

Heterogeneous Cellular Networks: From Theory to Practice

*Amitabha Ghosh, Nitin Mangalvedhe, Rapeepat Ratasuk, Bishwarup Mondal, Mark Cudak,
Eugene Visotsky, and Timothy A. Thomas, Nokia Siemens Networks*
*Jeffrey G. Andrews, Ping Xia, Han Shin Jo, Harpreet S. Dhillon, and Thomas D. Novlan,
The University of Texas at Austin*

ABSTRACT

The proliferation of internet-connected mobile devices will continue to drive growth in data traffic in an exponential fashion, forcing network operators to dramatically increase the capacity of their networks. To do this cost-effectively, a paradigm shift in cellular network infrastructure deployment is occurring away from traditional (expensive) high-power tower-mounted base stations and towards heterogeneous elements. Examples of heterogeneous elements include microcells, picocells, femtocells, and distributed antenna systems (remote radio heads), which are distinguished by their transmit powers/coverage areas, physical size, backhaul, and propagation characteristics. This shift presents many opportunities for capacity improvement, and many new challenges to co-existence and network management. This article discusses new theoretical models for understanding the heterogeneous cellular networks of tomorrow, and the practical constraints and challenges that operators must tackle in order for these networks to reach their potential.

INTRODUCTION

To address the explosive growth in data demands driven by smart phones, tablets, and other media-hungry devices, network operators will have to significantly increase the capacity of their networks as well as reduce the cost/bit delivered by perhaps two orders of magnitude. A number of studies have documented the over 100 percent annual growth in mobile data traffic which started around 2008, and is set to continue indefinitely, which projects a factor of 1000 increase from 2007–2016. Clearly, the typical cautious approaches to adding capacity are not up to this challenge.

An important new development is the deployment of heterogeneous base stations underlaid in a traditional (macro) cellular net-

work. In such a heterogeneous network, various classes of low power nodes (LPNs) are distributed throughout the macro cell network. There are various types of LPNs including micro base stations (often called eNodeBs, or eNBs), pico eNBs, home eNBs (also called femtocells), relays and distributed antenna systems (DAS, also called remote radio heads or RRHs). In heterogeneous network (HetNet) deployments, the overlay macro cell provides a wide area coverage umbrella while the LPNs are deployed in a more targeted manner to alleviate coverage dead zones, and more importantly, traffic hot zones.

A HetNet topology fundamentally challenges many time-honored aspects of cellular system design and analysis. Two prominent examples of outdated modeling are

- The use of a uniform hexagonal grid to model the base station locations
- The assumption that a mobile should generally connect to the base station providing the strongest signal, which in a HetNet is quite often not the one providing the best rate or network-wide performance

The goal of this article is to provide an overview of a heterogeneous network design, and show that its co-existence with a macro-network from an air-interface and an infrastructure point of view is highly feasible. We focus on a two-tier macro-pico network and provide a primer on new state-of-the-art theoretical analysis for HetNets as well as extensive detailed simulations. We show that the key trends predicted by both models and approaches are in broad agreement.

This article covers the following topics. A coverage analysis of multi-tier networks based on random spatial models is provided. We provide simulated performance of a baseline heterogeneous network with no inter-cell interference coordination (ICIC). A discussion of standardized ICIC techniques based on LTE Release-9 and 10 for a macro-pico scenario is given fol-

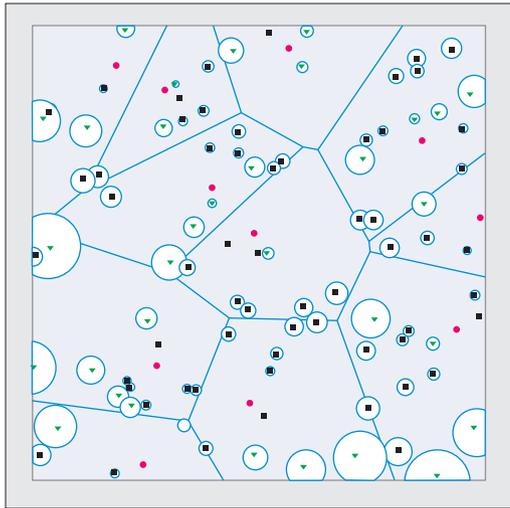


Figure 1. Max SINR downlink coverage regions in a 3-tier network with macrocells (red), picocells (green), and femtocells (black).

lowed by simulation results. The logistics of deploying heterogeneous elements are discussed including the installation, management, and provision of backhaul for street level pico nodes along with some basic HetNet Proof-of-Concept (PoC) results.

BASELINE COVERAGE AND THROUGHPUT ANALYSIS FOR MULTI-TIER NETWORKS

Cellular modeling and analysis has not changed very much in the last decade. Industry (and academic) simulations typically rely on a hexagonal grid model for the base station locations, and assume the user terminals (UEs) are uniformly scattered and connect to the strongest base station signal. Dozens of system parameters can be modeled and tuned in such simulations, and the results have been sufficiently accurate as to enable the evaluation of new proposed techniques and guide field deployments. Mathematical analysis by researchers has typically required either ignoring other-cell interference (single cell models), treating it as having a fixed value (sometimes called the “Wyner” model), or making other major simplifications that make the conclusions from such endeavors questionable. Not surprisingly, theoretical researchers and industry have wound up going in largely separate directions as a result [1].

Moving to the HetNets of tomorrow, even simulations become significantly more complex because each tier of base stations is likely to have very distinctly different characteristics. For example, macro base stations will be deployed more or less how they are currently — regularly spaced with fairly large coverage areas — having a transmit power of about 40 Watts plus large antenna gains. At the other extreme, femtocells will be deployed without central planning, often indoors, and have very small coverage areas, with transmit power

below 250 mW [2]. In between, picocells will be deployed in traffic hotspots, perhaps as many as 10 per macrocell, and will be neither random nor regular in their placement, with transmit power in the 250 mW–2W range. A conceptual illustration of possible downlink coverage regions in such a network are shown in Fig. 1, where the cell boundaries correspond to contours of maximum received power. The “red dots” are the conventional macro base stations which provide coverage for most of the plane.

EMBRACING A RANDOM SPATIAL MODEL

Even accurately simulating a multi-tier network appears to be nontrivial and analyzing it seems hopeless. Nevertheless, a random spatial model for the eNB locations is surprisingly tractable analytically and appears to capture some of the main HetNet performance trends. As we will now show, intuitive analytical results can be found for multi-tier HetNets that offer conclusions broadly in line with much more complex simulations based on real-world deployments.

