WiMAX Femtocells: A Perspective on Network Architecture, Capacity, and Coverage

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ABSTRACT

Femtocells are viewed as a promising option for mobile operators to improve coverage and provide high-data-rate services in a cost-effective manner. The idea is to overlay low-power and low-cost base station devices, Femto-APs, on the existing cellular network, where each Femto-AP provides high-speed wireless connection to subscribers within a small range. In particular, Femto-APs can be used to serve indoor users, resulting in a powerful solution for ubiquitous indoor and outdoor coverage, using a single access technology such as WiMAX. In this article we consider a WiMAX network deploying both macro BSs and Femto-APs, where it is assumed that Femto-APs have wired backhaul such as cable or DSL and operate on the same frequency band as macro BSs. Simulation results show that significant areal capacity (throughput per unit area) gain can be achieved via intense spatial reuse of the wireless spectrum. In addition, Femto-APs improve indoor coverage, where the macro BS signal may be weak. Motivated by the gains in capacity and coverage offered by femtocells, we review the state of the art of this “infant” technology, including use cases and network deployment scenarios, technical challenges that need to be addressed, and current standardization and industry activity.

INTRODUCTION

Due to advances in wireless technology, cell phones have become indispensable in everyday life. To improve user experience is the never-changing goal of the wireless industry. A common complaint with current cellular systems is their imperfect coverage, especially indoors. Due to the high penetration loss from walls, the signal strength received from an outdoor base station (BS) inside a building may be too low to attain acceptable performance. Since BSs cannot increase transmission power unlimitedly to enhance received signals in outage areas, a better solution may be to use additional devices to cover these locations. The traditional approach is to deploy additional BSs, which is economically inefficient because of the tedious location finding process and the high backhaul and implementation cost. Thus, a new concept, femtocell, is proposed by the cellular industry.

A direct interpretation of femtocell is a small coverage area such as a house or small office, home office (SOHO). An existing example of femtocell coverage is the WiFi access point (AP) whose typical coverage region is up to 100 m in radius. The success of WiFi has inspired cellular operators to cover a small area with a low-cost AP-like device. In the current cellular industry definition, femtocell can refer to either the coverage area or the device itself. This article uses the term Femto-AP for the device, which is a simplified low-power device that utilizes cellular technology (2G/3G/WiMAX) with IP backhaul through a local broadband connection, such as digital subscriber line (DSL), cable, or fiber. Ideally, the Femto-AP should be a low-cost simple plug-and-play device like a WiFi AP.

Through deployment of a large number of Femto-APs, significant gain in areal capacity and indoor coverage can be achieved, which is detailed in later sections. In addition, Femto-AP deployments have several advantages over other technologies. First, they are a cost-effective solution for indoor access since they are more likely to be deployed at places that need them most, and being a consumer device, the cost of a Femto-AP is expected to be under $200 [1]. Wireless operators save on backhaul costs since Femto-AP traffic is carried over wired residential broadband connections that connect to the IP backbone. The consumer can expect improved data speeds and service quality, and longer battery life as it is no longer necessary to connect to outdoor macro/micro BSs. Furthermore, Femto-APs enable the convergence of landline and mobile services since the same handheld device can be used to access the
There are two alternate technologies for femtocells that can offer continuous indoor cellular coverage: WiFi and relay. Seamless roaming between a WiFi AP and the cellular network is enabled via unlicensed mobile access (UMA) and dual-mode handsets. When subscribers are within WiFi AP range, voice/data traffic is carried over the IP network. This feature may be less favorable for cellular operators since they cannot charge for services carried over WiFi APs. For subscribers, dual-mode handsets with both cellular and WiFi technologies may be more expensive than Femto-APs due to size and power constraints. Also, quality of service and security over licensed exempt spectrum can be of concern. Alternatively, a relay station can provide indoor coverage by forwarding an improved version of the received signal from a macro BS to indoor users. This strategy has been proposed for evolution of the IEEE 802.16e standard; the IEEE 802.16j task group is designing mobile multihop relays (MMRs) to gain coverage extension and throughput enhancement. The relay uses wireless backhaul, so no landline resource is required; however, this reduces the amount of spectrum available for access.

In this article we focus on the case where Femto-APs serve as simplified WiMAX BSs with wireless backhaul available through residential broadband connections. The article is organized as follows. The next section discusses use cases of Femto-APs and associated network architectures. We then present our main results on the capacity and coverage performance of a WiMAX femtocell overlay network. The following section addresses the technical challenges associated with WiMAX Femto-AP deployments. We then summarize the industrial activities on femtocells. The final section contains conclusions.

**Usage Cases and Network Architecture**

Femto-APs are typically deployed on top of the existing cellular system, and their introduction forms a hierarchical overlay network, as shown in Fig. 1. It is expected that Femto-APs will support low-mobility users requiring high-rate connections, while existing macro/micro BSs will serve users moving at high speeds. Competing technologies such as WiFi and relay may coexist in the network.

Femto-APs can be installed at locations where users are experiencing unsatisfactory radio coverage or have higher data rate requirements than can be satisfied with existing radio conditions. For example, Femto-APs can help improve coverage of indoor users who suffer from poor reception due to wall penetration loss. There can be a single Femto-AP covering a house, or several Femto-APs covering a building or an enterprise environment. Besides indoor environments, outdoor hotspots such as stadiums or shopping malls can also be served by Femto-APs.

Consider two Femto-AP use cases. The first is for public usage, where all customers of a cellular service provider can access publicly accessible Femto-APs. The typical scenario for the public case is in a coffee shop or airport. The other case is for private usage, where only authorized users are allowed to connect to a privately accessible Femto-AP. The second is more suitable for home or enterprise environments. Unlike macro/micro BSs whose locations are carefully planned by operators, most Femto-AP installations will be consumer devices that are positioned based on users’ needs. Also, operators are likely to install a few Femto-APs at cell edges to improve system coverage and capacity in an efficient way.

As mentioned above, Femto-APs will be deployed to meet users’ demands and cannot be planned in advance by operators. Hence, the management of Femto-APs is a very challenging task. In traditional cellular systems, macro/micro BSs are directly connected to the operators’ network via dedicated landlines. Tens to hundreds of BSs are connected to a radio network controller (RNC), which is responsible for functions like radio resource management (RRM) and handoff between BSs. To integrate Femto-AP deployments with existing cellular networks, the main challenge lies in designing a network architecture that connects Femto-APs, which are connected to the IP-based network by a local Internet service provider (ISP), to the existing cellular infrastructure.

An example network structure for a WiMAX system with Femto-APs is illustrated in Fig. 2. The WiMAX network consists of two components, the access service network (ASN) and connectivity service network (CSN). An all-IP network structure is applied in the ASN where both operator-owned macro/micro BSs and customer-owned Femto-APs are connected to local ISP networks to reduce the backbone implementation cost. Typically, the IP networks to which macro/micro BSs are connected

![Figure 1. Hierarchical overlay network.](image-url)
are built and owned by operators, whereas Femto-APs are likely to connect to IP networks provided by local DSL or cable companies. In contrast, the CSN is an existing backend composed of servers such as an authentication, authorization, and accounting (AAA) server, mobile IP (MIP), home agent (HA), and policy server. The interface between ASN and CSN occurs at the ASN gateway (GW). Macro/micro BSs and Femto-APs communicate with ASN gateways through the packet-switched IP network, enabling exchange of necessary information with servers within the CSN. The ASN gateways conduct tasks like location registration, authentication, paging control, and service flow authorization.

This WiMAX network architecture is flat compared to typical cellular architectures (second/third generation [2G/3G]) since RNC functions are integrated into macro/micro BSs and Femto-APs. Thus, macro/micro BSs and Femto-APs in WiMAX networks should be more autonomous. Additionally, such a system is more robust since each BS, either macro/micro or femto, can connect to multiple ASN GWs such that there is no single point of failure. The role of a Femto-AP in WiMAX network is the same as a macro/micro BS. A Session Initiation Protocol/IP multimedia subsystem (SIP/IMS) gateway is required to interwork with existing 2G/3G networks and the public switched telephone network (PSTN).

### Capacity and Coverage Analysis

We study the potential capacity and coverage gain from WiMAX femtocells using system-level simulations. In our simulations we focus on downlink transmission, and compute long-term capacity based on path loss, slow fading, and interference. We assume the WiMAX system operates at 2.3 GHz carrier frequency with 10 MHz bandwidth. The same carrier frequency is used by all macro/micro BSs and Femto-APs. The worst case interference is modeled (frequency reuse): every macro/micro BS and Femto-AP uses the whole 10 MHz for transmission.

Figure 3 illustrates the deployment model used in the simulation. Overlaying Femto-APs on top of the macrocell network form a hierarchical cell structure. Macro-BSs are deployed in a hexagonal manner. There are a total of 19 macro-BSs, each with three sectors. Femto-APs (FS) are deployed within a hexagon with radius four times the macrocell radius. The locations of Femto-APs are randomly selected from a grid with 20 m separation. Therefore, a minimum distance of 20 m between neighboring Femto-APs is guaranteed. We assume each Femto-AP is located at the center of a house, where a house is approximated by a disk area of 10 m radius. Equal numbers of indoor and outdoor users are deployed within a hexagon with radius two times the macrocell radius. Indoor (outdoor) users are uniformly distributed inside (outside) of the houses. Statistics will be collected only from users covered by BSs or Femto-APs inside the center cell. Macro-BSs and Femto-APs outside of the center cell are deployed only to provide more accurate estimates of interference.

For each user in the center cell, we compute signal-to-interference plus noise ratio (SINR) and corresponding spectral efficiency (SE). The SE is estimated assuming a 3 dB gap to theoretical capacity. The following equation shows how we estimate the spectral efficiency:
When SE equals zero, the corresponding user is in outage. The percentage of users who are not in outage is denoted as coverage of the system. The other important metric, system capacity, is computed as follows. There are a total of 13 modulation and coding schemes (MCSs) available in our simulation. For each user, the MCS mode with maximum achievable SE is selected. To compute the average user rate, we multiply MCS-based SE by total bandwidth available. The mean data rate a macro BS/Femto-AP can support is the mean of average rates of all users associated with a particular macro BS/Femto-AP. Then the system capacity is given by the sum of the mean data rate of the macro BS and all Femto-APs located within the center cell. We also compute the areal capacity gain, which is equal to dividing the system capacity with Femto-APs deployed by the system capacity without Femto-APs.

The International Telecommunication Union (ITU) channel models [2] are used to model path loss and slow fading. We use the indoor office scenario to model the channel from Femto-APs to users in the same building. The channel from macro BS to outdoor users is modeled by a vehicular scenario. The outdoor-to-indoor path and pedestrian scenario is used to model the channel from macro BS to indoor users and the channel from Femto-APs to outdoor users. The channel from Femto-APs to users in different buildings is modeled by the outdoor-to-indoor and pedestrian scenario plus an additional penetration loss from a wall.

Two different macrocell settings are used in our simulation. The first one is the large cell scenario, where the macrocell radius is 1500 m and the macro BS transmission power is 46 dBm. The other one is the small cell scenario, where the macrocell radius is 500 m and the macro-BS transmission power is 36 dBm. In both cases, the macro BS antenna has a 15 dB gain with antenna height of 30 m. The main difference in the above two scenarios is that when there are no Femto-APs deployed, indoor coverage for the large cell can be further improved by increasing macro-BS transmission power, while in the small cell performance improvement is limited due to interference among macro BSs. Figure 4 shows coverage holes for indoor users in a large cell scenario (left), while small cell users receive enough power from a macro BS to penetrate buildings (right). Shadow fading is not simulated here for clarity.

We also consider different Femto-AP deployment densities to evaluate the effect of co-channel interference. There are about 10 Femto-APs per sector for the sparse deployment and about 100 Femto-APs per sector for the dense deployment. Lastly, both public and private Femto-AP usages are tested. When publicly accessible Femto-APs are deployed, the user selects the macro BS or Femto-AP that provides maximum received signal power as its home cell. For the private usage case, a user can access a Femto-AP only when they are in the same house. Thus, indoor users can choose between macro BSs and the private Femto-AP in their house, while outdoor users only select from macro BSs.

Simulation results are summarized in Tables 1 and 2. Table 1 shows that nearly 100 percent coverage is obtained for indoor users, but this coverage improvement decreases as more
Femto-APs are deployed. Femto-to-Femto interference becomes an issue for indoor coverage when private Femto-APs are densely deployed. In fact, in the case of dense Femto-AP deployments, increasing co-channel interference reduces outdoor coverage as well. This effect is more serious for privately accessible Femto-APs since outdoor users close to houses cannot be covered by private Femto-APs. In large-cell sparse deployments, the effect of co-channel interference from Femto-APs is not noticeable since Femto-APs are distant from each other. Hence, indoor coverage is greatly improved for both public and private scenarios. The coverage performance is also not satisfactory when the Femto-AP transmission power is too high. In order to achieve better coverage, further interference mitigation techniques, such as advanced power control, fractional time or frequency reuse, or multi-antenna techniques, should be considered.

Table 2 shows that high areal capacity gain can be achieved with femtocells (up to 300 times in dense deployments). The areal capacity gain comes from two aspects. The first one is that Femto-APs reuse the same bandwidth as the macro-BSs, so the available bandwidth per unit area increases. The other reason for higher spectrum efficiency is that most users associated with Femto-APs experience little signal attenuation, which results in high SINR and correspondingly high SE for these users. The spatial reuse gain is proportional to the number of Femto-APs per sector, which is about 10 times for sparse deployments and about 100 times for dense deployments. The SE gain varies with the density of Femto-APs. When the density of Femto-APs increases, the co-channel interference from neighboring Femto-APs gets stronger and reduces the supportable SE for each user. The SE gain is highest in the large cell sparse deployment, and lowest in small cell dense deployment.

Finally, we note that when private Femto-AP deployments get denser, there is a trade-off between areal capacity gain and coverage. Higher Femto-AP transmission power results in higher received signal strength and higher SE for indoor users, but causes more co-channel interference to neighboring Femto-APs. Hence, increasing Femto-AP transmit power increases areal capacity gain, but lowers coverage.

### TECHNICAL CHALLENGES

Developing a new technology is always a challenging task. In order for femtocells to be successful and provide significant capacity and coverage gains, several technical issues need to be addressed. In this section we discuss the technical challenges for femtocell deployments and possible solutions.

### NETWORK ARCHITECTURE

It is important to decide what kind of network structure should be adopted by femtocells. Traditional 2G/3G networks utilize centralized devices, RNCs, to control their associated base stations. Typically, there is an RNC in charge of radio resource management of about 100 BSs. Once Femto-APs are overlaid on the existing network, the number of devices an RNC needs to control will increase on the order of hundreds to thousands or tens of thousands. Current network control entities may not be scalable to handle so many devices. For WiMAX networks, scalability is less of an issue because of the flat all-IP network architecture. In such a distributed control structure, more radio resource management needs to be implemented at Femto-APs. Therefore, WiMAX Femto-APs need to be more autonomous and powerful. In addition, the large neighbor (cells) list that needs to be kept at a BS for timely handover can become difficult to manage. The network architecture also needs to consider infrastructure support for seamless
mobility during handover. Management protocols used in DSL systems, like TR-069 customer premises equipment (CPE) WAN Management Protocol can be adopted for efficient management of a large-scale femtocell network.

**INTERFERENCE MANAGEMENT**

In a hierarchical overlay network, where WiMAX Femto-APs operate on the same frequency band as macro BSs, co-channel interference becomes an important factor that limits overall network performance. When Femto-APs are installed indoors, however, walls help to alleviate the interference between macro BSs and Femto-APs. As the number of Femto-APs increase, the accumulated interference becomes a serious issue. At a minimum, power control is required in Femto-APs to avoid performance degradation to mobile terminals served by macro/micro BSs. To guarantee close to 100 percent coverage, further interference mitigation strategies such as fractional frequency reuse (FFR) could be applied. In order to apply these more advanced interference mitigation strategies, good synchronization is essential, as well as efficient means of exchanging messages between macro BSs and Femto-APs.

**SYNCHRONIZATION**

Synchronization is required in order to have successful handover between base stations. Furthermore, synchronization is essential for interference management in outdoor systems using time-division duplex (TDD) such as the 2.5 GHz systems planned for the initial release of mobile WiMAX. In today’s 2G/3G BSs, there are high-accuracy oscillators that are calibrated periodically by the timing signal sent from central controller over very reliable links (T1 lines). This solution is not applicable to the all-IP architecture of WiMAX networks. The synchronization requirement for WiMAX is less stringent than for 2G or 3G technology. The frequency accuracy suggested by the WiMAX Forum [3] is less than 2 parts per million (ppm), whereas 0.05 ppm is required in Global System for Mobile Communications (GSM)/wideband code-division multiple access (WCDMA)/CDMA 2000 systems. Synchronization in time to about 1 µs may also be required for TDD operation. Candidate calibration strategies include GPS and IEEE 1588. GPS is more accurate, and provides both time and location data. Localization may be a mandatory feature if operators want to avoid customers moving Femto-APs outside of their houses. However, GPS is more expensive and relies on GPS system availability. For indoor femtocells, GPS is not suitable since it requires line-of-sight from the satellite, which is difficult to achieve indoors. IEEE 1588, Precision Timing Protocol (PTP), is a more suitable solution for Femto-APs. It uses a master-slave structure. There is a master clock in the network providing timing reference to the slave clocks at Femto-APs. The timing signal is transmitted over IP/Ethernet backhaul. IEEE 1588 is a low-cost standalone solution that achieves submicrosecond accuracy. Field trial results in [4] show that under certain conditions, IEEE 1588 can achieve satisfactory frequency accuracy over networks. Application of IEEE 1588 to TDD WiMAX, which requires both time and frequency synchronization, is yet to be demonstrated.

**SECURITY AND PERFORMANCE**

In traditional cellular systems BSs are connected directly to the operator’s network. With the registration and authentication process, the cellular operator can thus easily prevent unauthorized users accessing its own network to ensure security. However, Femto-APs utilize local ISP networks, which may be different from the operators’ network and are much more difficult to protect. The public IP network can be accessed by almost everyone, including hackers who attempt to eavesdrop on conversations or control the Femto-AP. Therefore, in addition to a more sophisticated registration and authentication process, encryption of IP packets is necessary. Another issue with the IP network is that a cellular operator has no control over the channel and cannot prioritize voice packets from Femto-APs. To ensure system and user performance, collaboration and service level agreements between cellular and landline operators are required. For example, with higher priority given to voice packets from Femto-APs, end-to-end quality of service can be guaranteed.

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**Table 2. Areal capacity gain in different simulation scenarios.**

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<thead>
<tr>
<th></th>
<th>Large cell scenario</th>
<th>Small cell scenario</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Sparse deployment</td>
<td>Dense deployment</td>
</tr>
<tr>
<td></td>
<td>Public</td>
<td>Private</td>
</tr>
<tr>
<td>FS transmit power</td>
<td>0 dBm</td>
<td>54.479</td>
</tr>
<tr>
<td></td>
<td>10 dBm</td>
<td>57.764</td>
</tr>
<tr>
<td></td>
<td>20 dBm</td>
<td>57.4989</td>
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<tr>
<td>System capacity without Femto-AP</td>
<td>25.921 Mb/s</td>
<td>27.377 Mb/s</td>
</tr>
</tbody>
</table>

* Areal capacity gain = (system capacity with Femto-APs deployed)/(system capacity without Femto-APs)
**Self-Organization and Autonomous Operation**

WiMAX networks require a higher level of self-organization at both macro/micro BSs and Femto-APs because of the flat network architecture. For example, handover and radio resource management (RRM) are directly controlled by the BSs and Femto-APs. Cooperation is required among BSs and Femto-APs for successful handover and RRM information exchange. The communication between BSs/Femto-APs can be over the landline or even over the air. Latency can be an issue when sending control signals over the IP network. Faster communication can be carried out using the wireless medium, but the actual procedures remain to be standardized. Besides the self-organization functions shared with macro/micro BSs, a Femto-AP requires even higher autonomy since it should be a plug-and-play device that can integrate itself into the mobile network without user intervention. A configuration function in the device should be capable of adjusting parameters under various environments since the locations of Femto-APs cannot be planned in advanced, as for macro/micro BSs. Also, the large number of Femto-APs deployed within the network makes manual maintenance virtually impossible. The possibility of updating firmware and software of the Femto-APs could be an important requirement.

**Industrial Activities**

As a relatively new technology, femtocell has drawn lots of attention from the wireless industry. A new organization, Femto Forum ([5]), was launched in July 2007 to promote femtocell deployments worldwide. More than 60 companies have joined this not-for-profit organization, including mobile operators, telecom hardware and software vendors, content providers, and startups. Recently, Femto Forum has formed a partnership with the Next Generation Mobile Network (NGMN) Alliance. Their goal is to ensure that NGMNs can incorporate femtocells from the very beginning of their deployment. Unlike 2G/3G where femtocells are overlaid on top of existing cellular networks, NGMNs can evaluate the cost/performance ratios and carefully optimize the network by simultaneously deploying Femto-APs and macro/micro BSs.

Within WiMAX Forum, the Service Providers Working Group (SPWG) has started to draft system requirements for femtocells from the perspective of network operators. The goal is to specify possible business and usage scenarios, deployment models, functional requirements, and performance guidelines for the end-to-end system. Furthermore, there are several standard activities in this area, including in the Third Generation Partnership Project (3GPP) [6, 7] and IEEE 802.16m, which is the advanced interface task group for WiMAX. In 802.16m a new annex to the requirement has been added to efficiently support “very high data rates in smaller cells” [8].

Major WiMAX service providers such as Sprint-Nextel and KT are preparing for the introduction of Femto-APs into their networks. This action has accelerated the development efforts of many global manufacturers. A Femto-AP is expected to be a fixed-mobile substitution (FMS) solution for wireless carriers who can utilize it as a wireless DSL solution. Also, Femto-APs will provide new business opportunities for wireline carriers to enter the mobile virtual network operator (MVNO)-based wireless markets by fully utilizing their own broadband wireline access infrastructures.

**Conclusions**

The blossoming industrial activities arise from the potentially high gains in coverage and capacity expected from femtocell deployments, as well as the large number of deployments anticipated. A research report by ABI forecasts that by 2012 there will be 36 million shipments with an installed base of nearly 70 million femtocells serving over 150 million users [9]. Unsatisfactory coverage and the increasing number of high-data-rate applications are two of the driving forces of many global manufacturers. A Femto-AP is expected to be a fixed-mobile substitution (FMS) solution for wireless carriers who can utilize it as a wireless DSL solution. Also, Femto-APs will provide new business opportunities for wireline carriers to enter the mobile virtual network operator (MVNO)-based wireless markets by fully utilizing their own broadband wireline access infrastructures.

**References**


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