

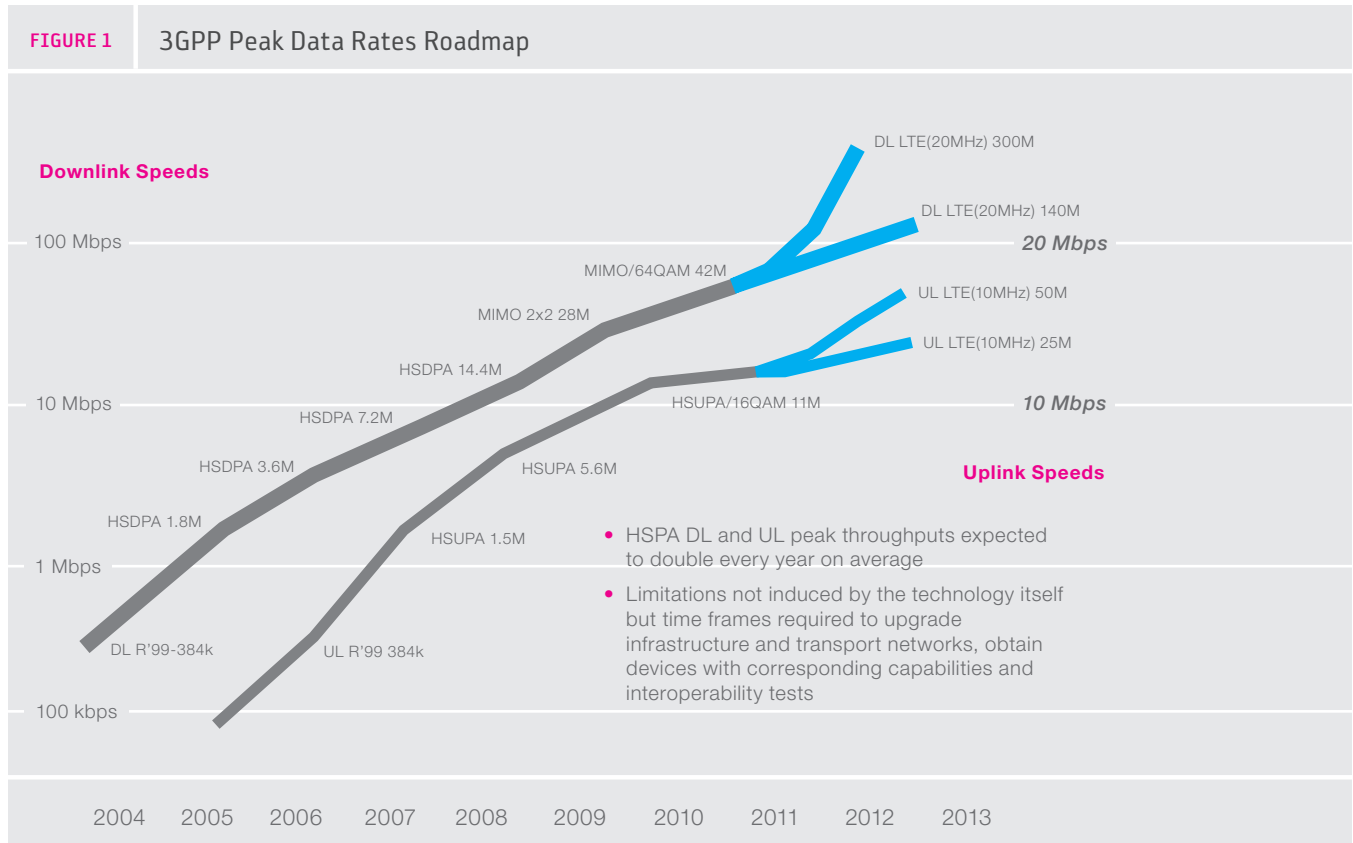
# Fuzzy Cells

Improving cell-edge performance  
in multi-carrier cellular systems

- Cellular systems evolution is making great strides in offering higher data rates, but there is a growing gap between peak and average rates
- Interference limits uniform performance and capacity across the cell and at cell-edge
- Fuzzy Cells technology improves cell-edge performance with higher throughput and better coverage
- With Fuzzy Cells, service providers can drastically improve user experience across the entire network