A concise and tractable model for HetNets begins with a spatial point process to statistically model the base station locations of each tier. The simplest and best known such point process is the Poisson point process (PPP), which assumes that base stations in tier k are independently distributed with density λ_k , which means that in an area of size A , there are on average $\lambda_k A$ base stations. Each tier can also be endowed with other characteristics such as an appropriate transmit power P_k and path loss exponent α_k (to model tower vs. in-home deployments, for example). More complex point processes can in principle be used to model repulsion between base stations, e.g. the Matern process places an exclusion radius around each point (eNB) drawn from a PPP [3]. In this article we use the baseline PPP model for each tier — which is about worst-case, since it would be hard to do worse than an i.i.d. placement of base stations.

This is not to advise against refining this spatial model in the future once picocell and femtocell deployments are better understood and more data is available to benchmark against. Rather, the PPP spatial model is broadly analogous to the Rayleigh distribution for the envelope of a fading wireless channel. Although it is widely understood that Rayleigh is not a particularly good channel model, it captures some of the essential variation of a wireless channel and has provided a rigorous first-order understanding of many forms of diversity, multi-antenna transmission, and other wireless design fundamentals. Like the Poisson spatial model, a Rayleigh envelope is simple and analytically tractable since it results in an exponential power probability distribution. This simplicity has enabled the rapid exchange of new ideas in the wireless community, even if the underlying model is of dubious accuracy. A similar case can be made for the Poisson model for better understanding how to design HetNets, which have a high degree of spatial “randomness.”

Cellular modeling and analysis has not changed very much in the last decade. Industry (and academic) simulations typically rely on a hexagonal grid model for the base station locations, and assume the user terminals (UEs) are uniformly scattered and connect to the strongest base station signal.

The problem is expected to be more severe in CDMA systems due to the near-far problem than in OFDMA where more orthogonal resources are available. Similarly, high mobility UEs will not always be connected to the strongest base station since handovers take some time.

CHARACTERIZING THE SINR DISTRIBUTION OF HETNETS

The single most important and general metric in a cellular network is the SINR distribution. Once the SINR distribution is known, the outage and rate histograms follow immediately, and the outage or average rate can be easily computed. In a baseline model with no interference management, the SINR offered by a base station at location x_i to a mobile station at the origin in a K-tier network can be expressed as

$$SINR(x_i) = \frac{P_i h_{x_i} \|x_i\|^{-\alpha}}{\sum_{j=1}^K \sum_{x \in \Phi_j \setminus x_i} P_j h_x \|x\|^{-\alpha} + \sigma^2} \quad (1)$$

where h is the fading to the UE, σ^2 is noise power, Φ_j is the point process for tier j which has density λ_j , and its points x generically refer to all the interfering base stations in that tier. The other parameters were defined when explaining the spatial model. The outage probability is then simply the event that no base station in any tier can provide a SINR higher than the threshold for that tier β_i and the coverage probability is the complement. The outage and coverage p_c are thus the CDF and complementary CDF of the SINR random variable, respectively. To be explicit, p_c is the probability that the maximum SINR (x_i) over all base stations is greater than some threshold value β .

One could pick an arbitrary set of point processes and fading distributions and plot the SINR distribution using a Monte Carlo simulation. However, applying various techniques and tools from stochastic geometry, it is possible to derive this SINR mathematically. This SINR distribution takes on a very simple closed form under four additional, but plausible, assumptions:

- Each mobile connects to the base station with the strongest signal, which is not necessarily the closest one
- Noise is negligible vs. interference,
- The SINR target is 0 dB or more for each tier¹
- Rayleigh fading

In this case, the coverage probability can be derived to be [4]

$$p_c = P[SINR > \beta] = \frac{\pi}{C(\alpha)} \frac{\sum_{i=1}^K \lambda_i P_i^{2/\alpha} \beta_i^{-2/\alpha}}{\sum_{i=1}^K \lambda_i P_i^{2/\alpha}} \quad (2)$$

where $C(\alpha) = (2\pi^2/\alpha) \csc(2\pi/\alpha)$ is a simple constant. All four of these assumptions can be relaxed and the SINR can still be computed very easily without simulation but it is usually not closed form² [5]. It is fairly surprising that such a precise and compact description of SINR can be achieved for a HetNet system model, when no such formula previously existed even for intensively researched one-tier grid-based networks. One can immediately observe from Eq. 2 that if all the target SINRs for each tier are the same, i.e. $\beta_i = \beta$, which might be a good approximation in practice, then Eq. 2 can be further simplified to

$$p_c = \frac{\pi}{C(\alpha)\beta^{2/\alpha}}$$

What does this mean? Under a simplified model of a HetNet — but not a terribly simplified one — it means that coverage probability is in fact independent of what would seem like crucial quantities: the number and density of different types of base stations; the number of tiers; their relative power levels; the fading distribution. In short, one can add tiers to the network, and base stations to any tier; they can have arbitrary power; and it *does not affect the coverage probability!*

This result contradicts the commonly held belief that adding femtocells, picocells, and other spectrum-sharing devices to a cellular network will erode performance by increasing interference. What this mathematical exercise shows is that in principle, this need not be the case. As long as the network is interference-limited and mobiles connect to the strongest base station, statistically speaking, their desired signal improves just as fast as the interference increases, so their SINR distribution does not change. It also shows that complex power control is not necessarily that important either.

THE IMPORTANCE OF ACCESS MODELS AND INTELLIGENT CELL ASSOCIATION

Naturally, some caveats should be given to the above results. First, this model is “open access,” i.e. any UE can connect to any base station, and it connects to the one that offers the best SINR. In practice, this may not occur for two important reasons. First, some nodes in the network, notably closed-access femtocells, will not be accessible to the rest of the UEs and so overall coverage probability may slightly decrease as femtocells are added. The problem is expected to be more severe in CDMA systems due to the near-far problem than in OFDMA where more orthogonal resources are available. Similarly, high mobility UEs will not always be connected to the strongest base station since handovers take some time.

A further important point is that it may be highly suboptimal from a network-wide point of view for UEs to simply pick the max-SINR base station, if a weaker one is available that is lightly loaded. For example, moving a UE from a heavily-loaded macro-base station to a nearby lightly-loaded picocell would benefit both that UE as well as the macrocell users by achieving better load-balancing. For example, a *bias* value B_k can be introduced for tier k , so that a UE will select a small cell in tier k even if it is a factor B_k weaker than the macrocell. Proceeding with the same model, [5] shows that with biasing the probability of a UE associating with a tier k is

$$\bar{A}_k = \frac{\lambda_k (P_k B_k)^{2/\alpha} \beta_k^{-2/\alpha}}{\sum_{i=1}^K \lambda_i (P_i B_i)^{2/\alpha} \beta_i^{-2/\alpha}}$$

Although all these theoretical results are for an idealized HetNet model, we show in the next section that the essential intuition of these mathematical results holds, and that the technical

¹ It is shown in [4] that the results hold down to about -4dB, which covers even cell edge users.

