TS 25.367 (release 11), 2011.
[89] ——, "Generic Access Network (GAN)," TS 43.318, 2011.
[90] S. Ghosh, K. Basu, and S. Das, "An architecture for next-generation radio access networks," *IEEE Network*, vol. 19, no. 5, pp. 35–42, Sep. 2005.
[91] L. Wang, Y. Zhang, and Z. Wei, "Mobility Management Schemes at Radio Network Layer for LTE Femtocells," in *Proc. VTC*, Barcelona, Spain, Apr. 2009, pp. 1–5.
[92] A. Golaup, M. Mustapha, and L. Patanapongpibul, "Femtocell access control strategy in UMTS and LTE," *IEEE Comm. Mag.*, vol. 47, no. 9, pp. 117–123, Sep. 2009.
[93] G. de la Roche, A. Valcarce, D. López-Pérez, and J. Zhang, "Access control mechanisms for femtocells," *IEEE Comm. Mag.*, vol. 48, no. 1, pp. 33–39, Jan. 2010.
[94] F. Meshkati, Y. Jiang, L. Grokop, S. Nagaraja, M. Yavuz, and S. Nanda, "Mobility and Femtocell Discovery in 3G UMTS Networks," Qualcomm Whitepaper, Feb. 2010.
[95] 3GPP, "Local IP Access and Selected IP Traffic Offload," TR 23.829 (release 11), 2011.
[96] ——, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2)," TS 36.300, 2011.
[97] ——, "Evolved Study on Management of Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC)," TS 36.816, 2011.
[98] ——, "Telecommunication Management; Self-Organizing Networks (SON); Concepts and requirements," TS 32.500 (release 11), 2011.
[99] ——, "Self-Configuring and Self-Optimizing Network Use Cases and Solutions," TS 36.902, 2011.
[100] D. Lopez-Perez, A. Ladanyi, A. Juttner, and J. Zhang, "OFDMA femtocells: A self-organizing approach for frequency assignment," in *Proc. PIMRC*, Tokyo, Sep. 2009, pp. 2202–2207.
[101] S. Feng and E. Seidel, "Self-Organizing Networks (SON) in 3GPP Long Term Evolution," *NOMOR whitepaper*, May 2010.
[102] Y.-Y. Li, M. Macuha, E. Sousa, T. Sato, and M. Nanri, "Cognitive interference management in 3G femtocells," in *Proc. PIMRC*, Tokyo, Sep. 2009.
[103] A. Adhikary, V. Ntranos, and G. Caire, "Cognitive femtocells: Breaking the spatial reuse barrier of cellular systems," in *Proc. ITA*, La Jolla, CA, Feb. 2011.
[104] L. Giupponi, A. Galindo-Serrano, and M. Dohler, "From Cognition To Docition: The Teaching Radio Paradigm For Distributed & Autonomous Deployments," *Elsevier Computer Communications, Special Issue on Applied Sciences to Communication Technologies*, vol. 33, no. 17, pp. 2015–2020, Nov. 2010.
[105] J. Hoydis and M. Debbah, "Green, Cost-effective, Flexible, Small Cell Networks," *IEEE Comm. Soc. MMTC*, vol. 5, no. 5, pp. 23–26, Oct. 2010.
[106] H. Claussen, L. T. W. Ho, and F. Pivit, "Leveraging advances in mobile broadband technology to improve environmental sustainability," *Telecommunications Journal of Australia*, vol. 59, no. 1, pp. 4.1–4.18, Feb. 2009.
[107] H. Claussen, I. Ashraf, and L. T. W. Ho, "Dynamic idle mode procedures for femtocells," *Bell Labs Technical Journal*, vol. 15, no. 2, pp. 95–116, Aug. 2010.
[108] J. G. Andrews, "Cellular 1000x?" Notre Dame University Wireless Leadership Seminar: http://users.ece.utexas.edu/ jandrews/publications.php, July 2011.
[109] S. Carlow and C. Wheelock, "Femtocell market challenges and opportunities," ABI Research Report, 2007.
[110] H. Claussen, L. Ho, and L. Samuel, "Financial Analysis of a Pico-Cellular Home Network Deployment," in *Proc. ICC*, Jun. 2007, pp. 5604–5609.
[111] S. R. Group", "The Business Case of Femtocells in the Mobile Broadband Era," Available at www.femtoforum.org, Mar. 2010.
[112] H. Claussen and D. Calin, "Macrocell offloading benefits in joint macro-and femtocell deployments," in *Proc. IEEE Personal, Indoor and Mobile Radio Communications*, Sept. 2009, pp. 350 –354.
[113] D. Niyato and E. Hossain, "Wireless broadband access: Wimax and beyond - integration of WiMax and WiFi: Optimal pricing for bandwidth sharing," *IEEE Comm. Mag.*, vol. 45, no. 5, pp. 140–146, May 2007.
[114] N. Shetty, S. Parekh, and J. Walrand, "Economics of femtocells," in *Proc. Globecomm*, Honolulu, HI, Dec. 2009.
[115] Femto Forum, "Regulatory Aspects of Femtocells - Second Edition," Available at www.femtoforum.org, Mar. 2011.
[116] A. Kaul, "Low-power 4G Spectrum: Ofcom's Bold New Proposal," ABI Market Research, Mar. 2011.



