Enhancing LTE Cell-Edge Performance via PDCCH ICIC

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Introduction

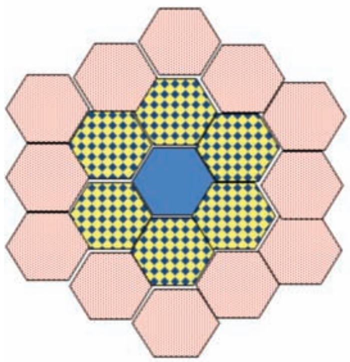
LTE uses universal frequency reuse (N=1) without soft handoff. Consequently, high levels of interference and low SINR can be expected near the cell edge. Traffic channel performance at the cell edge can be enhanced via ICIC.

However, it is commonly believed that control channels (such as the PDCCH) are more robust, so ICIC is not applied to the PDCCH. Real-life deployments of large N=1 heterogeneous networks under heavy load conditions can result in a "long tail" in the SINR distribution; high mobility makes the situation even worse. The cell-edge SINR can be so poor that even the most robust control channel will not function properly without some kind of ICIC.

This paper examines the challenge of optimizing cell-edge SINR, and discusses various strategies to enhance the cell-edge performance of PDCCH using the existing LTE standard.

Cell-Edge SINR from Simulation, Trial and Real-Life Networks

Before a real-life large-scale LTE network is deployed, network performance is estimated via results from system-level simulations and trial networks. The 3GPP Model [1] is commonly used for system-level simulation (Figure 1).



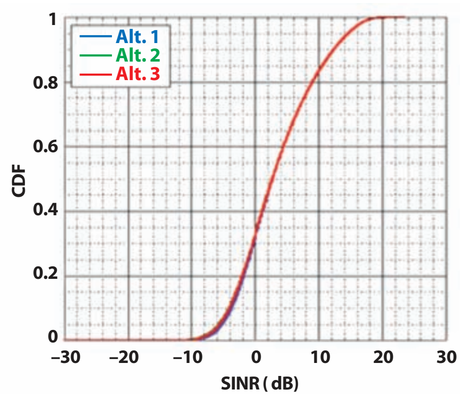


Figure 1: Under the 3GPP model, the cell-edge SINR values rarely go below SINR = –8 dB

There are several obvious limitations which make the 3GPP model ill-suited to estimate cell-edge performance. The model is too idealistic; it is difficult at best to find a real-life cellular network that contains only 19 eNodeBs with identical cell radii, identical antennas, identical tower heights and uniform user distribution. The effect of using this idealistic model is that the measured cell-edge SINR values from a large-scale real-life network (Figure 2) can be much worse than the SINR generated from simulation (Figure 1); in other words, the model is likely to underestimate these values.

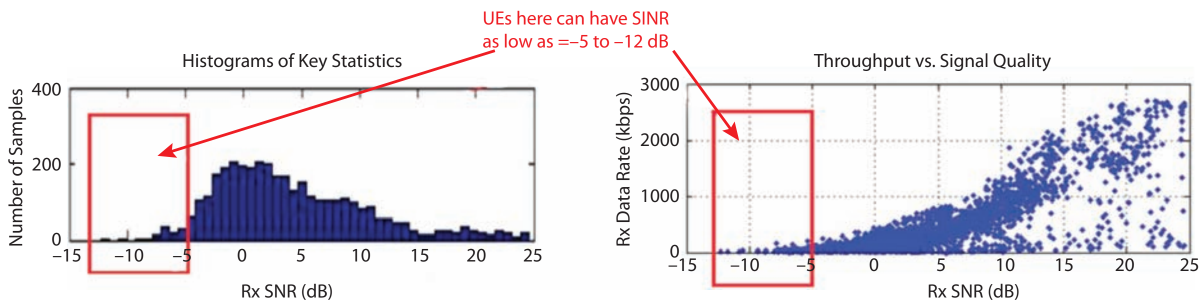


Figure 2: SINR distribution of a real-life N=1 OFDMA network has a much longer tail reaching SINR = –12 dB

Most trial networks only contain a few base stations; these few neighbor cells do not contribute sufficient out-of-cell interference even if they are all fully loaded. It is not cost-effective to maintain a trial network of appropriate size merely to create sufficient out-of-cell interference to generate realistic cell-edge SINR distributions. Some people believe that the out-of-cell interference is not important if it originates from cells that are physically far away from the center cell. This is not always true; cells that are located far away can still cause significant interference if they have line-of-sight (LOS) condition (see Figure 3).