² When $\alpha = 4$, a closed-form expression exists even with noise and arbitrary SINR.

arguments for adding heterogeneous elements to the existing cellular network are very strong.

SIMULATED PERFORMANCE OF BASELINE HETEROGENEOUS NETWORKS

In HetNets, LPNs are distributed throughout an overlay macro-cell network. LPNs are typically small base stations that are classified by the transmit power and backhaul type as described in [6]. A typical pico cell is formed by an open-access LPN with omnidirectional antennas rated between 24–33 dBm output power, providing standardized interfaces over backhaul and are deployed in a planned fashion. A femto cell is typically formed by a LPN with antennas rated between 20–23 dBm, providing access to few users, utilizing home broadband as backhaul and deployed in an unplanned manner. In this section, the simulated performance of pico cells with macro-cell overlay is summarized. The results are based on 3GPP scenarios outlined in [7] and compared to the analysis from earlier.

The LPNs can be deployed using the same carrier frequency as the macro network (F_1-F_1), or using a different carrier frequency (F_1-F_2). First, the performance of multi-tier networks without any ICIC techniques is summarized for both carrier frequency cases.³ The UE distribution follows Table A.2.1.1.2-5 defined in [8]. Configuration #4a represents a low degree of clustering of users, whereas Configuration #4b (performance not shown here) represents a high degree of clustering. In the simulations, the number of LPNs per sector is varied from 1 to 10. The following metrics are used to evaluate the performance of the resulting heterogeneous (equivalently, multi-tier) network.

- Average per user throughput for macrocell UEs, picocell UEs, and a UE that can be either in a macrocell or picocell.
- The 5th percentile and 95th percentile user throughput for the same 3 cases
- Total sector throughput
- Fraction of UEs attached to picocells

The system simulation parameters are given in Table 1. The performance of the multi-tier network based on the metrics defined in the previous paragraph is summarized in Table 2 for Configuration #4a and for transmit mode 3, TM3 (open-loop spatial multiplexing).

The following observations can be made from the table:

- Gains of up to 4X in average overall UE throughput and up to 2X in 5th percentile UE throughput can be achieved with the deployment of 10 pico cells within a macro cell area.
- Overall average and 5 percentile UE throughput improves as the number of picos/sector increases.
- Overall sector throughput improves linearly — although not quite in direct proportion — with the numbers of picos deployed per macro sector. This observation reinforces

the theoretical results of an earlier section, which showed that picocells can be added without in anyway degrading coverage, which implies that each added picocell should increase capacity.

Next the performance of the F_1-F_1 configuration (10 MHz BW) is compared with the F_1-F_2 (10 MHz BW each for F_1 & F_2) configuration for both FDD and TDD systems, and for two TDD configurations (configurations 1 (TDD C1, DL:UL= \sim 60:40) and 2 (TDD C2, DL:UL= \sim 75:25) are defined in [9]) without any ICIC techniques. Figure 2 shows the average and 5th percentile picocell UE throughput for these configurations using TM4 (closed-loop spatial multiplexing), instead of TM3 (open-loop spatial multiplexing). The following conclusions can be drawn:

- The raw picocell UE throughput for F_1-F_2 is almost doubled vs. F_1-F_1 since there is no inter-cell interference between the macro and pico layer in the case of F_1-F_2 . However, from a spectral efficiency point of view the performance of the two configurations are the same.
- Raw picocell UE DL throughput (both 5th percentile and average) is much better with (F_1-F_2) even with TDD Config-1 compared to FDD (F_1-F_1).
- Although both the average pico-cell throughput and the number of average UEs attached to each pico decrease with increasing number of picos/sector, the behavior of the average UE throughput is determined by how their ratio changes. Thus, different trends are observed with F_1-F_1 and F_1-F_2 , influenced by whether interference is dominated by the macro cell or other pico cells.

The performance was also evaluated for the uplink of a HetNet, with results given in Table 3. The conclusions are similar to the downlink with the main difference being that uplink rates are typically lower due to transmit power limitations. In fact, the picocell gains are even larger in the uplink for this reason, since the attachment is based on downlink reference signal receive power (RSRP) and therefore the attachment to macrocells is increased since the macrocells have higher transmit power and antenna gain. Therefore the uplink gain is larger when a UE does in fact attach to the picocell since it will have a higher transmit power on average than when it attaches to a macrocell. Here, we are assuming that the downlink and uplink attachment must be to the same eNB.

ICIC AND ENHANCED-ICIC TECHNIQUES TO IMPROVE COVERAGE

It was noted that without ICIC, the fraction of users attached to picocells was between 10–40 percent and varied with the density of picocells per sector (and UE layout). However, the number of users attached to picocells also depends on the propagation environment. To increase the number of UEs attached to picocells, cell

The downside of biasing is that UEs are no longer necessarily connected to the strongest eNB. As a result, both the control and data channel for the biased users is often weak and subjected to strong interference. To compensate, enhanced inter cell interference coordination techniques are used.

³ See next section for a description of some ICIC techniques.

FFR is an attractive ICIC technique because of its simple implementation and ability to balance the improvement in user experience at the cell edge through frequency reuse while still maintaining overall spectral efficiency by reusing most RBs in every cell.

Simulation Parameter	Value
Deployment scenario	1, 2, 4, and 10 pico nodes randomly overlaid onto Case 1 macro-cells (19-cell, 57-sector wrap-around)
Number of UEs and user dropping criteria	30 per macro-cell sector and 4a/4b
Serving cell attachment	RSRP-based
Scheduler	Proportional fairness
Bandwidth	10 MHz
Carrier Frequency	2 GHz
Pathloss models	As per 3GPP TR 36.814 model 1
Macro cell ISD	500 m
Max Macro Tx Power	46 dBm
Max Pico Tx Power	30 dBm
Noise figure	9 dB
Macro eNB antenna pattern	3D antenna pattern (3GPP TR 36.814)
Pico eNB antenna pattern	Omni-directional, 2D antenna pattern
Macro eNB antenna gain	14 dBi
Pico eNB antenna gain	5 dBi
Antenna configuration	2 cross-polarized Tx antennas for eNB, 2 VH-polarized Rx antennas for terminal (2 × 2 OL-MIMO, Mode-3)
Receiver type	MMSE
Minimum distance between pico and macro	75 m
Minimum distance between picos	40 m
Minimum distance between macro and UE	25 m
Minimum distance between pico and UE	10 m
Fast Fading Channel	Modeled

Table 1. System simulation parameters for DL/UL.

range extension (also called *cell biasing*) will be used. Biasing achieves the dual benefits of decreasing the load on the macrocell while pushing UEs onto lightly loaded picocells where they can receive more resources. The downside of biasing is that UEs are no longer necessarily connected to the strongest eNB [5]. As a result, both the control and data channel for the biased users is often weak and subjected to strong interference. To compensate, enhanced inter cell interference coordination (eICIC) techniques are used. In this section, ICIC techniques based on Release-8 and 10 are presented along with some system simulation results. We refer readers to [10] for a background tutorial treatment of key ICIC techniques, including fractional frequency reuse (FFR).

FFR FUNDAMENTALS

The two most common types of FFR are Strict FFR and Soft Frequency Reuse (SFR). As illustrated in Fig. 3 using three adjacent cells and 3–4 non-overlapping frequency bands, the basic idea of Strict FFR is to create partitions between edge and inner users based on SINR, reusing the resource blocks (RBs)⁴ of inner users in every cell and allocating edge users orthogonal FFR RBs, thus removing adjacent cell interference. In the case of SFR, higher per-cell RB utilization is achieved by reusing all RBs in every cell but with a higher transmit power given to edge users to mitigate the increased inter- and cross-tier interference. FFR is an attractive ICIC technique because of its simple implementation and ability to balance the improvement in user expe-

⁴ An RB is a unit of data allocation in LTE and is specifically 12 subcarriers by 14 symbols.

	Throughput type	Number of Picos/Sector			
		0	2	4	10
Macro cell UEs	Avg UE t'put	705	769	878	1117
	5th percentile UE t'put (kb/s)	126	132	144	194
	Sector t'put (Mb/s)	21.2	20.4	20.6	20.2
Pico cell UEs	Avg UE t'put (kb/s)	—	4037.1	4422.9	5218.3
	5th percentile UE t'put (kb/s)	—	601.0	648.8	829.2
	Sector t'put (Mb/s)	—	7.1	7.2	6.2
All UEs	Avg UE t'put (kb/s)	705.4	1149.5	1649.9	2745.9
	5th percentile UE t'put (kb/s)	126.4	139.4	163.2	249.1
	Sector t'put (Mb/s)	21.2	34.5	49.5	82.4
	Fraction of UEs attached to picos	—	0.12	0.22	0.40

Table 2. Performance of multi-tier networks for Configuration #4a (2×2 , TM3) w/o ICIC.

rience at the cell edge through frequency reuse while still maintaining overall spectral efficiency by reusing most RBs in every cell.

FFR IN LTE

A simple strategy was followed in implementing the Rel-8 based ICIC scheme for multi-tier networks. FFR was used in the overlay macro-cell network, where a portion of the time-frequency RBs was reserved in each sector for cell edge UEs. In the simulation Soft FFR was utilized with 18 RBs out of 50 RBs used in a 3 cell reuse pattern for scheduling cell edge UEs and the remaining 32 RBs were used in single cell reuse pattern. The underlay picocell network operated with single cell frequency reuse scheme without any FFR. Table 4 shows the 5th percentile overall (macro+pico) UE throughput with and without Rel-8 ICIC techniques for a multi-tier network. It may be observed that there is 20–40 percent improvement in overall cell edge throughput with no biasing. On the other hand when using a cell-range extension (CRE) bias and FFR on only the macro-cell layer, the overall cell-edge performance can be enhanced, but this enhancement may be difficult to implement because of control channel degradation.

The analytical approach presented earlier has recently been used to better understand the performance of single-tier and heterogeneous networks using FFR on one or multiple tiers by capturing the non-uniformity of coverage areas, which directly impact the distribution of edge user SINR under FFR, something not possible before with deterministic models [11, 12]. The analytical results predict a 5–8 dB increase in typical edge user SINR compared to no ICIC with an ideal control channel. Intuitively, with open access, the offloading effect of biasing works in combination with the SINR boost from the use of FFR to improve user experience and

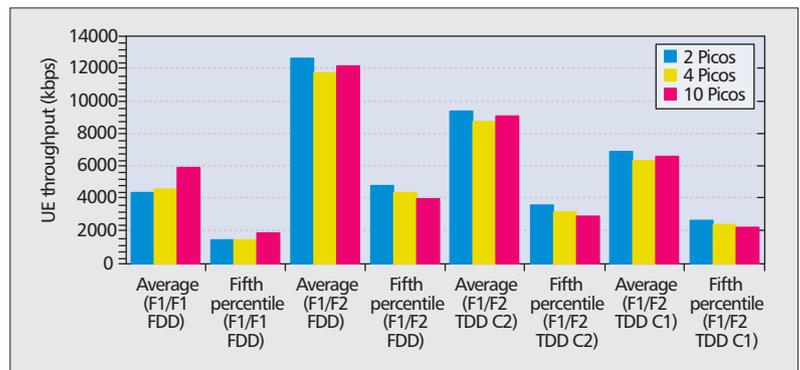


Figure 2. Picocell performance comparison of F_1 – F_1 to F_1 – F_2 configurations for FDD and TDD (Configuration #4a).

reduce the amount of RBs which need to be reserved. As the bias is increased, only the macro users with the worst SINR are allocated a FFR RB and these are the users who will reap the greatest benefit from FFR.

Next, Rel-10 based ICIC techniques are discussed briefly. Rel-10 e-ICIC can be broadly classified into two categories, namely

- Non-carrier aggregation (CA) based schemes
- Carrier based schemes (not discussed in this article)

The non-CA scheme uses a time division multiplexing (TDM) principle where the macro sends an almost blank subframe (ABS) or MBSFN (Multimedia Broadcast over Single Frequency Network) subframe pattern with a certain period along with the data ICIC frequency partition to the pico nodes and the pico nodes in turn send a small amount of long-term information like RSRP. This ABS approach is illustrated in Fig. 4, where the macro node transmits ABSs with a

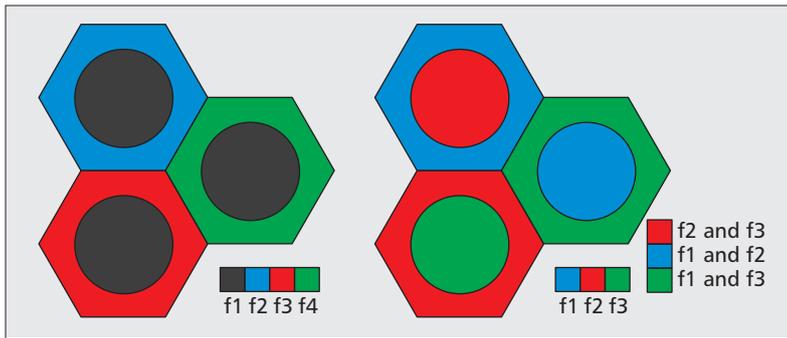


Figure 3. Strict FFR (left) and Soft FR (right) subband allocations.

