High-Capacity Indoor Wireless Solutions: Picocell or Femtocell?

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Picocells and femtocells are small cells belonging to the family of Low-Power Nodes (LPNs). Depending on the environment, the quality and type of communication service, one may be a better candidate than the other. This paper gives an overview of high-capacity wireless deployment considerations and concludes that the femtocell is generally a better candidate for high-capacity in-building solutions, while the picocell is a better candidate for serving outdoor hotspots.

Introduction

Wireless cells can be categorized as macrocells, microcells, picocells and femtocells, with decreasing cell radii and decreasing Tx power levels. The femtocell is the smallest, and the picocell is the second-smallest. Table 1 shows typical cell radii and Tx power levels for each cell type.

Cell Type	Typical Cell Radius	PA Power: Range & (Typical Value)
Macro	>1 km	20 W~ 160 W (40 W)
Micro	250 m ~ 1 km	2 W ~ 20 W (5 W)
Pico	100 m ~ 300 m	250 mW ~ >2 W
Femto	10 m ~ 50 m	10 mW~200 mW

Table 1: Different cell radii and Tx power levels

Note that the effective antenna height can significantly affect the achieved cell radius in addition to the Tx power level. An antenna installed in a location with higher or lower altitude will have more or less favorable RF propagation conditions, which will influence the size of the coverage footprint (cell radius).

One example is the so-called "boomer cell" (a.k.a. "super cell") for rural areas. A boomer cell is needed when the user densities in some areas are extremely low (e.g. a large area of desert), but cellular service must nevertheless be provided. In this case, the cell footprint must be as large as possible to minimize the total cell count. To achieve this, the antennas are installed on very high towers on top of very tall mountains; the cell radii of these boomer cells can be as large as 250 km.

The situation for in-building deployments is often at the opposite extreme. Generally, buildings are three-dimensional hot spots, particularly in the case of data traffic. Research studies have forecast exponential growth in data traffic, as shown in Figure 1, and these studies estimate that approximately 80% of data traffic will come from indoor locations [1]. Some types of buildings (e.g. football stadiums) are extreme forms of hotspots; it is very challenging to provide sufficient indoor capacity for the in-building wireless data users in such situations. In this case, the cell radii need to be as small as possible [2].

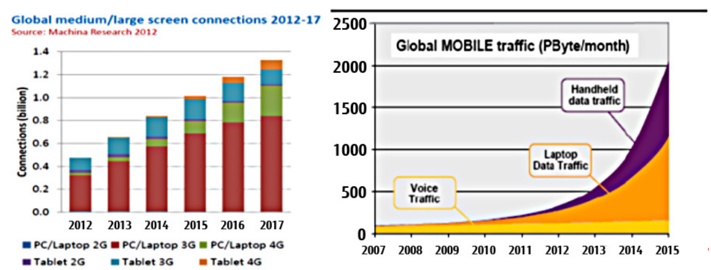

Figure 1: Market forecasts show exponential growth of data traffic, most of it from indoor users.

Smaller Cells for Higher Capacity

There are two very different in-building service objectives.

- Maximize the in-building coverage: to achieve this goal, the footprint from each indoor cell should be as large as possible in order to minimize the total indoor cell count.
- Maximize the in-building capacity: to achieve this goal, the footprint from each indoor cell should be as small as possible in order to maximize the total indoor cell count, which results in maximum capacity.

Obviously, for serving hotspots the main goal is to maximize the in-building capacity so one must minimize the footprint of each indoor cell.

Data capacity from a cell is defined as the aggregate cell throughput per cell. With identical conditions (e.g. same channel bandwidth), the aggregate throughput from a cell is the same regardless of the size. Therefore, regardless of whether it is a macrocell, microcell, picocell, or femtocell, the aggregate cell throughput from each cell remains the same[A]. It also means that total capacity is inversely proportional to the square of the cell radii, i.e. if the cell radii are halved, the total capacity is quardrupled (Figure 2).

A – Actually, the cell capacity is a function of several other variables such as user distribution, fading characteristic, UE moving speed, and so on. Users in femtocells are usually low mobility and located closer to the cell center with less fading, so the aggregate cell throughput from a small cell is actually higher than that from a macrocell. Thus, by splitting one large cell into multiple small cells, the actual achieved capacity gain is even higher than the "square law" illustrated in Figure 2.

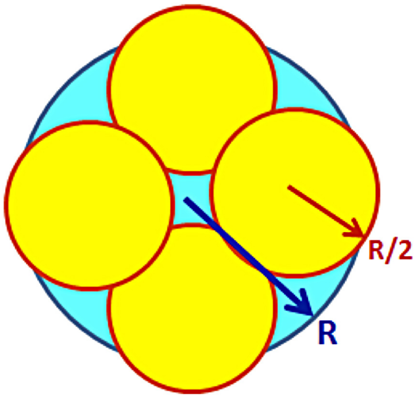

Figure 2: Halving the cell radii will quadruple the total capacity.