Jeffrey G. Andrews (S'98, M'02, SM'06) received the B.S. in Engineering with High Distinction from Harvey Mudd College in 1995, and the M.S. and Ph.D. in Electrical Engineering from Stanford University in 1999 and 2002, respectively. He is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Texas at Austin, where he was the Director of the Wireless Networking and Communications Group (WNCG) from 2008-12. He developed Code Division Multiple Access systems at Qualcomm from 1995-97, and has consulted for entities including the WiMAX Forum, Microsoft, Apple, Clearwire, Palm, Sprint, ADC, and NASA.

Dr. Andrews is co-author of two books, Fundamentals of WiMAX (Prentice-Hall, 2007) and Fundamentals of LTE (Prentice-Hall, 2010), and holds the Earl and Margaret Brasfield Endowed Fellowship in Engineering at UT Austin, where he received the ECE department's first annual High Gain award for excellence in research. He is a Senior Member of the IEEE, served as an associate editor for the IEEE Transactions on Wireless Communications from 2004-08, was the Chair of the 2010 IEEE Communication Theory Workshop, and is the Technical Program co-Chair of ICC 2012 (Comm. Theory Symposium) and Globecom 2014. He has also been a guest editor for two recent IEEE JSAC special issues on stochastic geometry and femtocell networks.

Dr. Andrews received the National Science Foundation CAREER award in 2007 and has been co-author of five best paper award recipients, two at Globecom (2006 and 2009), Asilomar (2008), the 2010 IEEE Communications Society Best Tutorial Paper Award, and the 2011 Communications Society Heinrich Hertz Prize. His research interests are in communication theory, information theory, and stochastic geometry applied to wireless cellular and ad hoc networks

Holger Claussen (M'01, SM'10) is head of the Autonomous Networks and Systems Research Department at Bell Labs, Alcatel-Lucent, for Ireland and the United Kingdom. He received his Dipl.-Ing. (FH) and M.Eng. degrees in electronic engineering from the University of Applied Sciences in Kempten, Germany, and the University of Ulster, United Kingdom, respectively. He received a Ph.D. degree in signal processing for digital communications from the University of Edinburgh, United Kingdom, for his work on low complexity multiple input-multiple output (MIMO) receiver architectures. Afterwards, Dr. Claussen joined Bell Labs in Swindon, United Kingdom, as Research Engineer in 2004. He became Department Head in the lab in Dublin, Ireland, in 2009.

At Bell Labs, Dr. Claussen has been working on auto-configuration and dynamic optimization of networks, self-deploying networks, distributed algorithms, flat cellular network architectures, fourth-generation (4G) systems, mobility, resource management, end-to-end network modeling, and improving energy efficiency of networks. More recently he has been directing research and technology transfer of self-management and efficient networking solutions. This has been commercialized as the Alcatel-Lucent BSR-Femto product. Dr. Claussen is author of more than 40 publications and 70 filed patent applications. He is senior member of the IEEE, member of the IET, and the Alcatel-Lucent Technical Academy.