50 percent periodicity but the pico nodes transmit normal subframes all the time. The UEs connected to pico nodes which may suffer from macro cell interference are scheduled during transmission of ABSs from the macros while UEs closer to pico nodes are scheduled during normal macro subframes. Note that this scheme requires strict synchronization between macro and pico nodes and also feedback from the pico and macro nodes over the X2 interface⁵ to set the optimum ABS pattern. Figure 5 shows the 5th percentile overall UE throughput gain compared to the UEs connected to macro cell only for different bias values and ABS patterns and with and without TDM-eICIC schemes. As an example ABS fraction of 1/4 signifies that the macro sends 10 ABS frames every four radio frames (40 ms). The following conclusions are drawn from the figure:

- As the bias value increases, the percent of UEs attached to macrocells decreases.
- The overall 5th percentile throughput initially increases and then drops after about a 5-dB bias if no ICIC techniques are applied.
- With Rel-10 TDM-eICIC the bias setting increases (resulting in more users being connected to picocell) along with the performance of the overall system. In the case

of Configuration-4b the optimum bias and ABS fraction setting are ~15 dB and 1/2, respectively.

The results shown are with fixed ABS pattern. In practical deployments the optimal ABS pattern is configured dynamically based on the UE distribution, number of picocells, and other system parameters. It may also be noted that to exploit the benefit of TDM eICIC schemes Rel-10 UEs are required. Currently, in Release-11 non-zero power ABS frames are also being studied where the PDCCH and PDSCH are transmitted at a lower power, while the other common channels are transmitted at full power to maintain coverage.

In addition to TDM eICIC, advanced UE cancellation receivers can also be used to help overcome the interference due to biasing. The receiver is designed to suppress interference caused by overhead channels such as common reference symbols, broadcast channels and synchronization signals. Suppression of the legacy interference from these signals/channels improves the decoding performance of both the control and data channels.

DEPLOYMENT LOGISTICS FOR HETEROGENEOUS NETWORKS AND TRIAL RESULTS

While deployment of small cells (e.g. pico, femto etc.) in a multi-tier network improves the user experience and capacity of the network it faces multiple new challenges with respect to backhaul deployment, Enhanced Packet Core (EPC) impact due to signaling load, ease of management and installation, security, electrical power, and the increased need for efficient self-organizing networks (SON). In this section, some of the above issues will be discussed for specific use cases (e.g., outdoor street level and indoor pico deployments). Also, we briefly discuss a HetNet field trial.

		Number of Picos				
		0	1	2	4	10
Macro cell UEs	Avg UE t'put (kb/s)	336.37	365.99	389.12	442.92	557.97
	5th percentile UE t'put (kb/s)	78.51	87.94	92.63	112.93	166.20
	Sector t'put (Mb/s)	8.79	8.69	8.63	8.51	7.27
Pico cell UEs	Avg UE t'put (kb/s)	—	4940.50	4885.70	4855.30	4894.30
	5th percentile UE t'put (kb/s)	—	192.48	237.85	344.19	946.41
	Sector t'put (Mb/s)	—	10.40	9.71	8.73	6.52
All UEs	Avg UE t'put (kb/s)	336.37	636.33	934.67	1447.67	2415.00
	5th percentile UE t'put (kb/s)	78.51	90.32	96.71	120.99	192.01
	Sector t'put (Mb/s)	8.79	19.09	28.04	43.43	72.45

Table 3. Uplink performance of multi-tier networks (w/o ICIC) for Configuration #4a.

⁵ The X2 interface is a logical link between eNBs.

BACKHAUL CONSIDERATIONS

Today's traditional cellular systems provide both coverage and capacity. With the extensive use of smart phones in the future, small cells with LPNs (e.g. picos, femtos, remote radio heads (RRHs)) will address the capacity needs especially in hot zones and clusters while coverage will be provided by macro cells. One of the scenarios addressed in this article is the deployment of pico cells on street poles. The picos needs to be connected to the core network using wired or wireless backhaul but providing wired backhaul using fiber from street level picos to the core network may be cost prohibitive compared to wireless backhaul. However, wireless backhaul has its own set of issues which are described below.

Wireless backhaul spectrum can be broadly classified in four categories namely

- Unlicensed @ 2.4 and 5 GHz
- Unlicensed @ 60 GHz
- Licensed @ 6–42 GHz and @70–90 GHz
- Operator owned licensed band. Specifics of the various wireless spectrum options for backhaul are summarized in Table 5.

The wireless backhaul between picos in a street level deployment can be configured in many different configurations like star, ring etc. The backhaul sizing depends upon how many hops one has to support, the environment, if the pico cells are isolated or clustered, the interference conditions, the traffic volume, etc. For the pico cells mounted on street poles and using 2 hops, an unlicensed backhaul at 2.4 or 5 GHz can support approximately 50 Mb/s of throughput. For street level pico deployment the backhaul can be near or NLOS and as such the most robust option is to use either unlicensed WiFi or LTE broadband wireless access subject to operators' spectrum asset availability. Note that unlicensed WiFi may suffer from interference which may affect the robustness of the backhaul link.

Picocell deployment using street poles offers many benefits as seen but the main benefit is the proximity to pedestrians in a semi-urban environment providing a hot zone in an area where people tend to congregate. Furthermore one can negotiate with a single entity (e.g. a certain municipality or power company) who owns the street poles compared a multitude of building owners if one were to deploy picos on buildings. However, two vexing issues associated with street pole pico deployments are: electric power and aesthetics. With respect to power, there are poles with continuous power supply (desirable) or there are poles that have "bank switched" power based on time-of-day. Other alternatives for power include running independent conduit to supply picos, which can be expensive or relying solar power cell which imposes additional design constraints and makes reliability dependent on the weather. Beyond power, aesthetics proves a daunting challenge as the picos must be visually pleasing and must blend in with the environment. Municipalities are sensitive to the appearance of the fixtures in the business and showing districts and also the aesthetic must meet the approval of the local zoning board.

# Picos per Macro	UE Cell Edge Throughput (0 dB bias, kb/s)		
	W/o ICIC	With ICIC	percent Change
2, Config#4a	144	201	39%
2, Config#4b	231	280	20%
4, Config# 4a	189	230	22%
4, Config# 4b	261	287	10%

Table 4. Overall (macro+pico) 5th percentile UE throughput using Release-8 ICIC.

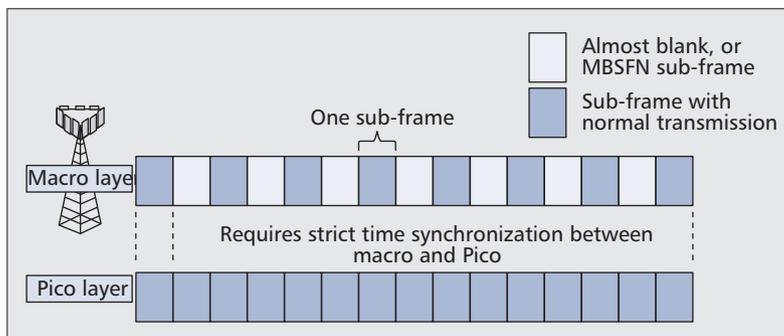


Figure 4. Transmission of ABS from macro layer (e.g., 50 percent blanking).

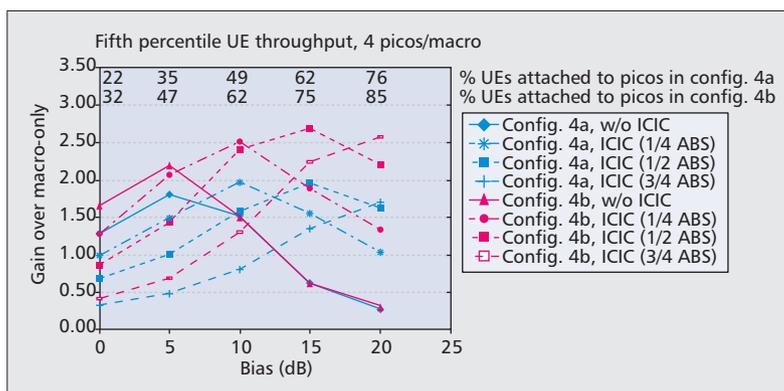


Figure 5. Overall 5th percentile UE throughput gain over macro network with CRE and with/without TDM e-ICIC.

Finally, a brief overview of the HetNet proof-of-concept (PoC) system, which was deployed in Europe at and around a NSN facility operating at 2.6 GHz is described in this section with some field results.

The environment is representative of a typical suburban business park with modern two-story glass and steel construction and ample open space between buildings with access for pedestrians. The PoC system leveraged an existing three-sector macro site located on a mast in adjacent parking lot used in previous field trials. Pico sites were deployed on eaves of the facility in a uniform fashion with 4 sites at the corners and one additional site splitting the longest side opposite the macro site. The building was 120 m by 36 m and the macro site was only 40 m away. The distribution of pico sites was intended to mimic what is envisioned

	Available Frequencies & Bandwidth	Duplex & Line of Sight (LOS)	Range	Throughput	Latency
Unlicensed 2.4GHz and 5GHz 802.11 a/b/g/n WiFi	2.4000–2.4835 GHz for 802.11b/g/n 5GHz UNII band for 802.11a/n with 23 available 20MHz channels	TDD LOS/nLOS/ NLOS	< 200 meters with Omni antenna.	LOS up to 150Mb/s each way TDD with 802.11n.	1ms ~ 3ms per hop
Licensed 6 to 38 GHz Microwave	6, 7, 8, 11, 13, 15, 18, 23, 24, 26, 28, 29, 31, 32, 38 GHz. 16, 32, 64, 128 and 256QAM up to 50 (FCC)/56 (ETSI) MHz channel bandwidth.	FDD LOS only	5 to 8 km using mid- range frequencies. Higher range frequencies with 1 foot antenna up to 2 miles.	Up to 400Mb/s FDD per link	0.2 to 0.5 ms one-way
Unlicensed 60GHz V-band	57 to 64 GHz	FDD(Typical)/TDD LOS only	Up to 2 km, stretchable to 3+ km	> 1 Gb/s FDD per link	< 50 us one-way
Light licensed 70 to 90 GHz E- band	71 to 76 GHz 81 to 86 GHz 92 to 95 GHz	FDD(Typical)/TDD LOS only	Up to 3 km, stretchable to 5+ km	> 1 Gb/s FDD per link	< 50 us one-way (best case < 5 us)
Broadband Wireless Access (in-band)	2.3GHz, 3.5GHz	TDD/FDD LOS/nLOS/ NLOS	1 to 2 km with sector antenna > 2km with directional antenna	Up to 10 bps/Hz OFDMA	< 2ms TDD, < 1ms FDD

Table 5. LOS/nLOS/NLOS backhaul options.

as typical commercial pico deployment where picos are placed on available structures with little or no detailed RF planning required by the network operator. As such, two of the picos were in direct line-of-sight of the macro sites. These two sites were included to demonstrate that even sub-optimally placed picos can provide a capacity gain and will not severely impact the macro performance. The performance of the system was evaluated over four walking routes — three outdoor and one indoor — that were selected to follow typical pedestrian path ways (Fig. 6). 6 UEs were distributed on the identified walking routes at specific points in the pico coverage areas based on the CINR CDF — 80 percent, 50 percent and 5 percent points. The results given in Table 6 show a 4X capacity improvement from the pico-macro system over macro site alone for outdoor locations. The highest gains, over 6X, are seen on the indoor locations since the low height of the pico site greatly improves the in-building penetration when Macro power is low. The pico signals need only propagate through the windows while the macro signal must pass through the roof and floors. At higher macro powers, a fairly aggressive macro down-tilt of 10 degrees, designed to cover indoor locations, creates significant interference at 5 percent point for the indoor locations. With the deployment of picos, the macro down-tilt may be relaxed further improving overall performance.

CONCLUSION

In this article, a theoretical framework of a multi-tier cellular network based on random spatial models was developed and it was shown that essential intuition of these mathematical results hold in practice. The technical arguments for adding heterogeneous elements to the existing cellular network appear to be very strong. Simulation results show that there is a 4X improvement in user experience with the deployment of picocells in a multi-tier network even without any ICIC techniques. Applying TDM based e-ICIC and cell range extension increases the number of users connected to the underlay network and improves the overall user experience compared to a macro cell network. A PoC system, where the picos were mounted on street poles was deployed in Europe and initial results show ~3–4X user-experience improvement over a single-tier macro system.

ACKNOWLEDGMENT

The authors would like to acknowledge Dr. David Chen for giving guidance on backhaul analysis, Dr. Klaus Pedersen for his insightful comments and to Joe Pedziwiatr and Dr. Weidong Yang for helping us to enhance our understanding of various HetNet concepts. They also acknowledge the contributions of Prof. Francois Baccelli and Prof. Radha Krishna Ganti in helping derive some of the featured theoretical results. In addition, the authors acknowledge

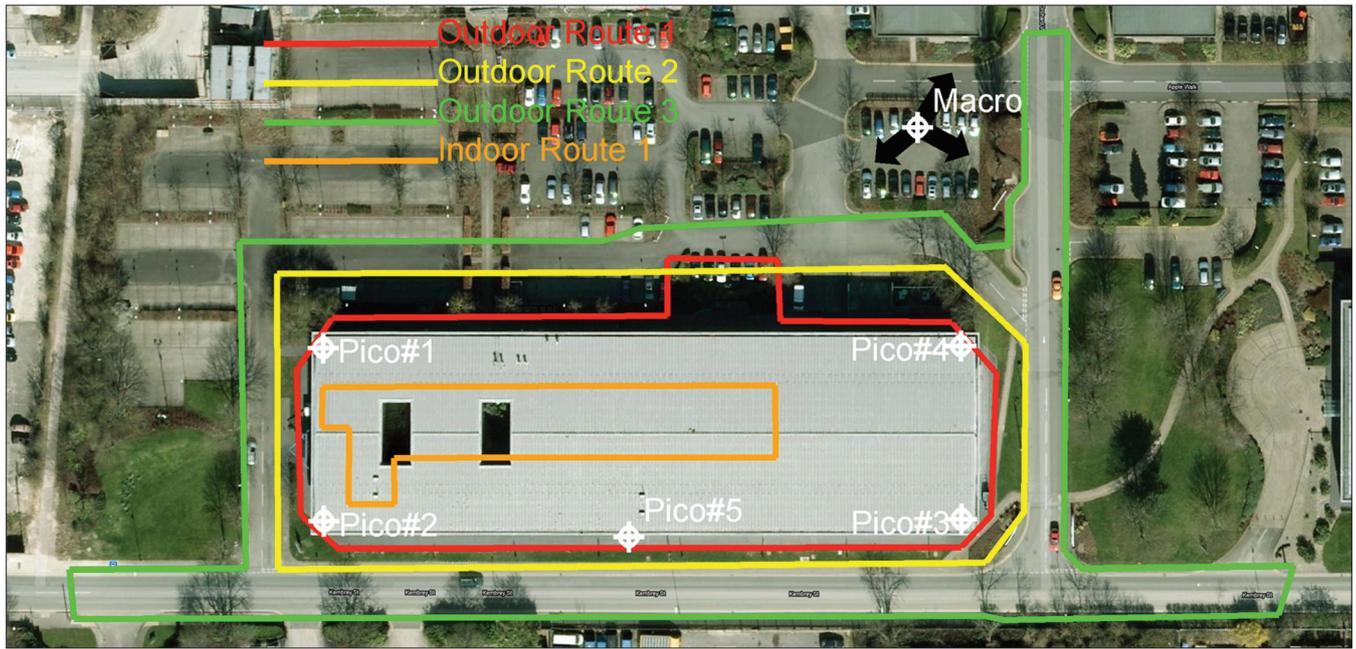


Figure 6. Aerial view of the proof of concept system and walking routes.

Alex Bonfield, Michael Brien, and David Padfield for their work on the HetNet PoC system.

REFERENCES

- [1] M. Dohler *et al.*, "Is the PHY Layer Dead?," *IEEE Commun. Mag.*, Apr. 2011.
- [2] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Commun. Mag.*, Sept. 2008.
- [3] F. Baccelli and B. Blaszczyszyn, *Stochastic Geometry and Wireless Networks, Foundations and Trends in Networking*, 2009.
- [4] H. Dhillon *et al.*, "Modeling and Analysis of K-Tier Downlink Heterogeneous Cellular Networks," to appear, *IEEE JSAC*, Mar. 2011, <http://arxiv.org/abs/1103.2177>.
- [5] H. S. Jo *et al.*, "Heterogeneous Cellular Networks with Flexible Cell Association: A Comprehensive Downlink SINR Analysis," submitted to *IEEE Trans. Wireless Commun.*, July 2011, available at <http://arxiv.org/abs/1107.3602>.
- [6] A. Ghosh *et al.*, "LTE-Advanced: Next-Generation Wireless Broadband Technology," *IEEE Wireless Commun.*, vol. 17, no. 3, June 2010, pp. 10–22.
- [7] 3GPP TR 36.814, Further Advancements for E-UTRA, v.1.5.2, Dec. 2009.
- [8] 3GPP TR 36.913, Requirements for Further Advancements for Evolved Universal Terrestrial Radio Access (E-UTRA), v.8.0.1, Mar. 2009.
- [9] 3GPP TS 36.211, Physical Channels and Modulation, v8.7.0, May 2009.
- [10] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag.*, vol. 47, no. 4, Apr. 2009, pp. 74–81.
- [11] T. Novlan *et al.*, "Analytical Evaluation of Fractional Frequency Reuse for OFDMA Cellular Networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, Dec. 2011, pp. 4294–305.
- [12] T. D. Novlan, R. K. Ganti, and J. G. Andrews, "Coverage in Two-Tier Cellular Networks with Fractional Frequency Reuse," *Proc. IEEE Globecom*, Houston, TX, Dec. 2011.

BIOGRAPHIES

AMITABHA (AMITAVA) GHOSH [SM] (amitava.ghosh@nsn.com) joined Motorola in 1990 after receiving his Ph.D. in Electrical Engineering from Southern Methodist University, Dallas. Since joining Motorola he worked on eight different wireless technologies starting from IS-95, cdma-2000, 1xEV-DV/1XTREME, 1xEV-DO, UMTS, HSPA, 802.16e/WiMAX/802.16m, Enhanced EDGE and 3GPP LTE. He has 50 issued

Route	Macro (W)	Pico (W)	% Macro Coverage	Percentage Gain		
				6 UEs Aggregate Throughput		
				5%	50%	80%
Outdoor	20	2	45%	101%	206%	371%
	2	2	23%	86%	342%	392%
	0.25	2	9%	57%	247%	448%
	0.25	0.25	23%	86%	322%	395%
Indoor	20	2	5%	-8%	65%	176%
	2	2	0%	-1%	104%	233%
	0.25	2	0%	37%	241%	536%
	0.25	0.25	0%	48%	223%	383%

Table 6. Proof of concept capacity gains for various routes and power settings.

patents and numerous external and internal technical papers. Currently, he is Head, Wireless Broadband Innovation within the CTO office of Nokia Siemens Networks and works in the area of current and future air-interface technologies for 3GPP LTE, LTE-Advanced and B-4G. His research interests are in the area of digital communications, signal processing and wireless communications. He is a co-author of the book titled "Essentials of LTE and LTE-A."

JEFFREY G. ANDREWS has in recent years focused his research on the coverage and capacity of heterogeneous cellular networks, in particular those overloaded with small short-range cells, such as pico and femtocells. He has received five IEEE best paper awards and gave the opening keynote address at the first IEEE Workshop on Femtocell Networks (at Globecom 2010) and has co-authored two popular textbooks on 4G cellular standards: Fundamentals of WiMAX and Fundamentals of LTE. He is an Associate Professor at UT Austin, where he is the Past Director of the Wireless Networking and Communications Group. He is a recipient

of the National Science Foundation CAREER award and holds a Ph.D. from Stanford University.

RAPEEPAT RATASUK joined Motorola in 1999 after receiving his Ph.D. in Electrical Engineering from Northwestern University, Evanston, IL and was a Distinguished Member of the Technical Staff in the Wireless Networks Systems and Technologies department. Currently he is a senior technologist at Nokia Siemens Networks working in CTO's office. He has extensive experience in 3G/4G cellular system design and analysis (LTE, HSPA, WiMAX, 1xEV-DV, WCDMA) including algorithm development, performance analysis and validation, physical layer modeling and simulations. He has 15 issued U.S. patents and over 35 journal and conference papers. His research interests are in the areas of digital communications, signal processing and wireless communications.

BISHWARUP MONDAL received the B.E. and M.E. degrees from Jadavpur University, Calcutta and the Indian Institute of Science, Bangalore in 1997 and 2000 respectively and the Ph.D. degree from the University of Texas at Austin in 2006, all in electrical engineering. He is presently with Nokia Siemens Networks, Arlington Heights, IL. His current research interests lie in the analysis and design of multiple antenna wireless systems with quantized or partial channel information at the transmitter. He is the recipient of the 2005 IEEE Vehicular Technology Society Daniel E. Noble Fellowship.

NITIN MANGALVEDHE is currently at Nokia Siemens Networks (NSN) working in CTO's office. Prior to joining NSN he was a Principal Staff Engineer at Motorola, where he has been employed since 1999 after receiving a Ph.D. in Electrical Engineering from Virginia Tech, Blacksburg, VA. He worked on various wireless access technologies, including GSM/EDGE/GPRS, WCDMA, IEEE 802.11a/b/g/n, and IEEE 802.16m, for several years as part of Motorola Labs, with a focus on advanced receiver algorithms and design of next-generation wireless systems. Since 2008, when he joined the System and Technologies group of the Networks division at Motorola, he has been focusing on modeling, development, and performance analysis of LTE/LTE-Advanced systems. His interests are in wireless communications and digital signal processing.

TIM THOMAS joined Motorola in 1997 after receiving a Ph.D. in electrical engineering from Purdue University. Currently he is a senior technologist at Nokia Siemens Networks working in the CTO's office. He was a Distinguished Member of the Technical Staff in the Wireless Network Systems and Technologies department and is working on next generation wireless communication systems. His research interests are in channel measurement, channel estimation, MIMO communications, and adaptive antenna algorithms for mobile broadband communications.

MARK CUDAK is a senior technologist with the Nokia Siemens Networks. He manages a research group working on next generation cellular technologies. Prior to joining Nokia Siemens Networks, Mark was with Motorola where he worked on several wireless data systems including GPRS,

WCDMA, HSPA, IEEE 802.16 and LTE. Mark has 37 issued patents, was a Motorola Dan Noble Fellow and received a M.S. in electrical engineering at the University of Illinois at Urbana-Champaign.

EUGENE VISOTSKY received a B.S., an M.S. and a Ph.D. in Electrical Engineering in 1996, 1998, and 2000, respectively, from University of Illinois at Urbana-Champaign. In June 2000, he joined the Communication Systems Research Laboratory at Motorola Labs, Schaumburg, IL. Since May 2011, he has been with Wireless Broadband Innovation within the CTO office of Nokia Siemens Networks. His main areas of research have included advanced signal processing techniques for spread spectrum communication systems, link adaptation, multicarrier modulation techniques, and multi-hop protocols applied in cellular systems. His current areas of interest are in advanced inter-cell interference coordination and cooperative transmission algorithms. He has a number of issued and pending US patents.

PING XIA is a Ph.D. student at UT Austin specializing on femtocell-overlaid cellular networks. He completed his B.E. in 2008 from Tsinghua University, China and his M.S. from UT Austin in 2010. His research has been supported by NSF and Motorola/NSN and he has held summer internships at Dell and Huawei. He has worked on such topics as closed vs. open access and heterogeneous network coordination and cell association.

HAN-SHIN JO received the B.S., M.S., and Ph.D. degrees in Electrical and Electronics Engineering from Yonsei University, Korea, in 2001, 2004, and 2009, respectively. He is currently a Postdoctoral Fellow in the Department of Electrical and Computer Engineering at The University of Texas at Austin. His research interests include theoretical analysis and interference management for femtocell/heterogeneous cellular networks, stochastic geometry and belief propagation.

HARPREET S. DHILLON received the B.Tech. degree in Electronics and Communication Engineering from IIT Guwahati, India, in 2008 and the M.S. in EE from Virginia Tech in 2010. His Ph.D. research at UT Austin has focused on the analysis of heterogeneous cellular networks. He is the recipient of the Microelectronics and Computer Development (MCD) fellowship from UT Austin and was also awarded the Agilent Engineering and Technology Award 2008. He has held internships at Qualcomm in San Diego, CA and Alcatel-Lucent Bell Labs, in Crawford Hill, NJ.

TOM NOVLAN received his Ph.D. at UT Austin working on intercell interference coordination techniques, particularly FFR. He completed his B.S. degree with High Honors at UT Austin in 2007, where he conducted undergraduate research in WNCG on WiMAX systems and the 802.16j multihop extension in particular. He was a 2006 participant in the NSF Eureka summer research program and is a recipient of the Virginia and Ernest Cockrell, Jr. Fellowship. He has held summer intern positions at Qualcomm, Intel, and AT&T Labs and is now with Samsung R&D in Richardson, TX.