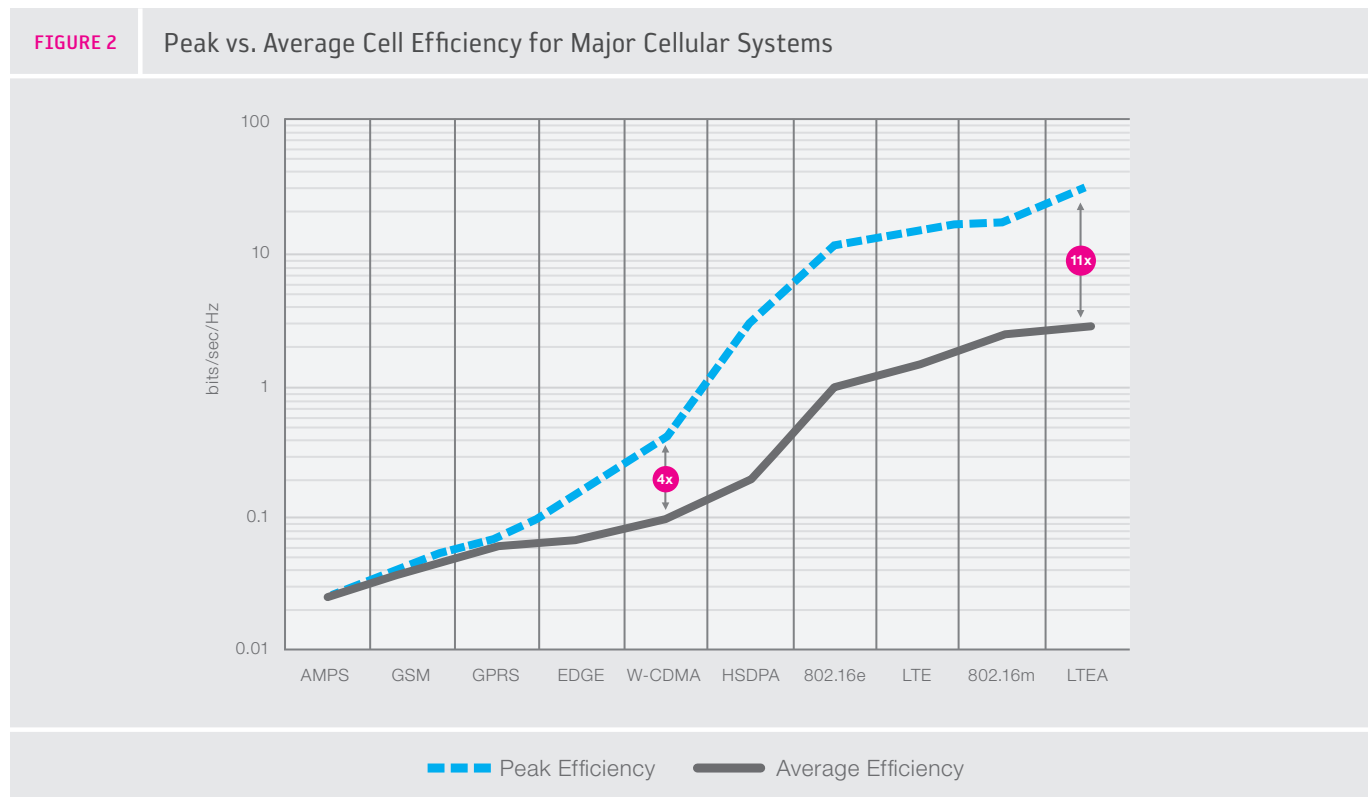
## Introduction

Over the past ten years, improvements in cellular technologies have been characterized by dramatic increases in peak data rates. Figure 1 illustrates substantial increases in theoretical peak data rates for 3GPP cellular systems - evolving from sub 1 Mbps to in excess of 100 Mbps. However, technology and standards have not placed enough emphasis on ensuring more uniform data rates and consistent user experience across the entire cell.



Source: 3G Americas' Member Company Contributions

When it comes to average data rates across an entire cell, there is a growing gap between the peak rates and average rates. This gap is more severe for users operating in poorer signal conditions or at the cell-edge. Figure 2 illustrates this gap by showing peak vs. average cell efficiency over time for the evolution of cellular systems. Based on the present understanding of the requirements for LTE-Advanced (LTE-A), this gap is projected to widen to an 11x difference when LTE-A is deployed.



Source: Agilent presentation + IMT submissions

It is imperative that service providers find solutions today for this growing spectral efficiency gap, which will become noticeably more severe over the next several years due to the expected explosive growth in demand for wireless data. In the 2010 National Broadband Plan wireless data demand will grow anywhere from 20x to 45x by 2014. This growth will be driven by the rapid shift from voice to data traffic, resulting from the increasing popularity of smartphones, netbooks and mobile consumer electronics (CE) devices. Wireless users will expect the same high degree of Quality of Experience (QoE) for data services as they currently demand for voice service, which will be a key differentiator among service providers. As with dropped voice calls and garbled voice reception, slow internet access, poor video streaming experiences and interruptions in real time data services due to poor cell throughput will also be motivators for churn. In order to overcome QoE challenges, caused by poor cell-edge performance, the traditional solution has been to reduce the size of existing cells through CAPEX/OPEX intensive cell-splitting. In addition to the costs of adding physical cell sites, scarce and valuable spectrum resources are consumed as well, and networks may require some re-planning to accommodate the new cells.

Regardless of the technology used, service providers will be faced with the challenge of providing exceptional user experience for data services, just as they have had to do for voice services, in order to maintain and grow their data user subscriber base and service revenues. Those who adequately address these challenges early-on, can use their higher levels of network quality as a competitive differentiator. Today, wireless technology leaders use a more holistic approach to wireless network optimization by developing new technologies that consider the Radio Access Network (RAN), Packet Core and Circuit Switched Core Networks (CNs) together in contrast to the traditional focus on only optimizing each subsystem individually. Wireless network operators will need to take advantage of these new developments in network technologies to find cost effective ways to meet the ever increasing demand for capacity and higher levels of QoE across the entire cell area while ensuring a high level of customer satisfaction.

## Roadmap of Solutions for Cell-Edge Performance Gains

InterDigital has consistently been one of the key contributors to the 3GPP and IEEE wireless standards bodies in pushing higher peak data rates. In addition, the company has an advanced roadmap of next generation cellular technologies, as shown in Figure 3, that are expected to greatly improve cell edge throughput in order to address user experience across the entire cell.

Many aspects of this roadmap will form the foundation for InterDigital's contributions to the 3GPP standard releases 11 and 12, and relevant future releases. Some of these advanced technologies may not end up in a standard, and therefore present an excellent opportunity for infrastructure OEMs and operators to create a competitive advantage with proprietary solutions that deliver superior and differentiated network performance.

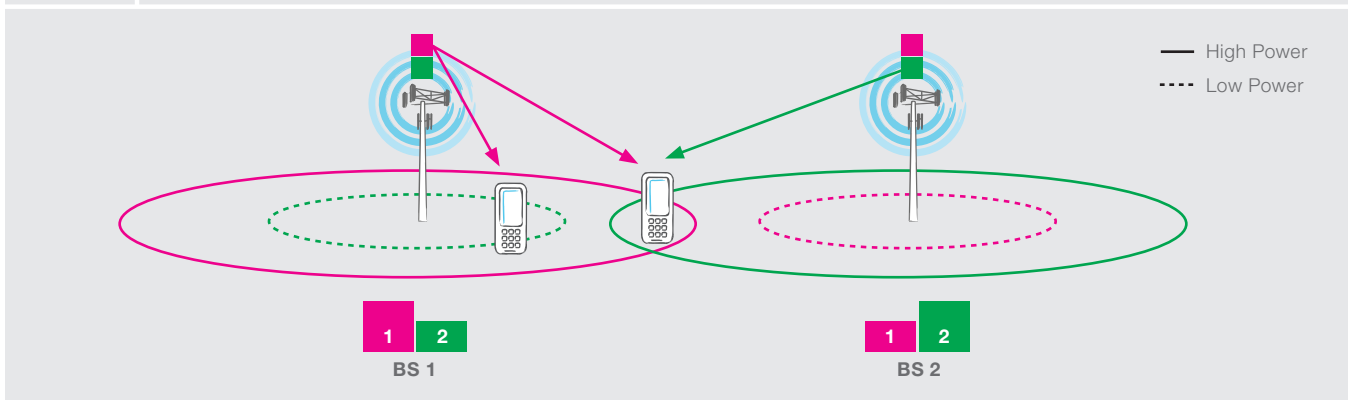
**FIGURE 3** InterDigital's Roadmap of Next Generation Cellular Technologies

	Short Term (0-5 Years)	Mid Term (5-10 Years)	Long Term (>10 Years)
<b>Spectral Efficiency Solutions</b>			
Fuzzy Cells	✓		
Coordinated MultiPoint (E-CoMP)	✓		
<b>Spectrum Opportunities</b>			
Unlicensed/Lightly Licensed Spectrum			✓
High Frequency Solutions			✓
<b>Advanced Topologies</b>			
Enhanced Relays		✓	
Cellular-Controlled Direct Mobile-to-Mobile Communications			✓

## Fuzzy Cells - Enhancing User Experience at Cell-Edge

In current and evolving cellular systems, such as Long Term Evolution (LTE) and Multi-Carrier High Speed Packet Access (MC-HSPA), the user experience at cell-edge is limited by interference from other cells. In the standard frequency reuse-1 case, the cell-edge downlink (DL) Signal-to-Interference-plus-Noise-Ratio (SINR) can be several dB below zero, limiting such users' throughput. In LTE systems that comply with the 3GPP Release 8 standards version, the 3GPP specifications are effectively single carrier systems and can selectively use parts of the carrier spectrum for data transmissions, but not for control. The introduction of Carrier Aggregation in Release 10 of the 3GPP LTE Standards (also referred to as LTE-A) provides a means for a User Equipment (UE) or terminal to connect to multiple Component Carriers (CCs) at the same time. Each CC is similar to a Release 8 carrier that has its own control channel, pilots, scheduler, etc. It is important to clarify the terminology with respect to Component Carriers and Component Carrier Frequencies. For example, in the simplest cellular deployment case of a single sector per site deployment with a single frequency (i.e. a reuse-1, single sector deployment), each cell site represents transmission of one CC over one CC frequency. In a site with a single frequency and 3 sectors (with 1 antenna per sector), the site is serviced with 3 separate CC's, since each sector is separated from the other with its own pilots, control channel, scheduler, etc. When an additional CC frequency is added to the same site, each antenna supports the two frequencies for the sector it is communicating in, resulting in the formation of 6 CCs on 2 CC frequencies for the entire site. Extending this example to a 6-sector, 2 frequency site results in the formation of 12 Component Carriers within the site. Fuzzy Cells technology enables CCs to be transmitted at different power levels and in various directions. Using Fuzzy Cells technology, UEs can connect to CCs that originate from a variety of base stations; resulting in the overall improvement in cell-edge performance. This is illustrated in Figure 4 wherein the red frequency is transmitted at higher power from the site on the left and the green frequency is transmitted at a higher power at the site on the right. The UE in the center of the figure is enabled to receive data from both sites (green from right site and red from left site).

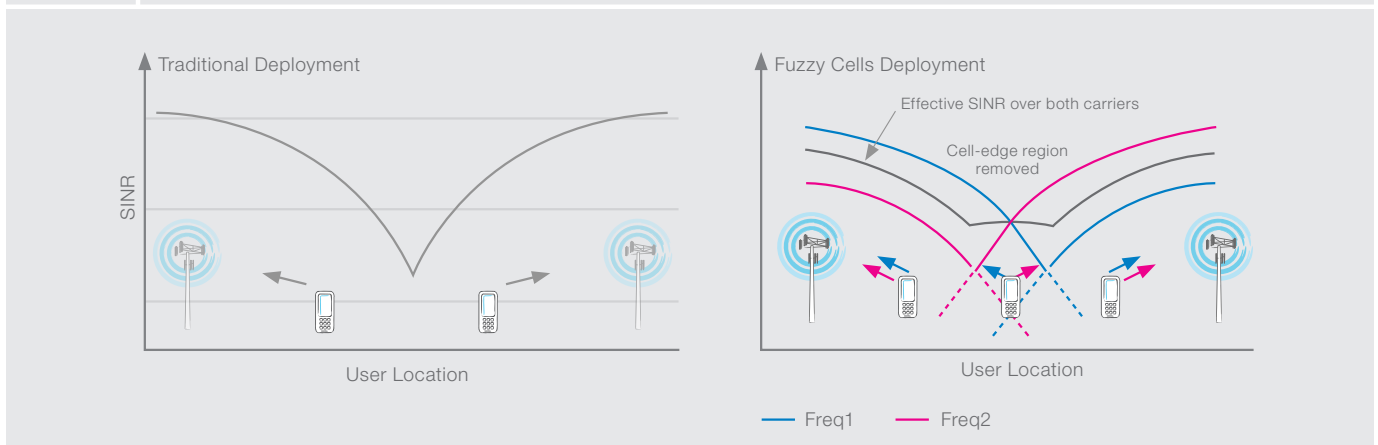
**FIGURE 4** Illustration of different coverage areas in different frequencies and UE connections



With Fuzzy Cells, the coverage area of each CC is altered in a controlled way such that for each CC frequency, the cell boundaries are in different locations. The aggregate effect over all CC frequencies is to blur the cell boundary - hence the name "Fuzzy Cells." On the left side of Figure 5 is a traditional deployment with the downlink SINR for points between two sites in a standard frequency reuse of 1 and with equal Transmit (Tx) power. Note the deep drop in SINR at the cell boundary. On the right side of Figure 5, the system bandwidth is split into two CC frequencies (red and blue). The UE is free to connect to either site for each CC frequency. The black curve in this figure illustrates the effective SINR for the UE when it is connected to both the blue and red frequencies and is free to choose the best site in any position. The effective SINR is nearly the same as the SINR in the left side of the figure when the UE is near the base station and is significantly better than the figure on the left when the UE is near the cell edge.

One of the key aspects of Fuzzy Cells technology is the ability to split the UE data between two different base stations. From an architectural point-of-view, this can be done in either the Core Network (CN) or remain entirely within the Radio Access Network (RAN) domain. The benefit of keeping this function within the RAN is that it can be deployed in an earlier timeframe due to having less impact on the system specifications as compared with data-splitting in the CN. The disadvantage is that this method is less efficient than if the data-splitting was performed in the CN prior to distribution to the RAN nodes involved in communication with the subject UE.

**FIGURE 5** Illustration of Fuzzy Cells Technology Benefits



## Relation to Coordinated Multi-Point (CoMP) Technology

Several types of CoMP technology to manage intercell interference have been discussed in wireless standards forums such as 3GPP. These include Joint Transmission (JT), Fast Cell Selection (FSC), Coordinated Scheduling (CS) and Coordinated Beamforming (CB). Of these, CoMP JT has superficial similarity to Fuzzy Cells in that both schemes include simultaneous data-transmission from multiple sites. However, there are fundamental differences. The data transmission in CoMP JT is generally envisioned as a kind of Soft Hand Over (SHO), where the same data and DeModulation Reference Signals (DMRS) are sent from two or more sites in such a way that the receiver only perceives a single data transmission (PDSCH), albeit through a different propagation channel than if the transmission came from a single source, as is the case for the control channel (PDCCH). Such transmission would preferentially be precoded (i.e., have antenna weights applied) so that the received signal would be received with the highest possible quality, cause the least interference or, otherwise, optimize some system performance metric. This places very tight requirements on the synchronization between transmissions of multiple sites that current X2 interfaces would have difficulty supporting. The same data must first be available at both sites, the selection of radio resources need to be coordinated, the selection Modulation and Coding Set (MCS) needs to be coordinated, and the effective Channel Quality Indicator (CQI) and proper precoding for the joint transmission need to be determined.

The requirements to support Fuzzy Cells are much more relaxed. Each site needs to have data that will be transmitted to the UE, but it is not the same data. Since data is not sent in a SHO-like manner, but rather as two separate data flows, there is also no need to coordinate the selection of MCS or compute the effective CQI and joint precoders. The resulting demands on the X2 interface are therefore comparatively small.

It has been noted in recent contributions to 3GPP RAN1 that much of the gains associated with CoMP require high accuracy CSI feedback. While the exact overhead to support such CSI has not been determined, there is no expected requirement for improved CSI for Fuzzy Cells.

Fuzzy Cells technology can also be viewed as supplemental to CoMP. CoMP is envisioned as a mechanism to improve cell-edge performance, in part because it is those UEs that can benefit from a multi-site transmission. Such UEs are able to receive transmission from multi-sites at approximately the same power, which is needed to show gains. Since Fuzzy Cells actually increase the geographical region in which an UE can find transmissions from multi-sites at about the same received power, the region over which CoMP is useful may be extended.

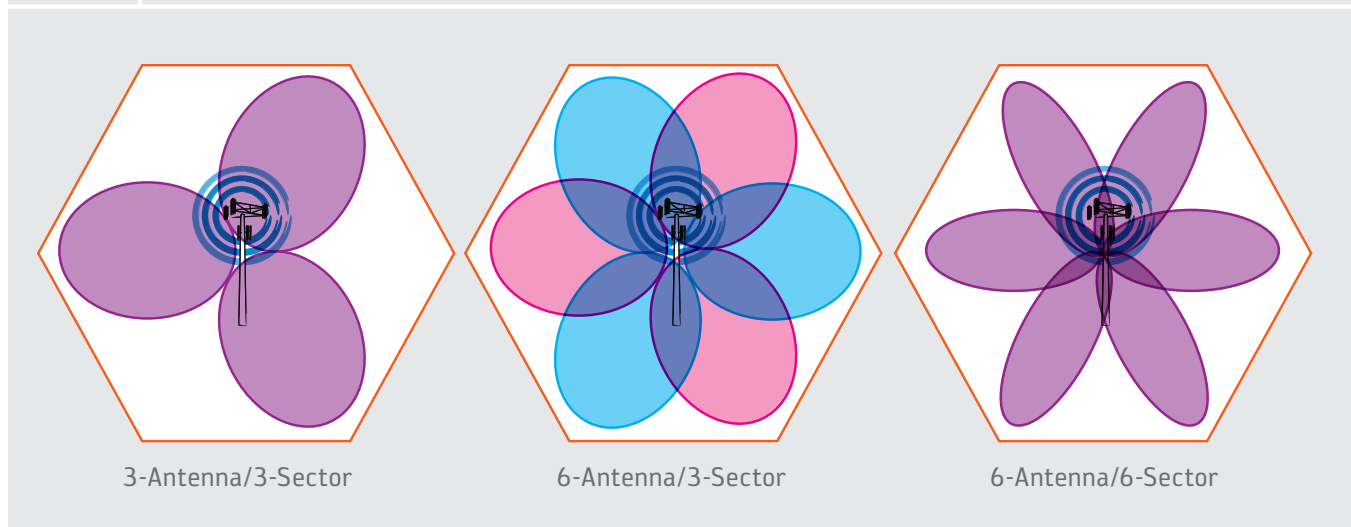
While Relay technology is quite different and distinct from Fuzzy Cells technology, Relays are mentioned for completeness as they are another solution being actively discussed and specified within the standards forums. The initial deployment models for Relay technology will primarily be for coverage extension beyond the cell-edge. Later deployments of more sophisticated Relay technology will consider coordinated operation of the Relay within a cell in order to improve cell-edge throughput. The main disadvantage of Relays with respect to Fuzzy Cells is the additional CAPEX and OPEX impact of deploying the Relay since it is essentially a light version of a base station and must have an approved site for installation, power, etc.

## Demonstrating Fuzzy Cells Benefits

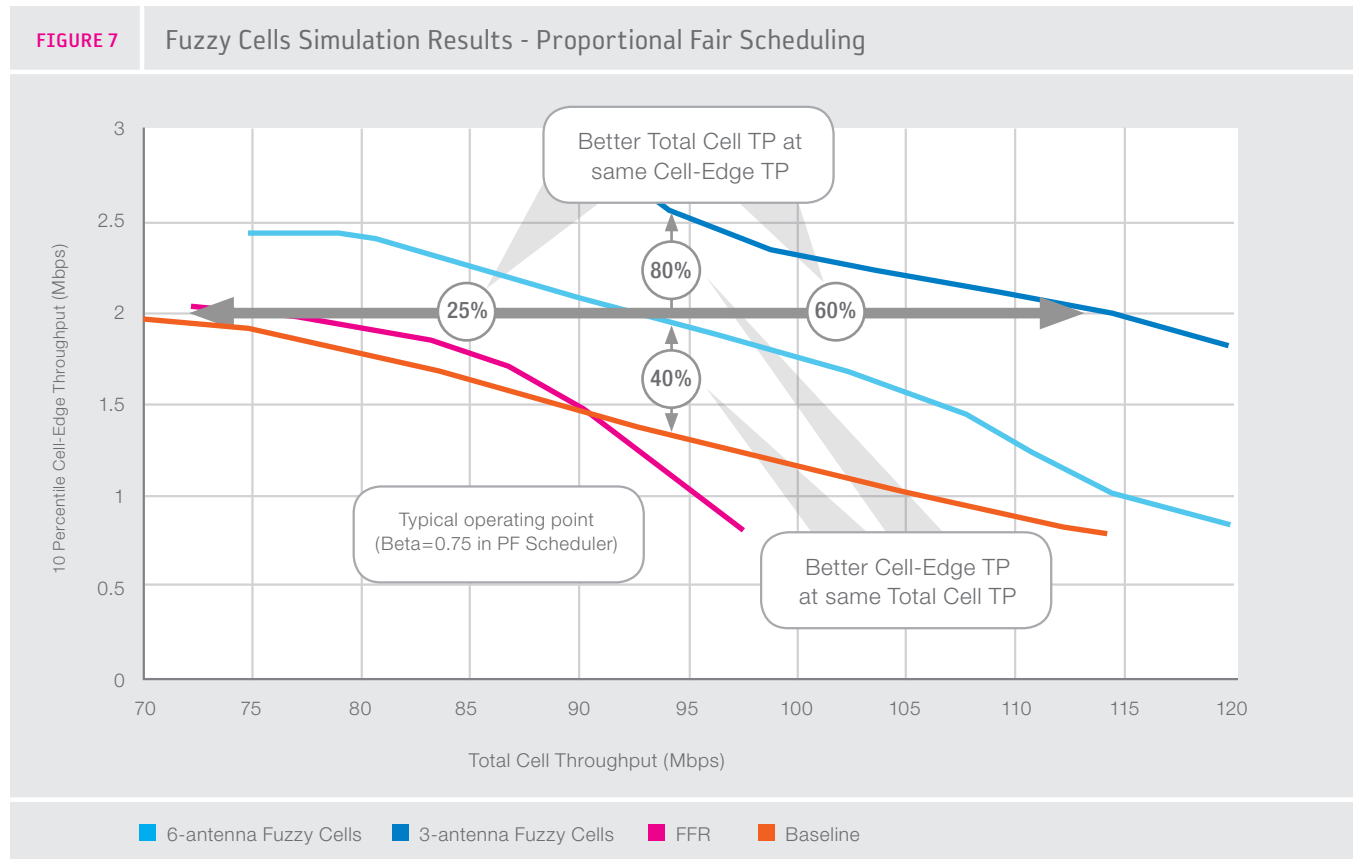
A one-dimensional analysis of SINR between two sites does not give a complete picture of the potential of Fuzzy Cells. In order to provide a more accurate view of Fuzzy Cells benefits, results from a system level simulation of a two dimensional deployment are presented. The simulation is conducted by randomly placing many UEs throughout the system that then must compete for radio resources, referred to in LTE as Resource Blocks (RBs). Each such placement of UEs is referred to as a “drop” and many such drops are required to provide meaningful statistics about the system performance. Many UEs are dropped at once and compete for resources. Scheduling and UE-CC association rules are developed for use in a Fuzzy Cells system deployment. This analysis is conducted using a hexagonal arrangement of sites and multiple CC frequencies. Two cases are simulated and shown in Figure 6: A typical case using 3 antennas per site, each with coverage of 120 degrees is shown on the left side of the figure. The full system BW (i.e., all CC frequencies) is supported by each antenna. The center of Figure 6 illustrates the second case which uses a total of six antennas per site; however, each antenna still has 120 degree coverage. Three of the antennas are deployed as in the left side of the figure, but the other three are deployed with a 60 degree rotation relative to that set. Additionally, each antenna only supports a fraction of the full system BW (e.g., if there are two CC frequencies in the system, One CC frequency is used for each set of antennas. Note that this Fuzzy Cells deployment scenario requires a total of six CCs within the site for a two CC frequency deployment (i.e. three CCs using one CC frequency and three CCs on the second CC frequency, with each antenna supporting a single CC). This latter case causes an intentional antenna pattern overlap, which has the effect of blurring the intra-site cell edges. For reference, the right side of Figure 6 illustrates a typical 6-sector site with non-overlapping antenna patterns. In this case, given the same two CC frequency deployment scheme within the site, the full system BW is supported by each antenna with 60 degree coverage. Note that in this case, 12 CCs are required, or twice as many CCs compared to the 6-antenna/3-sector Fuzzy Cells case.

The two main metrics of interest are the total cell throughput and the cell-edge throughput. The cell-edge throughput is typically measured in terms of the performance of a set of the lowest performing UEs; for example, if we arrange all UEs by their performance and take X% of those with the worst performance, these would be considered the cell-edge UEs. The threshold for a cell-edge UE is taken to be the 10%-tile user throughput UE in this case. Since there are two measures of interest, it is better to present data as the possible trade-off available between these metrics, i.e., a curve of cell-edge throughput vs. cell total throughput.

**FIGURE 6** Antenna Patterns for 3-Sector and 6-Sector Cell Sites



A comparison of the throughput trade-off curves for different techniques is shown in Figure 7 below using a common Proportional Fair scheduling algorithm and full-buffer traffic models for Fuzzy Cells. The other deployment scenarios are Fractional Frequency Reuse (FFR) and the reuse-1 baseline case. FFR offers a means to trade-off cell-edge and total cell throughput, but note that the trade-off for Fuzzy Cells is much more favorable. In fact, as one can see from the chart, for the 6-antenna case, Fuzzy Cells offers up to 60% better cell-edge throughput performance at comparable total cell throughput in this scenario. For the 3-antenna case, Fuzzy Cells still outperforms FFR by up to 25% better cell-edge performance.



When considering the available cell-edge throughput at the same total cell throughput for the different scenarios, Fuzzy Cells technology in the 6-antenna deployment offers up to 80% better cell-edge performance versus a reuse-1 deployment; and even with a basic 3-antenna configuration, Fuzzy Cells outperforms the reuse-1 case by up to 40%.

## Improving Handover Performance

Robust handover between sectors or sites is vital to a cellular system. While data applications today are a bit more tolerant than voice service supported on a circuit switched (CS) connection, in due time high Quality-of-Service (QoS) services such as Voice Over IP (VoIP) will be supported on cellular wireless data networks with expectations of seamless handovers and no dropped calls under high mobility conditions. In addition to improving cell-edge throughput performance, Fuzzy Cells technology can also improve the performance of Handover (HO). Several aspects of HO improvement are addressed with Fuzzy Cells technology:

- **Fundamental HO Improvement:** The variation in coverage areas of different CCs means that HO is indicated at different times for each CC frequency. By enabling the UE to change the set of CCs that it is connected to one at a time and across sites, the probability of occurrence of dropped voice calls and/or data sessions during HO is reduced.
- **Radio Link Failure (RLF) Reduction:** Reduction in RLF (a defined state in which the UE is at least temporarily not connected to the network) can be achieved by allowing the UE to remain connected to the network through any CC of high enough quality (signal strength). Since Fuzzy Cells deployment is specifically designed to make sure each UE sees at least one good quality CC at all times, RLF probability is reduced, thus improving QoS/QoE in otherwise degraded cell-edge conditions. This is true even if the UE requires only a single CC to support its service, e.g., in a voice call.
- **Maintaining Control Plane Signaling:** Control plane signaling is more easily maintained because control channels may be supported on any CC and the UE only needs to start monitoring a designated CC in another CC frequency as it starts to get close to the cell boundary in the current CC frequency. In this way, even CS voice calls may see reduced drop rates during HO in multi-carrier systems that support CS calls.
- **Reducing Data Plane Interruption:** During reconfiguration, data plane interruption is also mitigated by re-routing higher priority traffic to a CC with better quality and overlapping coverage. Also, by taking the Radio Resource Control (RRC) Connection establishment out of the critical path, RRC signaling associated delays are also reduced.

## Fuzzy Cells and Standards

While certain aspects of Fuzzy Cells may be supported within the framework of specifications defined in Release 10 of the 3GPP LTE standards, not all features are expected to be. For example, transmission of different CCs at different power levels and through different antennas will likely not be specifically excluded and could still be advantageous when implemented as a proprietary solution. Other aspects of Fuzzy Cells are very unlikely to be supported in Release 10 without upgrading the specifications such as data flow splitting between sites controlled by distinct base stations, such as enhanced-NodeB's (eNodeBs) and, by extension, reduced radio link failure in HO. These aspects are required in order to realize the full benefits of the Fuzzy Cells technology and are good candidates to bring into later releases (Release 11 or 12) of the 3GPP LTE standards.

The data-flow splitting is used to route UE data to multiple sites in Fuzzy Cells, but may use independent scheduling for the sub-flows from each CC to the UE. Compared to techniques like CoMP, data-flow splitting eliminates inter-site synchronization of packet data transmissions. It may, however, impose additional transmission latency as the inter-arrival time varies due to differences between sub-flow routing path delays. The re-ordering entity at the receiving end handles the sub-flow merging and transmission latency for each packet delivered within the requested QoS latency requirement. This approach makes transport layer routing change transparent to network layer protocol such as TCP. Therefore, the introduction of Fuzzy Cells data flow split does not impose any substantial synchronization issues. In fact, Fuzzy Cells improves TCP performance during handover by decreasing handover latency. This minimizes TCP round trip time (RTT) variance introduced by HO delay, and therefore, reduces potential TCP packet drops due to congestion window changes.

While Fuzzy Cells technology has been explained in terms of an LTE system as a framework, it can be applied to any multi-carrier Radio Access Technology (RAT) that allows certain flexibilities in the configuration of the multiple carriers. MC-HSPA is one such RAT to which Fuzzy Cells can be applied with similarly low complexity. The carriers in MC-HSPA are treated very much as separate cells and in that sense are similar to CCs in LTE.

## Conclusion

Today's wireless service providers are facing a growing gap between cell peak data rates and the performance at cell-edge. This results in a growing performance disparity between users who are close to the base station and those further away. With growing demand for wireless data, subscribers will demand better service from their service providers as they did with the evolution of mobile voice service. The use of cell-splitting provides the traditional, but costly, solution to improving coverage and capacity in poorly served areas of a cell. Fuzzy Cells technology offers an intelligent way to improve cell-edge performance and to increase overall cell spectral efficiency in a cost effective manner.

InterDigital extends an invitation to fellow global market participants in the wireless eco-system to collaborate on integrating its advanced technologies into products and services for field testing and deployment.



## About InterDigital®

InterDigital develops fundamental wireless technologies that are at the core of mobile devices, networks, and services worldwide. As a long-standing contributor to the evolution of the wireless industry, we solve many of the industry's most critical and complex technical challenges years ahead of market deployment. Our advanced solutions support more efficient wireless networks, a richer multimedia experience, and new mobile broadband capabilities. Accordingly, we have established licenses and partnerships with many of the world's leading wireless companies.

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