Mischa Dohler is now leading the Intelligent Energy [IQe] group at CTTC in Barcelona, with focus on Smart Grids and Green Radios. He is working on wireless sensor, machine-to-machine, femto, cooperative, cognitive and docitive networks. Prior to this, from June 2005 to February 2008, he has been Senior Research Expert in the R&D division of France Telecom, France. From September 2003 to June 2005, he has been lecturer at King's College London, UK. At that time, he has also been London Technology Network Business Fellow receiving appropriate Anglo-Saxon business training, as well as Student Representative of the IEEE UKRI Section and member of the Student Activity Committee of IEEE Region 8 (Europe, Africa, Middle-East and Russia).

He obtained his PhD in Telecommunications from King's College London, UK, in 2003, his Diploma in Electrical Engineering from Dresden University of Technology, Germany, in 2000, and his MSc degree in Telecommunications from King's College London, UK, in 1999. Prior to Telecommunications, he studied Physics in Moscow. He has won various competitions in Mathematics and Physics, and participated in the 3rd round of the International Physics Olympics for Germany. In the framework of the Mobile VCE, he has pioneered research on distributed cooperative space-time encoded communication systems, dating back to December 1999. He has published 138 technical journal and conference papers at a citation h-index of 24 and citation g-index of 49, holds 13 patents, authored, co-edited and contributed to 19 books, has given 25 international short-courses, and participated in standardisation activities. He has been TPC member and co-chair of various conferences, such as technical chair of IEEE PIMRC 2008 held in Cannes, France. He is EiC of ETT and is/has been holding various editorial positions for numerous IEEE and non-IEEE journals. He is Senior Member of the IEEE. He is fluent in 6 languages.

Sundeep Rangan (M'02) received the B.A.Sc. at the University of Waterloo, Canada and the M.Sc. and Ph.D. at the University of California, Berkeley, all in Electrical Engineering. He has held postdoctoral appointments at the University of Michigan, Ann Arbor and Bell Labs. In 2000, he co-founded (with four others) Flarion Technologies, a spin off of Bell Labs, that developed Flash OFDM, one of the first cellular OFDM data systems. Flarion grew to over 150 employees with trials worldwide. In 2006, Flarion was acquired by Qualcomm Technologies where Dr. Rangan was a Director of Engineering involved in OFDM infrastructure products. He joined the ECE department at Poly in 2010. His research interests are in wireless communications, signal processing, information theory and control theory.

Mark C. Reed received his B. Eng. (Honors) in Electronic Engineering from the Royal Melbourne Institute of Technology (RMIT) in 1990, and Ph.D. in Communication Engineering from the University of South Australia, Australia in 2000. He is an Associate Professor (Adj.) at the College of Engineering and Computer Science (CECS) at the Australian National University (ANU) and Founder and CEO of InterfereX Communications Pty. Ltd., a company specializing in improving system performance for small cells. He has previously been a Principal Researcher and Project Leader at NICTA where he led a research- inspired commercial project on femtocells. This project was first to demonstrate a real-time hardware realization of uplink interference cancellation at radio frequencies for a 3G/WCDMA femtocell modem. Mark previously worked for Ascom Systec AG and developed a real-time world- first Satellite-UMTS demonstrator for the European Space Agency. He has also led a team at NICTA in the development of an advanced real- time wireless proof-of-concept mobile WiMAX modem demonstration system.

Mark's research interests include applications of iterative techniques to signal processing problems, fundamental limits of heterogeneous wireless networks, modem signal acquisition, and signal tracking techniques. Mark pioneered the area of iterative (turbo) detection techniques for WCDMA base station receivers and has more than 64 publications and eight patent applications. He has a mix of real- world industrial experience as well as research experience where he continues to put his techniques into practice. He won the Australian Information Industry Association Award (iAward, Merit - R&D Category) at the National level in 2010. He is also the recipient of Engineers Australia IREE Neville Thiele Award in 2007.

Mark was responsible for Sponsorship and Travel Grants for the IEEE ISIT - 2004, was co-chair of the Acorn Wireless Winter School (2005, 2006), and Publication Chair and member of the TPC for IEEE VTC - 2006. He is a Senior Member of the IEEE and from 2005-2007 he was an Associate Editor for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY.