Interference management in LTE networks and devices

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1. Introduction: capacity and interference in LTE

The relentless growth in wireless traffic forces mobile operators to aggressively increase network capacity to meet subscriber demand. However, spectrum availability is not growing at the same rate as traffic; in fact spectrum resources are in markedly short supply, and, as a result, their cost remains high.

To increase capacity, operators have to increase spectral efficiency – packing more and more traffic into the spectrum they own. They can do so by acting on multiple fronts:

- Using new technologies like long-term evolution (LTE) and eventually upgrading to LTE Advanced
- Adopting a frequency reuse of 1 (using the same spectrum channel for neighboring cells)
- Creating multilayer heterogeneous networks (HetNets) in which small cells are located within the coverage area of macro cells and share the same spectrum channels.

As they strive to increase spectral efficiency and capacity in their networks, mobile operators face higher levels of interference.

Effective, real-time management of interference is crucial to fully reaping the benefits of LTE.

A multipronged approach that involves both the RAN and the UE best serves the need to minimize interference.

While these are essential tools for increasing capacity density where it is needed, they also carry a substantial price. They elevate the interference level in the network by increasing the portion of cell-edge areas where two or more base stations compete for coverage and can transmit to and receive from the same user equipment (UE) device. In turn, higher interference is reflected in a lower signal to interference plus noise ratio (SINR), a degradation of network performance and user experience, and diminished efficiency of use of network resources. Careful radio frequency (RF) planning can prevent this to an extent, but interference cannot be entirely eliminated, and in fact the successful management of contained levels of interference leads to better network performance than its aggressive suppression.

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To compensate for the decrease in the SINR, operators have to step up their efforts to manage interference, using all the tools at their disposal. They can act from the radio access network (RAN) to improve transmission and reception of the signal, but at the same time they can take advantage of the UE's capabilities to reject interfering signals. This paper discusses how interference arises in LTE networks, the tools operator can use to manage it in real time, the tools' benefits and requirements, and their effect on the subscribers' experience.

2. Where can interference be managed?

As capacity density increases in LTE networks, so does the potential for interference, with a consequent disruption in subscriber experience and efficiency of use of network resources. Some interference can be prevented from arising by careful RF planning, but it cannot be entirely eliminated, and in fact the successful management of contained levels of interference leads to a better network performance than its aggressive suppression.

The selection of a frequency reuse scheme illustrates this. Figure 1 shows the spectrum allocation for a frequency reuse of 1 with single-sector eNodeBs (eNBs), and for a frequency reuse of 3 for single-sector eNBs and for a three-sector eNB configuration that is commonly used in cellular networks. A frequency reuse of 3 increases the SINR and allows higher modulation, but reduces the spectral efficiency (bps/Hz), as each channel is used less intensively.

There are multiple sources of interference, and they have to be managed using different approaches.

Mobile operators can manage interference both in the RAN and in the UE to minimize its impact.

Frequency reuse of 1
Single-sector eNBs
Same spectrum channel used by all eNBs

Frequency reuse of 3
Single-sector eNBs
Three spectrum channels (different colors) used to ensure that at the cell edge there is an non-overlapping channel

Frequency reuse of 3
Three-sector eNBs

Figure 1. Frequency reuse. *Source: Senza Fili Consulting*

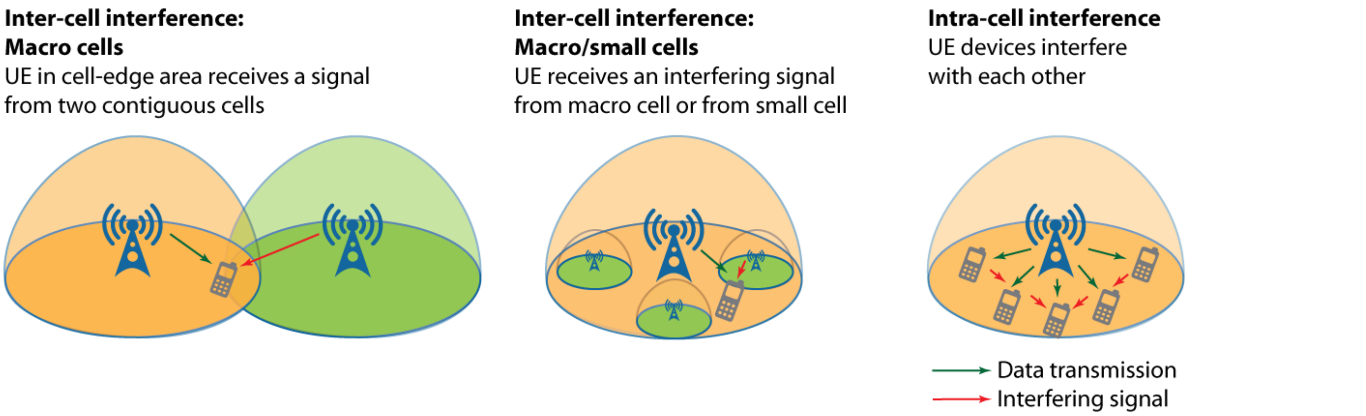

Figure 2. Types of interference. *Source: Senza Fili Consulting*

LTE operators may choose a high frequency reuse pattern (e.g., 3) to suppress interference in their network, but in doing so they face suboptimal utilization of spectrum and network resources, and have a network with less capacity than if they use the most commonly used frequency reuse of 1. A frequency reuse of 3 lowers interference at the cell edge, as neighboring cells use different spectrum channels in their overlap area at the cell edge, but it decreases the overall network capacity compared to a reuse frequency of 1, as three times as much spectrum is needed to cover the same footprint. When using a frequency reuse of 1, the same spectrum channel is used at the overlapping cell edge. Even though the level of interference is higher, the operator extracts better performance from the network, but only if it successfully manages the ensuing higher levels of interference.

Instead, the paper will focus on the interference that arises within an LTE network, either at the cell edge, where two cells overlap (i.e., inter-cell interference, with the UE receiving signal from two contiguous cells) or within the coverage area of one cell (i.e., intra-cell interference, caused by UE interfering with each other) (Figure 2). Traditionally, inter-cell interference was limited to cell-edge areas, which covered by more than one cell. With the deployment of HetNets, interference will increasingly originate from small-cell coverage areas located inside the macro-cell coverage area, where the UE receives a signal from both the macro and the small cell.

The tools available to operators for managing real-time interference within their LTE networks work at three levels:

- **Within the RAN.** These tools use exclusively RAN elements to manage interference, although they do take into account traffic conditions that are driven by UE devices. They include inter-cell interference coordination (ICIC), enhanced ICIC (eICIC), and coordinated multipoint (CoMP) transmission and reception.
- **Coordinating between RAN and UE.** These mechanisms require both RAN elements and UE devices to have an active role in managing interference. In LTE Advanced, the main focus is on multiple-input multiple-output (MIMO) enhancements, including multiuser MIMO (MU-MIMO) and single-user MIMO (SU-MIMO).
- **Within the UE.** These are tools such as maximal ratio combining (MRC), interference rejection combining (IRC), and interference cancellation (IC) with receiver beamforming (BF) that take into account network conditions and work exclusively from UE devices that support them.

Availability of UE-based tools is dependent exclusively on the UE vendor and therefore can be rolled out as soon the UE vendor supports them. Tools that involve the RAN have to go through a standardization process to ensure interoperability and conformance to the standards and typically take longer to be adopted. ICIC and MU-MIMO and SU-MIMO are already available, but eICIC and the enhanced versions of MU-MIMO and SU-MIMO will become available soon. CoMP, to be finalized in LTE Release 11, will be the last tool among those discussed here to become available (Figure 3).

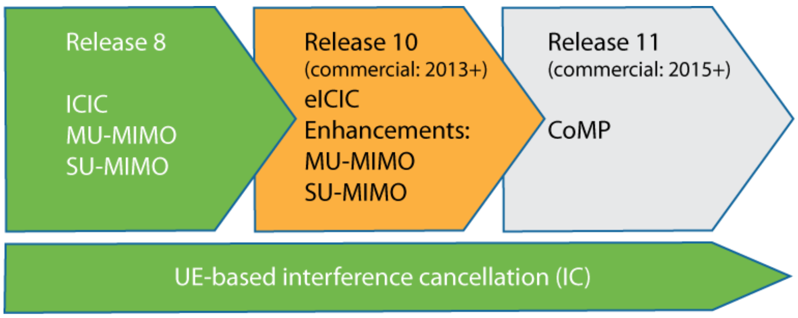

Figure 3. Interference management roadmap. *Source: Senza Fili Consulting*

3. Managing interference in the radio access network (RAN)

Inter-cell Interference coordination (ICIC)

ICIC functionality has been introduced in LTE Release 8 to coordinate network resources across neighboring cells either without requiring collaboration between eNBs (autonomous schemes), or use of the X2 interface among eNBs (coordinated schemes). ICIC is effective in mitigating interference and improving performance in cell-edge areas by allocating spectrum and power resources among interfering cells, either on a static basis dependent on network configuration or on a semi-static basis dependent on near–real-time traffic distribution across UE devices.

Fractional frequency reuse (FFR) is an ICIC static mechanism used to reduce cell-edge interference in networks with a frequency reuse of 1, by limiting transmissions in different parts the cell-edge areas to different portions of the spectrum channel used in the network. This approach is comparable to using a frequency reuse of 1 in the area immediately surrounding the cell site and a frequency reuse of 3 at the cell edge (Figure 4).

New interference management tools in LTE promise to give mobile operators an unprecedented ability to contain interference.

Initially they will address cell-edge interference in macro networks.

In a second phase, new tools like eICIC and CoMP will add capability to fight interference in multilayer HetNets.

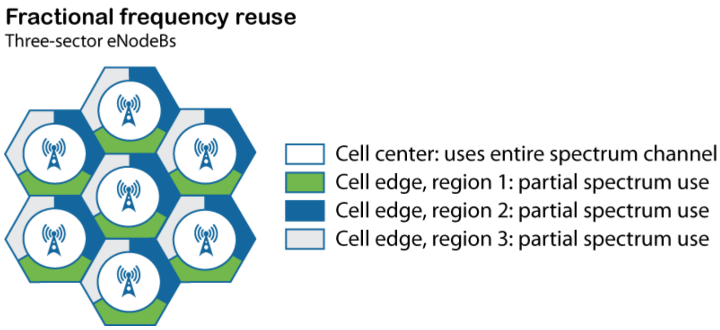

Figure 4. Fractional frequency reuse. *Source: Senza Fili Consulting, Huawei (redrawn)*

The semi-static ICIC mechanisms that use the X2 interface can be used to achieve similar effects in response to changing network conditions, but they are more difficult to implement because they require coordination among neighboring cells.

Enhanced inter-cell interference coordination (eICIC)

The features included in Release 8 ICIC specification target interference arising from cell-edge areas in a macro network. The introduction of HetNet topologies with multilayer networks that may include indoor and outdoor small cells (including residential femto cells) carries specific interference challenges, because the small-cell or femto-cell coverage area is typically enclosed within the coverage area of the macro cell. When this is the case, the UE receives a signal from both the macro cell and the small cell, and these two signals interfere with each other.

There are two opposite interference scenarios in HetNet deployments:

- Signal to the UE from the macro cell is stronger, due to higher transmission power at the macro cell
- Signal to the UE from the small cell is stronger, due to closer proximity to the small cell.

In some cases, the UE device may be prevented from connecting to the small cell if it belongs to a closed subscriber group (CSG) that limits access to specific users (e.g., subscribers living in a household). In this case, the impact of interference on the UE is particularly severe, because the signal from the small cell is stronger.

To manage these sources of interference, Release 10 introduced time-division multiplexing eICIC (TDM eICIC), which is expected to become commercially available in 2013–2014. With TDM eICIC, one of the interfering cells – either the macro cell or the small cell in the HetNet eNB (HeNB) – sends almost-blank subframes (ABSs) that contain no data or signaling, with the exception of common reference signals (CRS) to preserve support to legacy terminals. This gives the other cell the opportunity to successfully send a subframe that does contain data. Because the sending of ABSs alternates between the two cells that interfere with each other, tight coordination between the HeNB and the macro eNB is required, using the X2 interface, which in turn requires low latency and additional capacity in the backhaul. These requirements are particularly challenging in residential femto cells, which typically use residential broadband connections for the backhaul.

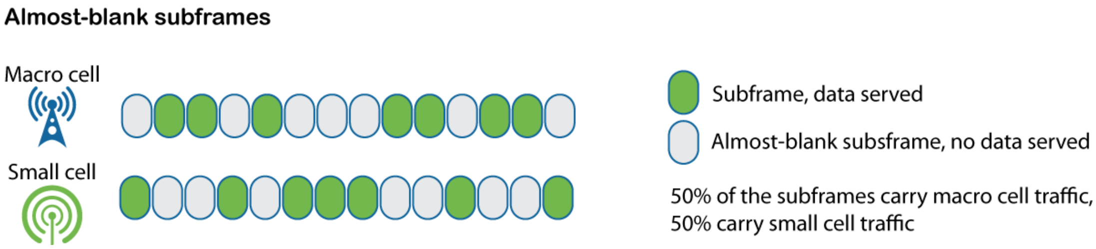

Figure 5. Almost-blank subscframes in eICIC. *Source: Senza Fili Consulting, Qualcomm, Nokia (redrawn)*

Changes in transmission power at the HeNB can also mitigate the impact of interference by optimizing the transmission power balance between macro and small cells. By increasing its transmission power, a small cell may extend its coverage area and serve additional UE devices. The resulting small-cell range extension allows macro cells to offload more traffic to small cells, thus increasing the overall network capacity.

Coordinated multi-point (CoMP) transmission and reception

CoMP includes various tools to be introduced in LTE Release 11 that minimize inter-cell interference when one or more UE devices are located at the cell edge and receive a signal from more than one cell. CoMP is expected to bring an increase in cell-edge performance and cell capacity, either by minimizing the negative impact of the interfering signal or by coordinating transmission and reception. Release 11 has not been finalized yet, so CoMP will not be commercially available for a few more years.

There are two main components in CoMP (Figure 6):

- **Joint processing (JP).** JP enables cells to positively gain from the management of interfering transmission and reception, by using either:
  - Joint transmission (i.e., simultaneously transmitting to a single UE device from multiple cells) and joint reception (i.e., receiving the UE device's transmission at multiple cells) or
  - Dynamic cell selection, to allow the eNB(s) to select in real time which cell should transmit to the UE.

  Joint transmission and reception can be thought of as an extension of MIMO (and, for this reason, it is sometimes referred to as network MIMO), with antennas transmitting from different cells. JP can be coherent (JP-Co) or not coherent (JP-NCo). The first is more effective, but requires tighter coordination among cells.
- **Coordinated scheduling (CS) and coordinated beamforming (CB).** As in the JP case, the UE is located at the cell edge and within the coverage area of two cells. CS uses signaling between the two cells to determine which cell should transmit a subframe to the UE, thus eliminating the interference from the other cell. When multiple UE devices are located in the same edge area, the cells can coordinate scheduling to determine which UE each cell should transmit to. With CB, the transmitting beam is narrowly directed to the desired UE to reduce interference.

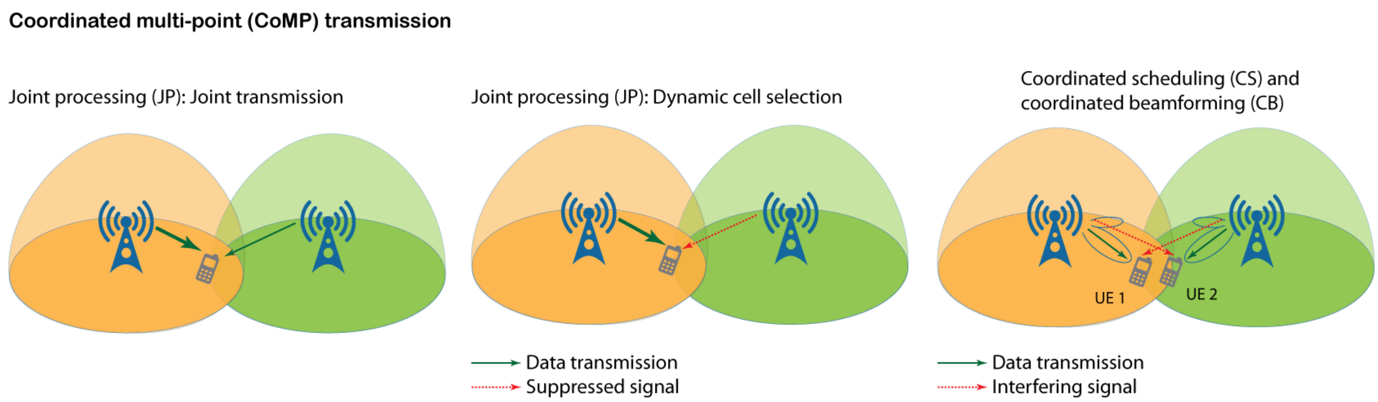

Figure 6. CoMP. *Source: Senza Fili Consulting, NTT DoCoMo (redrawn)*

Two implementations of CoMP are available, based on the topology of the network in which CoMP will be used:

- **Centralized control.** Multiple cells are connected to a single central eNB, within the same cell site or with remote radio equipment (RRE) at different sites connected to the eNB by optical fiber.
- **Autonomous distributed control.** Neighboring eNBs coordinate transmission using the X2 interface over the backhaul. This architecture is more difficult to implement because multiple eNBs are involved, and the backhaul requires very low latency and higher capacity, but it can be used within a wider range of cell topologies.

CoMP operates both in the downlink and in the uplink, but the capacity and cell-edge performance gains are higher in the downlink. However, in both cases, the interference management takes place in the RAN network, with UE reception and transmission being unaffected by CoMP.

Table 1 summarizes the features of RAN-based interference management methods.

Table 1. Summary of RAN-based interference management tools

Domain	Method	Response to UE distribution and interference conditions	Environment
Frequency	ICIC	Slow (FFR) to almost real time (semi-static ICIC); limited ability to respond to variations in interference levels, but easier to implement	Cell-edge areas in macro networks
Space	CoMP	Fast response to UE interference conditions; enables management of interference at the subframe level.	
Transmission power	eICIC		HetNet multilayer topologies
Time			

4. Coordinating interference management between the RAN and the UE

Multi-antenna MIMO and adaptive beamforming allow operators to manage interference and increase spectral efficiency, transmit rates and overall network capacity. MIMO is most effective in areas with high SINR, including cell edges and HetNet deployments. While the impact of MIMO varies substantially depending on the RF environment in which cells are located, increasing the number of antennas typically results in an improvement of performance. However, adding antennas in cells and UE is expensive, and operators have to carefully evaluate the tradeoffs between the expected improvements in performance and the cost for the upgrade.

MIMO functionality and effectiveness are expanding in LTE Advanced with MU-MIMO and SU-MIMO.

MIMO is particularly effective in high-SINR areas, which is where the need to tame interference is strongest.

To maximize MIMO's benefits, the number of transmit antennas supported in the uplink and downlink has increased from Release 8 to Release 10 (Table 2) to enable two types of MIMO (Figure 7):

- Multi-user MIMO (MU-MIMO)
- Single-user MIMO (SU-MIMO).

MIMO determines the optimal number of transmission layers using rank adaptation, on the basis of channel conditions and feedback from the UEs.

Multi-user MIMO (MU-MIMO)

With MU-MIMO, a cell can transmit to up to 8 UE devices concurrently using the same spectrum, by directing an adaptive beam to the UE. In an environment with high interference levels, MU-MIMO can substantially increase cell capacity and UE throughput for all UE devices, even those that do not support MU-MIMO. Beamforming is used in conjunction with MU-MIMO to more finely direct the beam to the UE and to further improve performance.

Table 2. Multi-antenna MIMO in LTE Release 8 and Release 10

	Release 8	Release 10
Downlink	4 transmit antennas 4 receiver antennas	8 transmit antennas 8 receiver antennas
Uplink	1 transmit antennas 1 receiver antennas	4 transmit antennas 8 receiver antennas

Single-user MIMO (SU-MIMO)

SU-MIMO takes an approach that is complementary to MU-MIMO, with the cell concurrently transmitting to and receiving from a single UE device over up to 4 layers (Release 10). SU-MIMO improves the data rate of UE devices that support it (but has no impact on legacy devices). It also increases the spectral efficiency and capacity of the cell. It provides increased benefits in networks that have light traffic so that network resources can accommodate multiple transmissions from a single device.

MIMO enhancements in LTE Advanced

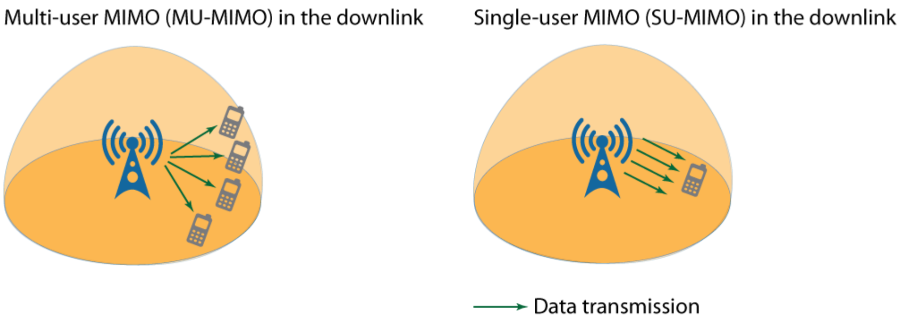

Figure 7. MIMO enhancements in LTE Advanced. *Source: Senza Fili Consulting, NTT DoCoMo (redrawn)*

5. Managing interference from the UE

A third approach to interference management takes place entirely within the UE, using tools such as maximal ratio combining (MRC), interference rejection combining (IRC), and interference cancellation (IC). Because these tools act independently of the RAN, they can be deployed in any network, regardless of the RAN vendor(s) selected, and at any time as long as the devices support them. As a result, they can be deployed at the same time the device is introduced, without further need of integration, and have an immediate impact on reducing interference levels.

MRC is a receiver-diversity technique that strengthens link reliability (but not the link rate) in low SINR environments. The signal is received by two separate receivers and after channel compensation it is linearly re-combined in a composite signal.

IRC is a more advanced receiver-diversity technique than MRC that incorporates the analysis of the spatial component of the received signal. It is designed to improve the SINR by computing the temporal and spatial correlation of received signals to eliminate the interfering ones.

UE-based IC gives mobile operators a new weapon in their attempts to optimize network performance, and it can be deployed as soon as devices are introduced in the market.

UE-based IC is effective at minimizing cell-edge interference, which in today's macro networks is the dominant source of interference.

UE-based IC operates as an interference management tool complementary to those involving RAN elements that we have discussed in the previous pages. IC contributes to further improvement of the SINR and, consequently, of the subscriber experience.

It requires a firmware upgrade to the UE and leverages the existing hardware, thus limiting the implementation cost. Because coordination with the RAN is not needed, IC does not require access to network resources or add complexity to the RAN.

UE-based IC is mostly effective at targeting inter-cell interference and improving the performance of the UE devices that support it. In particular, lower interference rates at the UE give subscribers higher data rates and longer battery life, due to avoidance of retransmission. In turn, the lower interference and higher data rates for supported UE results in improvements in overall network capacity, because network resources are used more efficiently.

Beamforming techniques, similar to those used by eNBs, can be used to define a narrow receiver beam oriented toward the serving cell (Figure 8). When the UE is in a cell-edge region and receives a signal from two cells, the UE can direct its receiving beam toward the stronger (or the preferred) signal, and ignore the interfering signal from the other cell.

Because IC operates independently within the UE, standards-based interfaces (such as the X2 interface used for CoMP and eICIC) and support for legacy UE or infrastructure are not necessary, streamlining IC's deployment to the UE devices that can support it, without any need for a network-wide plan. Approaches to UE-based IC are necessarily vendor specific (and, as a result, give vendors and operators a wide scope for differentiation) and will have no interoperability requirements across vendors in the overall network.

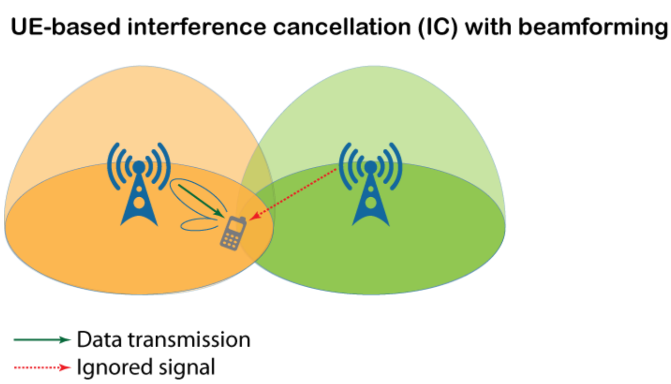

Figure 8.UE-based IC with beamforming. *Source: Senza Fili Consulting*

6. Interference management strategies

Interference management tools differ widely in their requirements, benefits, costs, and efficiency (Table 3). Different operators may decide to adopt some but not others, depending on their network topologies, their spectrum assets, their technology roadmaps, and the traffic load on their networks.

Fundamentally, however, interference management is an incremental process in which the implementation of additional tools brings further performance improvements, although they are likely to affect different performance aspects (Figure 9). For instance, SU-MIMO has a stronger impact on cell-edge performance, while MU-MIMO's biggest benefit is on average cell performance. While some tools are mutually exclusive (e.g., JP and CS), others work better in conjunction. This is the case for CoMP and SU-MIMO and MU-MIMO.

Interference management requires the gradual adoption of multiple tools that address specific sources of interference and have different requirements.

Availability, need, and complexity are important considerations in defining a successful interference management strategy.

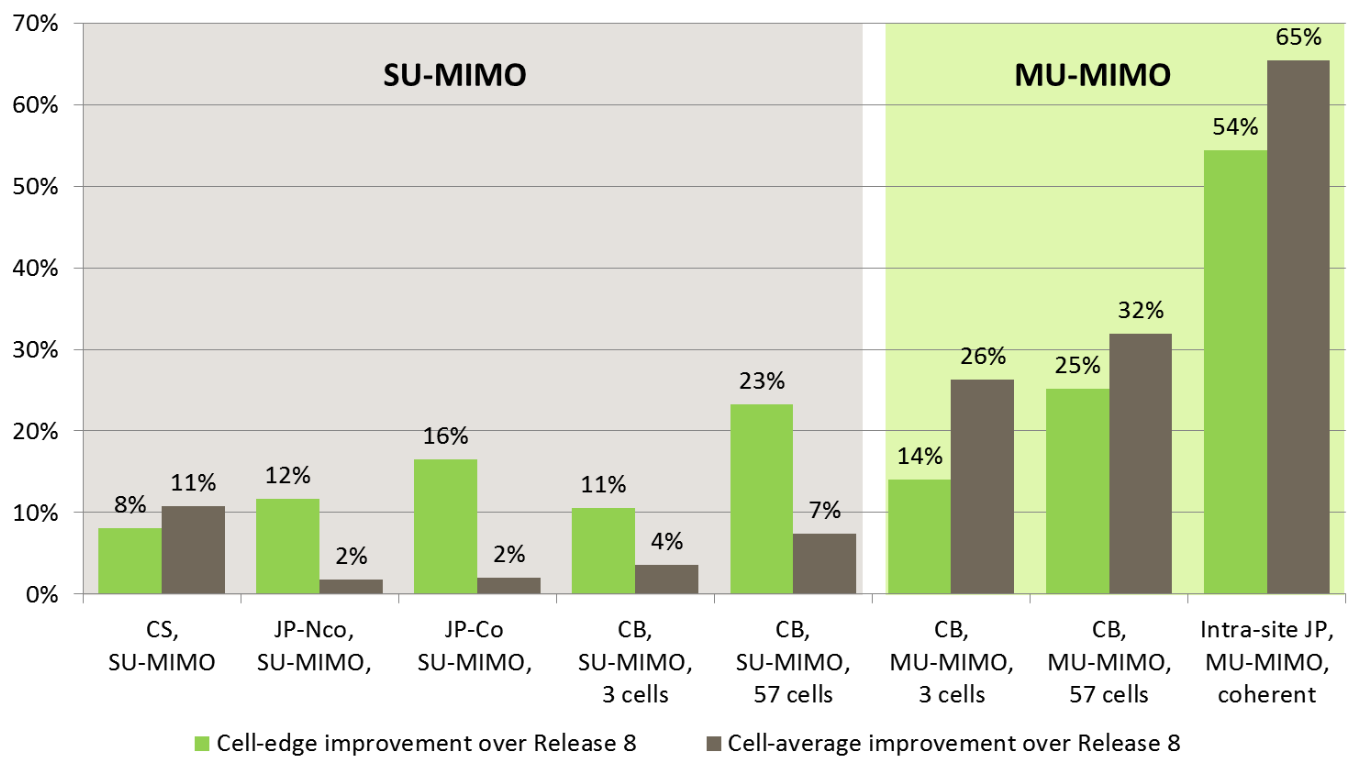

Figure 9. Performance gain with MIMO and CoMP. *Source: 4G Americas (redrawn)*

Table 3. Managing interference in LTE

	Advantages	What it does	Requirements	Standardization
RAN				
ICIC	Improves cell-edge performance.	Network resource coordination among neighboring cells. Fractional frequency reuse.	If the X2 interface is used, low latency backhaul is required.	LTE Rel 8
eICIC	Increases in capacity and utilization of network resources in HetNets.	Real-time traffic coordination, with alternating transmission from macro and small cells over the time domain. Power management at the small cell for range expansion.	Tight coordination between macro cells and HeNBs through the X2 interface. Low latency backhaul is required.	LTE Rel 10
CoMP	Improves cell-edge performance and cell capacity.	Used when a UE device at the cell edge receives a signal from two cells. With CS, only one cell transmits to the UE, to reduce impact from the interfering signal on the second cell. With JP, both cells transmit to and receive from the UE by coordinating the signal.	Software-based, additional complexity and processing overhead in the RAN. Higher power and network resource requirements, more signaling traffic, requiring additional backhaul capacity. Low backhaul latency is required. Ideally implemented in conjunction with MIMO.	LTE Rel 11
RAN/UE				
MU-MIMO	Improves data rates and capacity, mostly in high- SINR environments.	Concurrent transmission through multiple beams to multiple UEs.	Hardware upgrade requires additional funding and deployment time and effort. Multiple antennas in the UE mean additional cost and complexity.	LTE Rel 8 and Rel 10
SU-MIMO	Provides higher data rates for enabled UE, mostly in high-SINR environments (both at cell edge and in HetNets).	Concurrent transmission from single UE over multiple beams.		
UE				
MRC	Increases link reliability	Receiver-diversity method (time domain)	UE support	LTE Rel 8
IRC	Improves SINR	Receiver-diversity method (space and time domain)		LTE Rel 8
UE-based IC	Improves cell-edge throughput, UE data rates, and battery life.	Receiver beamforming, to direct antenna toward serving cell and ignore interfering one.	Firmware update at the UE. It does not affect the RAN or add complexity or cost to the network.	N/A

Similarly, UE-based IC is designed to work in conjunction with other tools that require RAN elements, by providing a further, independent interference management tool. UE-based IC is more effective where the signal from the serving and the interfering cells can be separated, as it is in a single-layer network (e.g., in a macro network, or between neighboring small cells in a HetNet that uses separate spectrum channels in the macro- and small-cell layers). Furthermore, it delivers the strongest gains in high-modulation and high-mobility usage scenarios, where beamforming is most effective. In lab simulations, IC has been shown to deliver up to a threefold performance increase over MRC in a low-mobility scenario with quadrature phase-shift keying (QPSK) modulation and where serving and interfering cells transmit at the same power level. In a high-mobility scenario with 64 quadrature amplitude modulation (QAM) and the interfering cell 3 dB higher than the serving cell, IC may be required for the UE to establish a connection.

7. Conclusions: Improving the subscriber experience

Keeping interference at a minimum is an imperative for mobile operators. An effective interference management approach allows operators to extract better performance and value from their LTE networks. The additional capacity and improved coverage enable mobile operators to transport rapidly increasing loads without succumbing to congestion.

In LTE, the high spectral efficiency brings increased network capacity to mobile operators which are under intense pressure to meet subscriber demand.

But LTE also increases the level of interference to be managed.

Mobile operators, RAN vendors, and UE vendors will have to work together to minimize the impact of interference and to enhance the subscriber experience.

Higher capacity and better coverage directly translate into improved subscriber experience. With lower levels of interference, subscribers will experience higher data rates, lower latencies, and a more reliable mobile broadband experience, especially for real-time content, such as video, audio and voice. A signal less prone to interference also reduces the incidence of retransmits, which in turn alleviates the frustration due to delays and extends mobile devices' battery life.

The improvement in performance for subscribers will be particularly noticeable in cell-edge areas, where subscribers often experience degraded connectivity, but do not typically know why (because they are unaware they are in an edge area and what the implications are). A better cell-edge performance is thus likely to create a perception of greater network reliability among subscribers.

Mobile operators are naturally the first line of defense against interference, because they have end-to-end control of the network. Vendors, too, have a role in facilitating the deployment of interference management tools and ensuring that they can be implemented in increasingly complex, multilayer, multivendor networks. With the emergence of UE-based interference management solutions, device vendors also have the opportunity to contribute, by further minimizing interference at the UE. UE-based interference management benefits mobile operators as it increases the overall network performance, improves the experience of subscribers whose devices support it, and can be a powerful performance differentiator in the highly competitive device market.

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