The total capacity from the building can be increased significantly by using a large number of femtocells with very small footprints. The cell radii of femtocells are about 10%–30% of those of picocells. Therefore, by using a large number of femtocells, the total indoor capacity can be increased by a factor of 10–100 compared to the case of using a few picocells. An example of a large number of femtocells serving a football stadium is shown in Figure 3.

Because the femtocell is designed to be the smallest cell, obviously this is a better candidate for providing maximum indoor capacity.

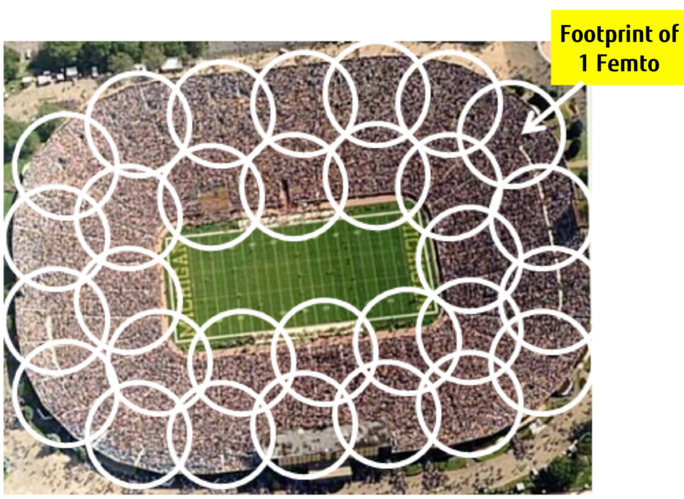

Figure 3: With small footprints, a much larger number of femtocells can be used to cover the stadium

Why the Picocell is not the Best Candidate for a High-Capacity Indoor Solution

To understand why the picocell is not the best candidate for a high-capacity indoor solution, it is necessary to consider the purpose for which they are designed. The picocell has higher PA power and larger cell radius, which makes it a more appropriate candidate for applications that demand larger coverage footprints (> 100 meters). Examples are dense "urban canyons" (Figure 4), outdoor theme parks, and so on. These areas need high capacity, but a high percentage of traffic is voice (which requires each cell to connect a higher number of active users). Also UE may be moving at driving speed, so larger cell radii and faster handover are needed.

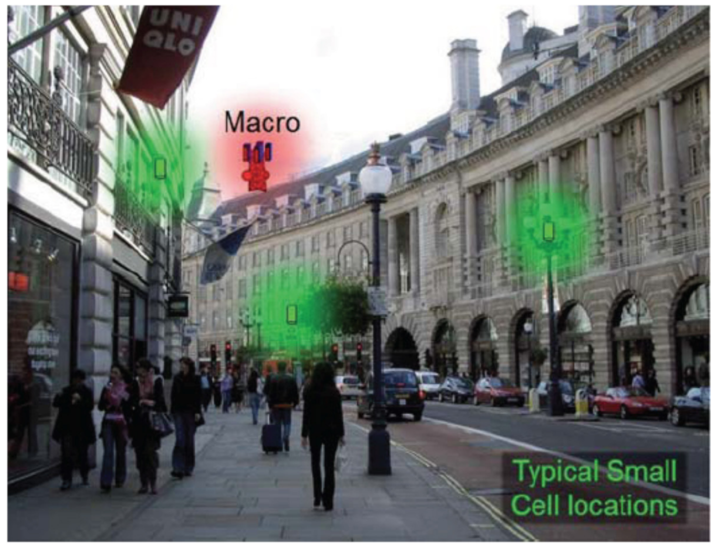

Figure 4: Picocells serving "urban canyons"

Picocells generally have higher PA power, higher processing power and can connect a higher number of simultaneous active users, in addition to faster handover capability. They are typically more expensive than femtocells, but also the better candidate for serving outdoor hotspots.

Indoor Coverage Solutions

Indoor services do not need to handle UE that is moving at high speed. Within the small footprint of a femtocell, the number of simultaneous connections does not need to be as large as in an outdoor situation. The combined factors of lower PA power and lower processing power make the cost of a femto-eNodeB (HeNB) much lower, but also make femtocells more suitable for high-capacity indoor applications.

Although most buildings do need high capacity, especially data capacity, let us first consider coverage. Using a small number of picocells with higher PA power can cover the entire building. But, when comparing the following coverage options:

(a) Small number of picocells with higher power

(b) Larger number of femtocells with lower power

Option (b) will provide much more uniform coverage in a highly cluttered indoor environment, as shown in Figure 5.

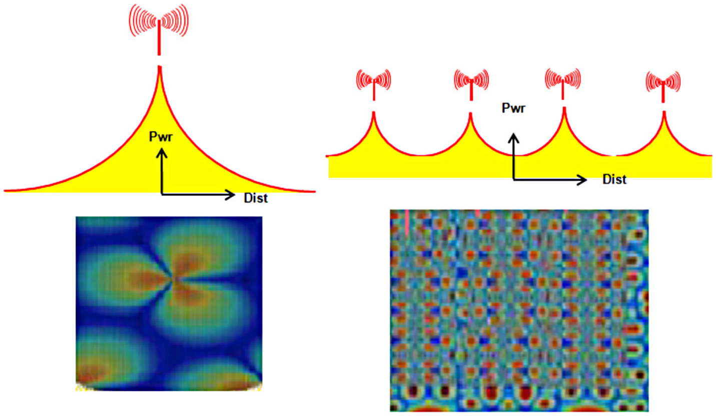

Figure 5: Comparison of coverage provided by one high-power source (left) versus coverage provided by many low-power sources (right)

Unless the indoor environment is an "open hall" type (i.e. one large open space without obstacles), most in-building environments will have many man-made objects that act as obstacles to radio propagation; therefore one must consider the so-called "shadowing effect." A large number of low-power femtocells provides much better "macroscopic diversity" (i.e. each location will likely receive signals from multiple cells arriving from different directions), which is very effective in combatting the shadowing effect (Figure 6).

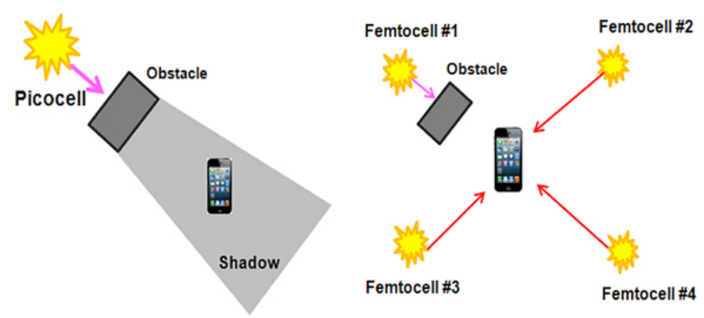

Figure 6: (Left) Single picocell: a single obstacle will cause a coverage shadow. (Right) Multiple femtocells: no shadow is caused unless all femtocells are obstructed

Figure 7 shows the simulation result of an indoor coverage situation provided by a single cell in a highly cluttered indoor environment. The coverage would be much better (more uniform) if the area can be served by multiple cells.

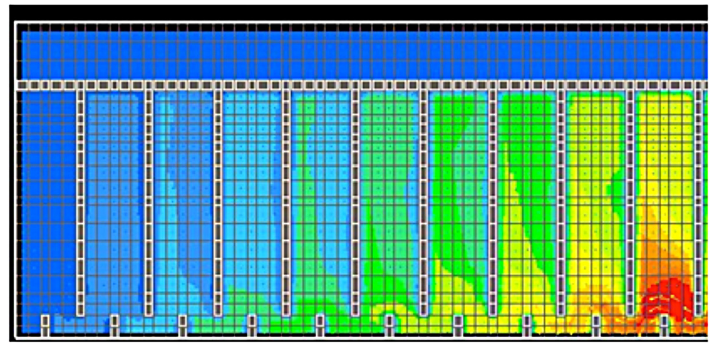

Fig. 7 Severe shadowing effect observed in a complicated indoor environment where coverage is provided by just one single cell

Out-of-Cell Interference

If a single high-power source does not provide sufficient capacity and cannot combat the shadowing effect, could multiple high-power sources provide a solution? In other words:

- For indoor deployment, can one simply install a large number of picocell eNodeBs into the indoor area and reduce the inter-cell distance, so the picocells effectively act like femtocells?
- A similar question applies for outdoor deployment: can one simply install a large number of macrocell eNBs and reduce the inter-cell distance, so these macrocells can act like microcells?

In the early days of wireless communication, when a very limited base station product portfolio was available (limited to the choice of a macro base station and a pico base station), many networks were indeed deployed this way. However, there are several undesirable effects if high-power base stations are deployed too close to each other.

There used to be a misconception that putting neighboring base stations very close to each other would cause no harm. This was thought to be the case because both the in-cell signal level (S) and the out-of-cell interference level (I) will increase together, and as a result, the signal-to-interference ratio (S/I) will not change. This is not true. A simple thoeretical calculation is given below to show that putting neighboring (large cell) base stations too close to each other is highly undesirable.

Using a flat-earth model, the radio propagation approximately follows a two-slope model (Figure 8) with a "break point" at:

Equation 1: $$B \approx \frac{4hH}{\lambda}$$

where H and h are the antenna heights for the base station and UE, λ is the RF wavelength.

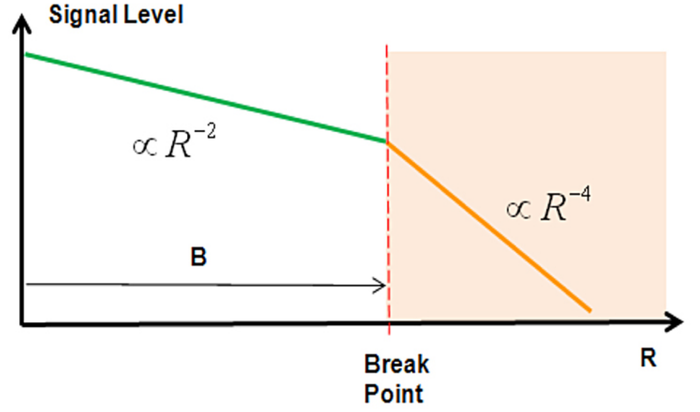

Figure 8: Two-slope RF propagation model

One can see that the signal power attenuates more slowly (with a shallower path-loss slope) before reaching the break point (B); after the break point, the power attenuates faster (with a steeper path loss slope). Therefore, it is desirable for the inter-cell distance (D) to be slightly more than twice the value of B, i.e. $D > 2*B$ (Figure 9), so that the in-cell signal level will have a slower attenuation ($\propto R^{-2}$) but out-of-cell interference will have a faster attenuation ($\propto R^{-4}$). Since B is a function of the base station antenna height H, for a certain antenna height H, only properly spaced base stations can maximize the S/I.

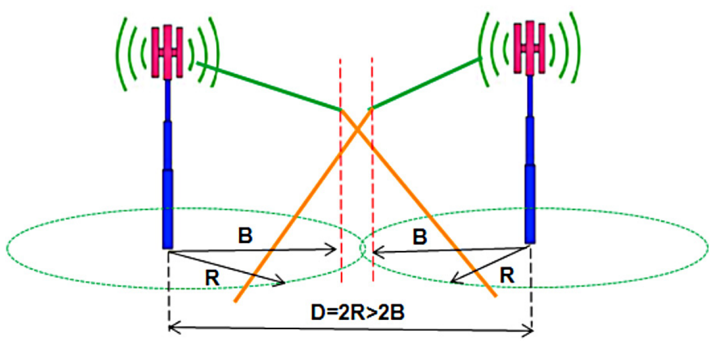

Figure 9: Properly spaced base station distance will maximize the signal and minimize out-of-cell interference.

If the neighboring base stations are installed too close to each other so that the inter-cell distance $D < 2B$, then the out-of-cell interference will not attenuate fast enough, thus the overall S/I degrades, as shown in Figure 10.

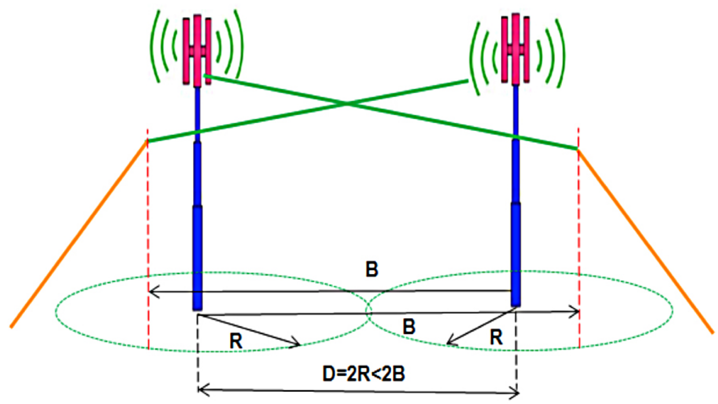

Figure 10: Inter-cell distance too small, undesirable.

Since an outdoor cellular system is two-dimensional, to calculate the total out-of-cell interference, one has to use a two-dimensional model (Figure 11).

Total out-of-cell interference = Sum of {

Interference contributed from the first-tier neighbors +

Interference contributed from the second-tier neighbors +

+ …..+

Interference contributed from the k-th tier neighbors}

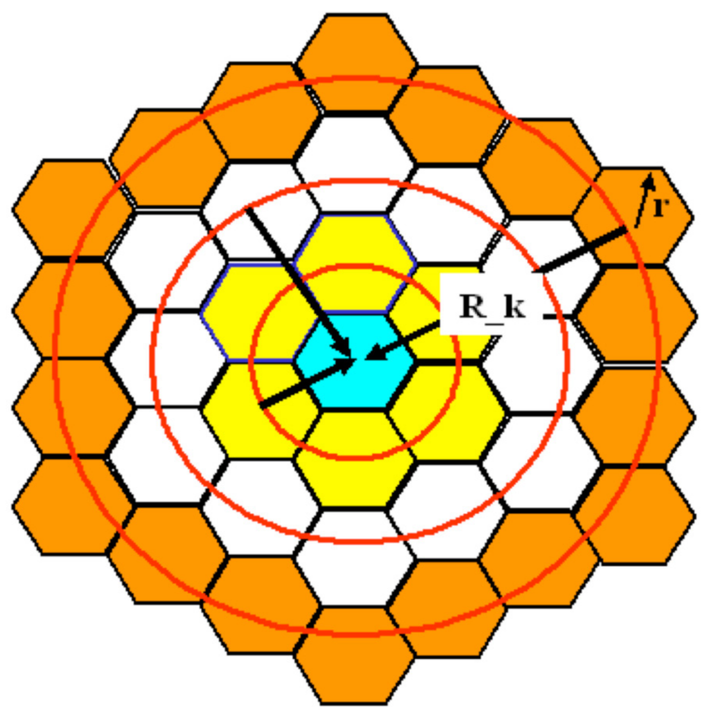

Figure 11: Total out-of-cell interference to one cell (blue) is the sum of interference contributed from all neighbors

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Note that, as each tier of neighbors is physically located farther away, it also contains more cells, i.e. a higher number of interferers. For example, the first tier of neighbors contains six cells (colored yellow in Figure 11); the second tier of neighbors contains 12 cells (colored white); the third tier of neighbors contains 18 cells (colored orange), and so on. The average distance from the center cell (blue color) to the k-th tier neighbor is R_k, the number of cells in the k-th tier is proportional to the circumference of the k-th tier (2* π*R_k).

The total out-of-cell interference can be expressed mathematically as:

Equation 2: $$I_{total} = \sum_{k=1} I_k = \sum_{k=1} \frac{O(2*\pi*R_k)}{O(R_k^{\ \alpha})}_k$$

Where I_k is the total out-of-cell interference contributed from the k-th tier neighbor cells and α is the propagation path-loss slope exponent.

One can see that if α =4, then $I_k \rightarrow O\left(\frac{1}{R_k^{\ 3}}\right)$ and the series [2] converges very quickly. This means that if the propagation path loss slope is steep, the interference contributed from neighbor cells that are located far away will attenuate very fast and is negligible; so one only needs to worry about neighbor cells that are located physically nearby.

However, if α =2, then $I_k \rightarrow O\left(\frac{1}{R_k}\right)$ and the series [2] diverges.

This means that if the propagation path loss slope is too shallow, the interference contributed from neighbor cells that are located far away will be significant; every time a new tier of neighbor cells is added, the total interference goes up and the total out-of-cell interference is not bounded. This will have a very negative impact on *S/I*.

Traditional outdoor cellular networks are two-dimensional, but buildings are three-dimensional objects. Thus, for in-building deployment, one needs to look at a three-dimensional picture. Generally, the interference situation in a three-dimensional environment is even worse than that in a two-dimensional environment. Only if the floor penetration loss were infinity would there be no interference from upper or lower floors and the environment would become two-dimensional so the interference could be expressed by Equation 2.

If the floor penetration loss is not infinity, each cell will receive interference not only from the same-floor neighbor cells, but also interference from neighbor cells on other floors, as shown in Figure 12.

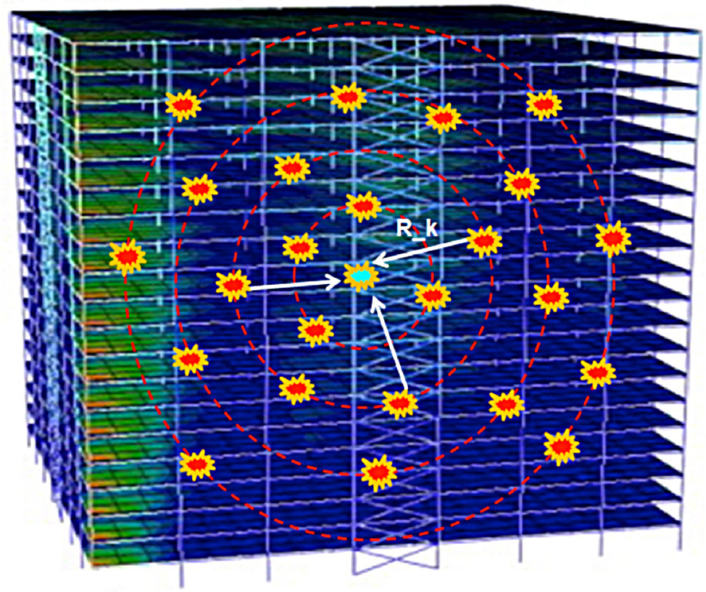
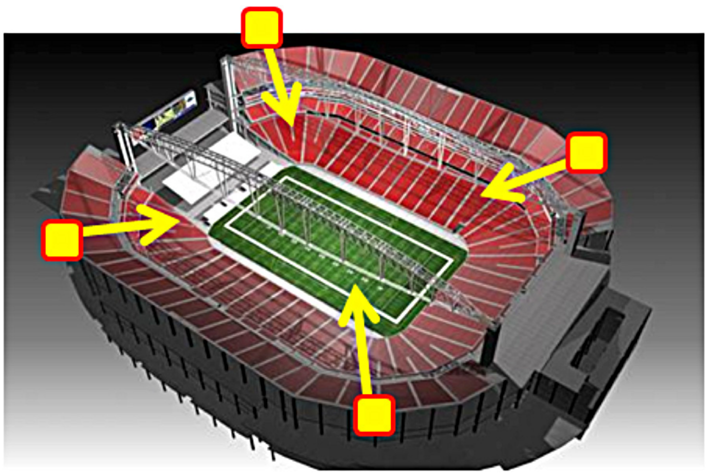


Figure 12: Each indoor cell will receive interference from neighbor cells on the same floor, as well as cells on other floors.

Therefore, for indoor deployments, it is even more important that the attenuation of out-of-cell interference is fast enough so that the total out-of-cell interference is contributed by only a few direct neighbors. It is not a good idea to install picocells (with higher power) too close to each other.

As an example, if picocells are used to provide indoor services to a stadium, due to the much larger cell radius, only a few picocells can be used, either installed on the ceiling or on the sidewalls, as shown in Figure 13.

(a) Ceiling deployment



(b) Sidewall deployment

Figure 13: If picocells are used to serve the stadium, only a small number can be used

However, if femtocells are used, due to the much smaller cell radius, a much larger number of femtocells can be used as illustrated in Figure 3. Femtocell antennas will be installed with much lower effective antenna heights (Figure 14). Obviously, the option of using femtocell results in much higher total indoor capacity.

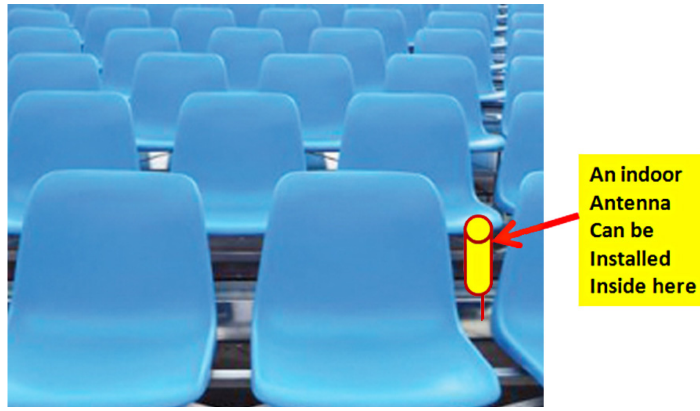


Fig. 14 Femtocell antennas can be installed very close to the ground level

If picocell base stations were used for femtocell deployment, one could reduce power by adding attenuators to the Tx and Rx paths, so that the transmitted power level is "padded down" and the receiver sensitivity is reduced. This is achievable, but it is a waste of money; it is more expensive to make a PA with higher power level as well as to make a receiver with better receiver sensitivity. Picocells are best used where larger coverage footprints are needed. Femtocells, which are designed to be the smallest cells, are best suited to these types of situations. An indoor deployment with a large number of picocells with attenuators will cost much more than with the same number of femtocells.

Indoor Deployment Summary

Generally, it is not desirable to make small cells by using large-cell base stations and put them very close to each other. If small cells are needed, small-cell base stations are the appropriate chioce, since this is what they are specifically designed for.

An indoor deployment using a large number of femtocells will result in much higher capacity and more uniform coverage, with less shadowing effect.

Operational Cost, Plug-and-Play

One of the strong arguments in favor of displacing picocells with femtocells for in-building deployment is the low operational cost, both in terms of ease of installation and low ongoing maintenance cost.

Picocells are not intended to be installed by the end user and require physical security and access for installation and maintenance by a carrier. This is a bit of a specialized niche for wireless. LTE picocells do also enjoy the SON benefits, so the cost for setting up a 4G picocell is lower than that of a 3G picocell. Picocell products are, however, clearly not 100% plug-and-play.

Femtocells, on the other hand, are designed with full plug-and-play features, including sniffing and auto-configuration. Service providers can put these units into service on the network and configure the necessary parameters automatically without any action from a technician. The installation steps are extremely simple, as shown in Figure 15. Replacing a femtocell is also very easy: simply unplug the old unit, return it to the factory and substitute a new, self-configuring unit.

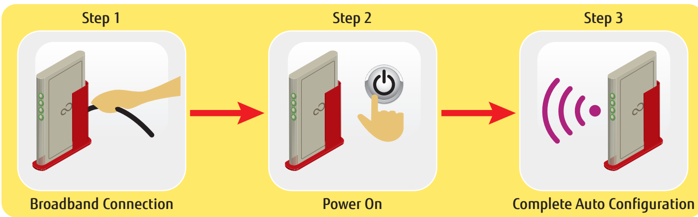


Figure 15: A simple three-step process to install a femtocell

Wi-Fi Offload via LIPA

Today, although Wi-Fi is installed in almost all enterprise buildings, cellular and Wi-Fi are still two different types of networks. Note that 3GPP does define internetworking between LTE and Wi-Fi[B] [3], however, if picocells are used for indoor coverage, it will be either cellular or Wi-Fi, not both at the same time. The problem is this: Wi-Fi does not offer QoS; cellular does offer QoS but is too expensive.

Release 9 introduced a new feature into the femtocell called Local IP Access (LIPA) [4], [5]. The schematic diagram of LIPA is shown in Figure 16. The beauty of this feature is that it can offload part of the traffic to Wi-Fi without impacting the end-user's QoS. LIPA actively monitors the current load level of Wi-Fi and determines which network will actually deliver the data to the UE.

- If Wi-Fi's load is light, most traffic will be delivered by Wi-Fi.
- If Wi-Fi's load is heavy, only best-effort traffic will be delivered by Wi-Fi; QoS-sensitive applications will be delivered by the LTE network.
- VoIP traffic will always be delivered by the LTE network.

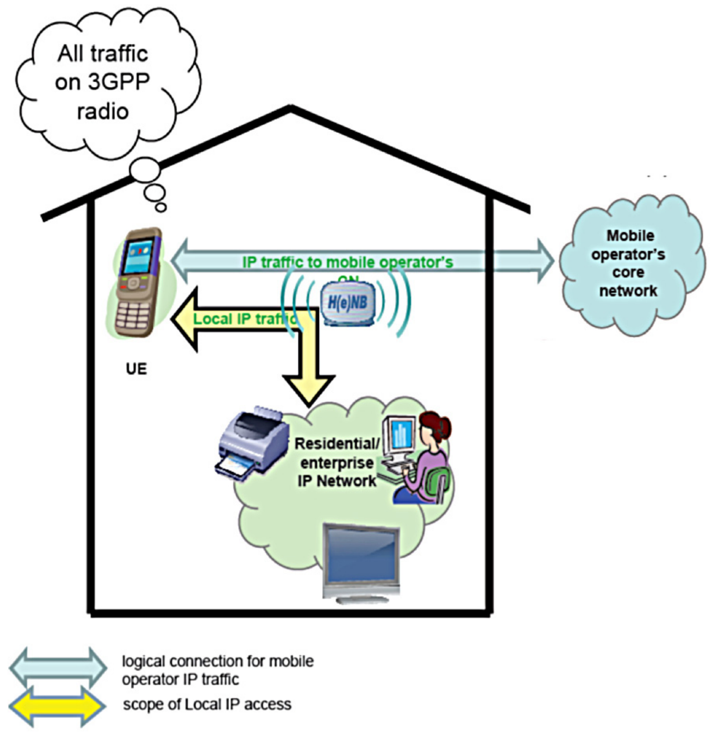


Figure 16: LIPA and Wi-Fi offload

The primary motivation for using LIPA is economics, i.e. reduce the unit cost of delivering a given amount of data. According to an industry analysis, the use of femtocells can lower the marginal cost per GB of data delivery by a factor of four compared to the cost of using the current macrocellular technology. When LIPA is used, the cost saving is even more significant; the estimated cost per GB for a macrocellular network is $4.80 compared with $0.07 for the femtocell + LIPA.

B – Wi-Fi is considered "un-trusted non-3GPP Access" in [3].

Note that picocell is a pure cellular solution; the femtocell with LIPA is a cellular + Wi-Fi solution. Figure 17 shows a comparison of data delivered via picocell (cellular network only) versus data delivered by femtocell + Wi-Fi (LIPA).

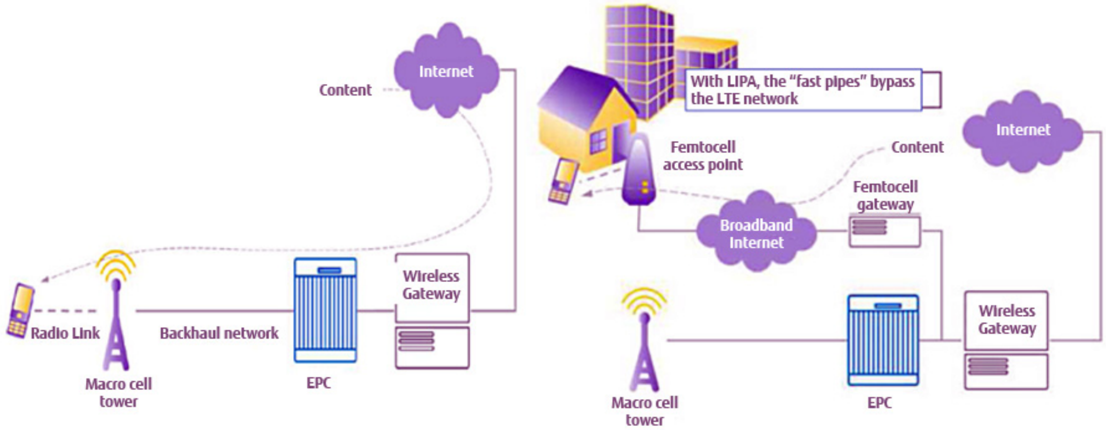


Figure 17: Comparison between picocell (cellular only) versus femtocell + Wi-Fi (LIPA)

LTE/Wi-Fi Switching Control

The Fujitsu femtocell product has a proprietary feature called LTE/Wi-Fi Switching Control. This feature is used to minimize the inter-layer interference in a co-channel HetNet deployment. If interference from the macro-layer is so severe that the coverage footprints of femtocells shrink too much, the femtocell will direct femtocell UEs to switch to Wi-Fi, as shown in Figure 18.

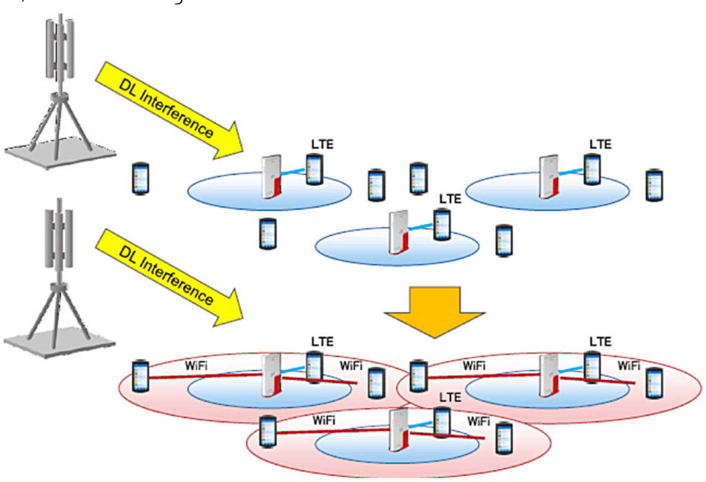


Figure 18: LTE/Wi-Fi Switching Control feature.

Femtocell Cell Boundary Control

Another Fujitsu proprietary femtocell feature is Cell Boundary Cotrol, which provides optimum coverage as a function of current users' locations. It is a centrally controlled intelligent algorithm that can adjust the Tx power levels of individual femtocells, to produce overall optimum coverage for the current user distribution, as shown in Figure 19.

In additional to this centrally controlled mechanism, each femtocell can also individually control its Tx power based on the currently measured interference level.

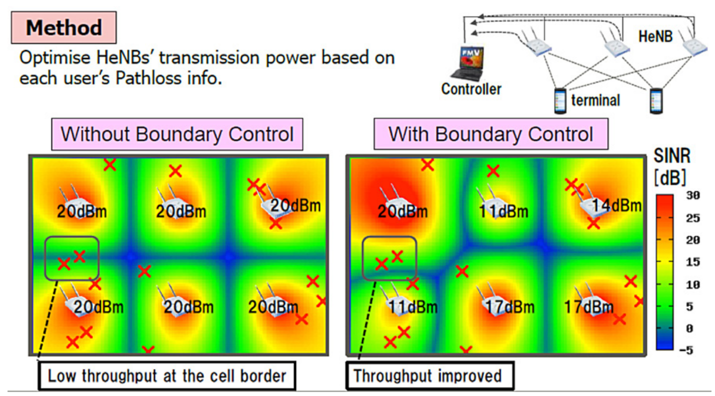


Figure 19: Footprints of femtocells are changed to provide optimum services based on current user locations

Comparing Backhaul Links

Small cells have slightly different backhaul requirements compared to macrocells [6], [7]. Options for picocell backhaul are similar to those of macrocell/microcell backhaul; the most common are optical links or microwaves. High-frequency microwaves (e.g. E-band) are very convenient for picocell deployment in dense "urban canyon" types of environment (Figure 4). Cable operators may also use coaxial cables for picocell backhaul.

Femtocell backhaul can be any type of broadband network meeting a certain minimum bandwidth and quality requirements. They can be DSL, cable, GPON, or EPON, for example. Performance targets for femtocell backhaul are somewhat relaxed.

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For enterprise deployment, femtocells can piggyback on the existing IP network infrastructure provided by the business IT department, who could use mechanisms to prioritize the traffic above mainstream data traffic to ensure high voice quality. Corporations would expect to benefit from lower-cost calls within their enterprise locations in return for installing and maintaining these systems, which would also be offset by not requiring fixed phones at the desk.

All of these factors make femtocells particularly attractive for in-building deployment.

Summary and Conclusions

Cell radii can vary from less than 10 m to more than 250 km. The larger the cell radius, the wider the coverage; the smaller the cell radius, the higher the capacity per unit area it can provide.

The cells can be categorized as macrocell, microcell, picocell and femtocell. Each type of cell is designed to best serve a certain type of environment. In other words, for each type of environment, there is one type of cell that is the best candidate for it.

Most buildings are three-dimensional hotspots. The user traffic, especially data traffic, generated from indoor areas is generally much higher than that generated from outdoor areas. Providing sufficient in-building capacity is always a challenge. Therefore, the logical choice will be using the smallest cell possible in order to achieve the highest in-building capacity, which means using femtocells.

Other factors, such as easy deployment and easy maintenance (plug-and-play), Wi-Fi offload (LIPA), and the convenience of broadband backhaul, also make femtocell more attractive than picocell for indoor deployment.

Additionally, the Fujitsu femtocell product offers a wide variety of proprietary features that can further enhance the user experiences. Examples are optimum coverage based on user locations, interference mitigation, and Wi-Fi offloading/interworking.

All of the above factors make the femtocell the best candidate for providing high-capacity in-building solutions.

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Acronyms

eNB	Evolved Node B (LTE base station)
HeNB	Home eNB (LTE femtocell)
LIPA	Local IP Access
LPN	Low Power Node
PA	Power Amplifier
QoS	Quality of Service
Rx	Receive
SON	Self-Organizing Network
Tx	Transmit
UE	User Equipment

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