The consequences of relying on results from simulation and trial networks is that, although performance can look very promising, cell-edge performance in an actual large-scale deployment can be much worse than originally anticipated, especially under heavy traffic loads. This puts the responsibility for problem solving in the hands of the field engineers. Sometimes performance can be only brought up to acceptable levels through lengthy trial-and-error processes; other times performance cannot be corrected because the "defects" are in the current release of the standard. Once the industry realizes that the problems are valid, corrections are made in the next release of the standard. But it takes years for the next release of the standard to be implemented in the field. In the meantime, network performance can only be "as good as the field engineers can make it."

This kind of situation is a common occurrence, especially when a new system is deployed. For example, when the first system with universal frequency reuse (N=1) was deployed, no one realized how bad the out-of-cell interference could be when the load became heavy. The measured SINR distributions from the field turned out to be much worse than the SINR distributions obtained from simulations or from trial networks (a long tail toward the negative values with SINR < –12 to –15 dB).

What are the causes of such low cell-edge SINR? Multiple factors are involved, but the main cause is "irregularities" from real-life cellular networks. These irregularities can cause very negative SINR in some locations (although they can result in good SINR in other locations); the net result is a long tail in the SINR distribution.

The situation is better for N>1 networks (such as GSM or AMPS) because in that case, the "interferers"(co-channels) are physically located farther apart from each other due to the frequency reuse distance. The situation is worst for N=1 networks since in that case, every cell is an interferer. "Pilot pollution" (or "no dominant server") describes a situation where power transmitted from many different cells appear in a location, but none is significantly better than others. As a result, the composite signal level is high, but the SINR from any single cell is poor because the total interference is too high. The result is poor RF performance even with a high overall signal level.

Figure 3 shows one common cause of the "no dominant server" problem. The cells located nearby have unfavorable RF propagation conditions; but the cells located far away have favorable RF propagation conditions. The net result is: many servers appear in a location but no server is offering a strong enough signal. Without soft handoff, the terminal can only treat received power from one cell as "signal;" power from all other cells is treated as "interference." Thus, the "no dominant server" problem means high interference and poor SINR:

$$SINR = \frac{S}{n + \sum_{k=1} I_k} = \frac{S}{n + I}$$

where S = received signal level; n is the thermal noise energy which is a constant,

$I = \sum_{k=1} I_k$ is the total out-of-cell interference contributed from all neighbor cells. The larger the value of I, the worse the SINR.

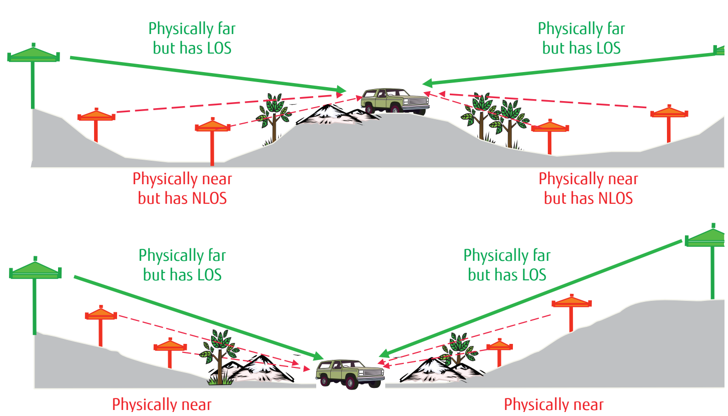


Figure 3: "No dominant server" problem caused by special 3D terrain conditions

Figure 4 shows an indoor deployment. The upper floors of high-rise buildings have LOS, with many cells on the ground. The composite signal levels on the upper floors can be very high, but no server is much better than the others, so the combined SINR from every server is poor.

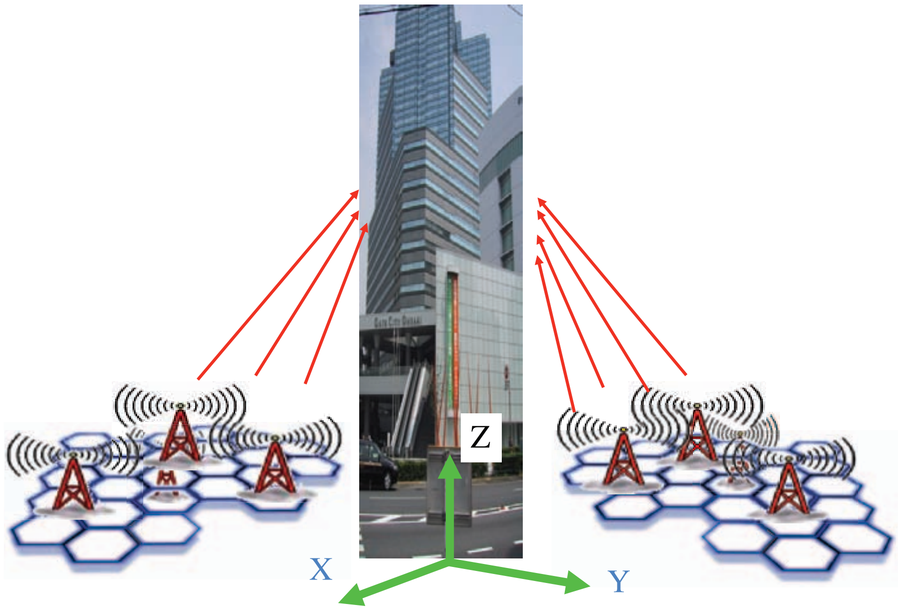


Figure 4: "Pilot pollution" of upper floors caused by cells on the ground

Effects Caused by Mobility

Vehicles moving at high speed may be subject to much worse cell-edge SINR due to a "handover dragging effect." Essentially, this is caused by the fact that a fast-moving UE cannot always be served by the best server, because handover is not triggered until the UE has moved across the cell border, and there is a time lapse while handover completes.

When a UE moves across the cell border, before handover completion, it is served by the original cell (serving cell), which now becomes the second- or third-best server. The UE will not be served by the best server until after the handover is successfully completed (Figure 5). The reason the serving cell cannot be the best server is due to the handover trigger condition (Event A3 as defined in [2]): The RSRP from a new candidate cell must be better than the RSRP of the current serving cell by a certain margin (=Hysteresis) in order for the handover trigger to happen. Therefore, at the handover trigger point, the serving cell is not the best server, but the candidate cell is. Also there is a time-to-trigger after Event A3, so the faster the moving speed, the farther away the UE will go before it can be switched to the best server.

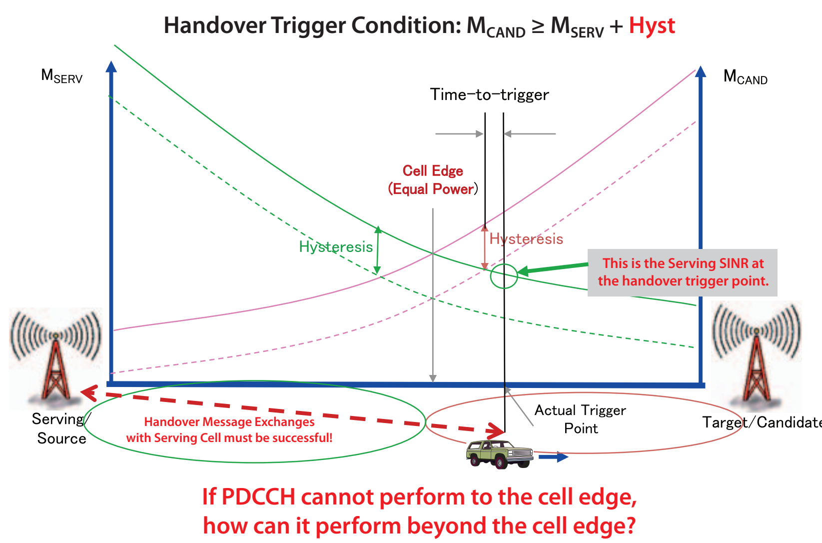


Figure 5: Factors influencing successful LTE cell handover

However, the UE must first have message exchanges to the current serving sell (which is not the best server), and handover can only be successful after these message exchanges are successful with the current serving cell (Figure 6). Handover message exchanges are defined in [3].

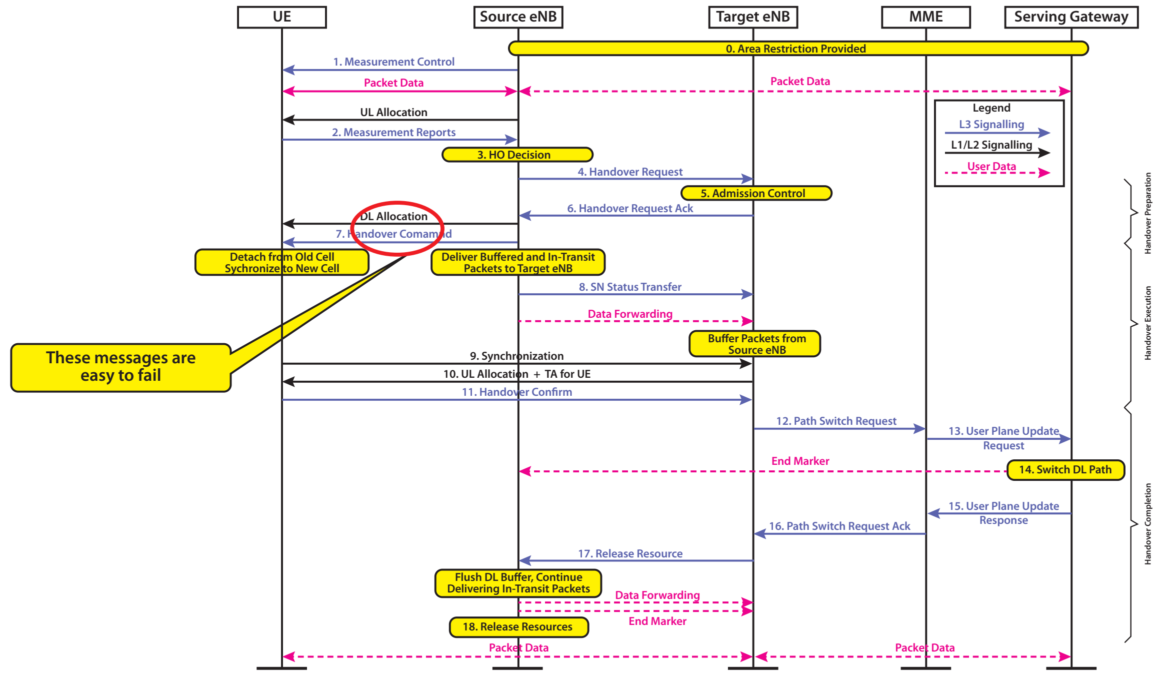


Figure 6: Handover message exchanges, first with the serving (source) cell, then with the candidate (target) cell

The common problem is that near the cell edge, the SINR from the best server is already very poor, and the SINR values from the second- and third-best servers are even worse. Figure 7 shows the overlapping regions among the best, second-best third-best servers near the cell edges. 3GPP simulation only shows the SINR distribution from the best server. However, in real-life situations, the UE also has to work with the second- or –third-best server, so the real-life situation is less favorable.

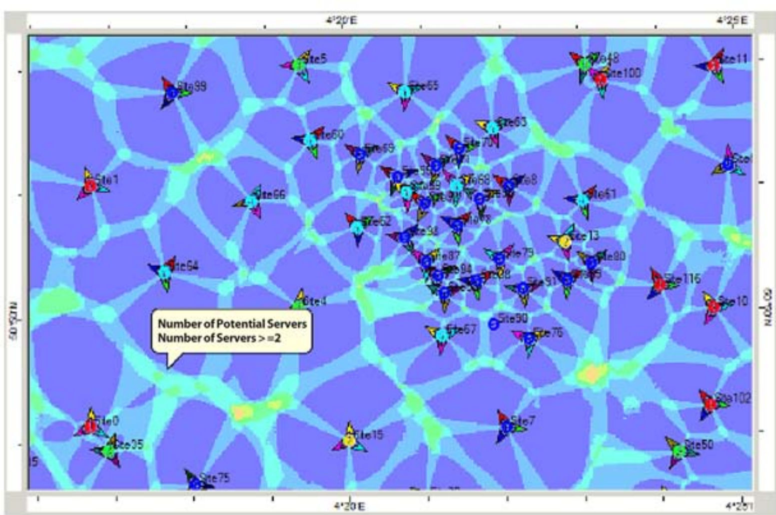


Figure 7: Overlapping areas of the best-, second-best and third-best servers near the cell edge

Failure rates for message exchanges with the serving cell, under the worst-case scenario, can be high. Figure 8 shows the simulated cell-edge SINR values for different mobile speeds [4], [5]. One can see that the high-speed mobile may see cell-edge SINR values worse than –30 dB; no channel can operate with such poor SINR values.

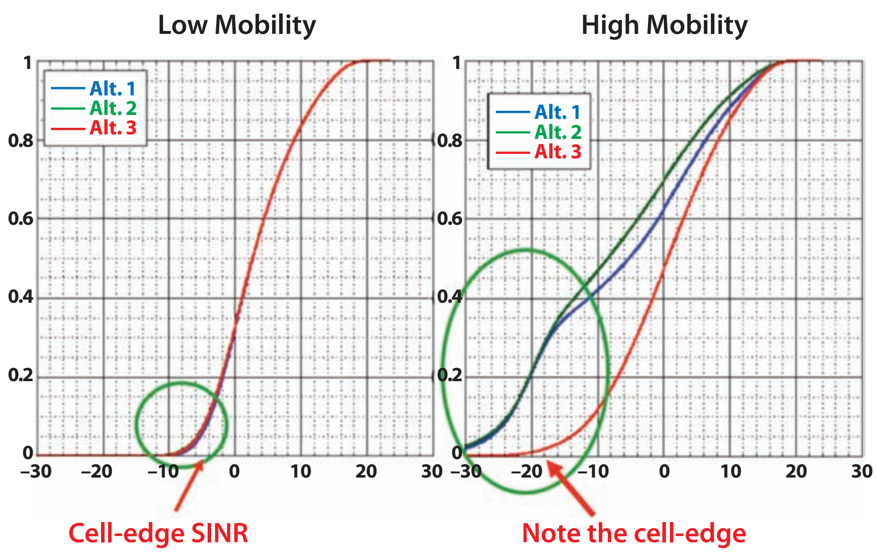


Figure 8: SINR distributions of UE with low mobility (left) and high mobility (right)

Note that Figure 8 is based on simulations using the 3GPP model, which is very idealistic; every handoff has a well-defined cell border and unique target cell. In reality, these boundaries and targets are far from clear, especially in areas with "no dominant server" (Figure 9). There can be multiple cell borders and different target cells at different times, due to fast variation of SINR from each server (Figure 10). This SINR fluctuation is the reason a relatively large hysteresis is needed in the handover triggering condition, otherwise it will "ping pong." However, the larger the value of the hysteresis, the worse the handover dragging effect will be, and the worse the cell-edge SINR from the serving cell.

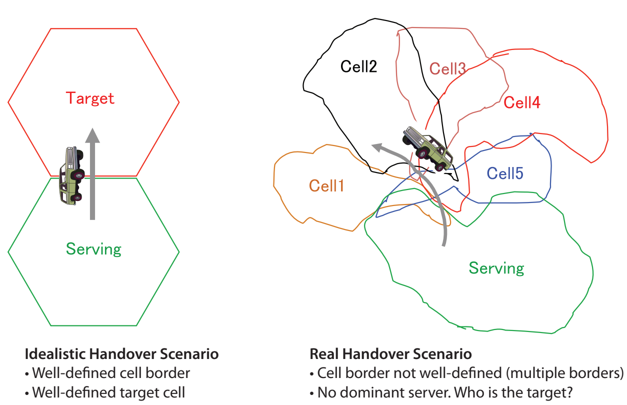


Figure 9: Idealistic and real handover scenarios

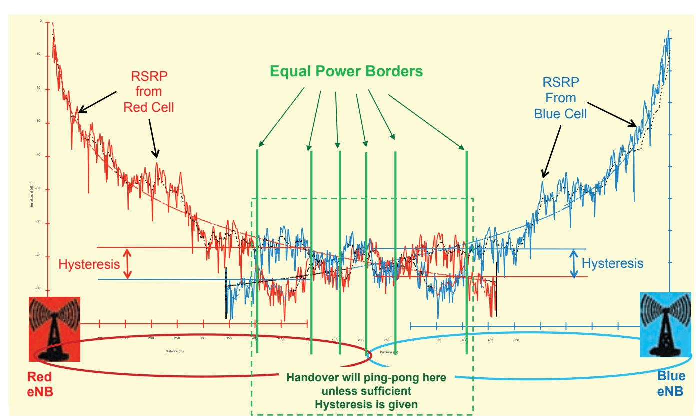


Figure 10: Even if there are only two cells, there can still be multiple "cell borders" (equal power borders)

This handover dragging effect is particularly severe for small cells with high-speed UEs, which is a difficult situation for any cellular system. Some people argue that high-speed UEs should not be in urban areas with small cells, due to frequent red-light stops. This is not always true. In modern cities, highways can go through cities and cars can drive at high speeds without making stops; bullet trains can also pass through cities at high speeds, as shown in Figure 11.

Figure 11: Examples of high-speed vehicles in urban environment with microcells

Radio Link Failure and PDCCH Performance

PDCCH's performance is important not only because it delivers the scheduling information to the UEs. It is also important because the RLF condition is based on BLER on PDCCH/PCFICH.

- When a UE first tries to access the network, PDCCH failure can result in delayed access or access failure.
- During handover, PDCCH failure will cause handover failure since downlink messages (response from the eNodeB) cannot be successfully delivered to the UE.
- While BLER of 10% is normal for traffic channel in the first transmission (thanks to H-ARQ re-transmissions), the BLER target for PDCCH must be much lower, since H-ARQ cannot be applied to control channels. As a matter of fact, PDCCH BLER exceeding 10% means RLF [6]. Figure 12 shows the UE behavior during RLF, as defined by [7].

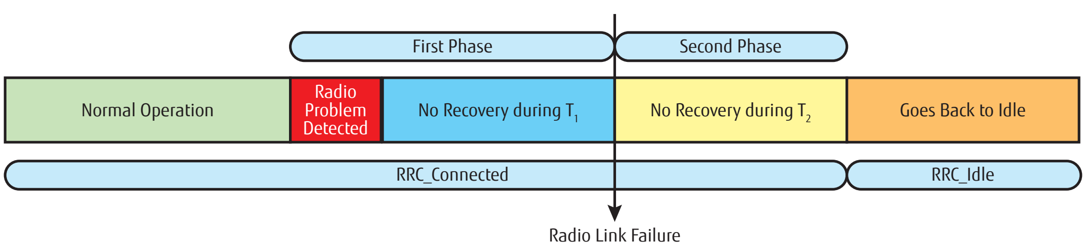


Figure 12: Two phases of RLF as defined in TS 36.300, Section 10.1.6

What kind of SINR will result from a PDCCH BLER in excess of 10%? Vendors have performed simulations and the results are summarized in RAN-4 documents [8]-[14]. One can see from Figure 13, that the BLER of PDCCH reaches 10% when SINR values drop to between –3 dB and –5 dB.

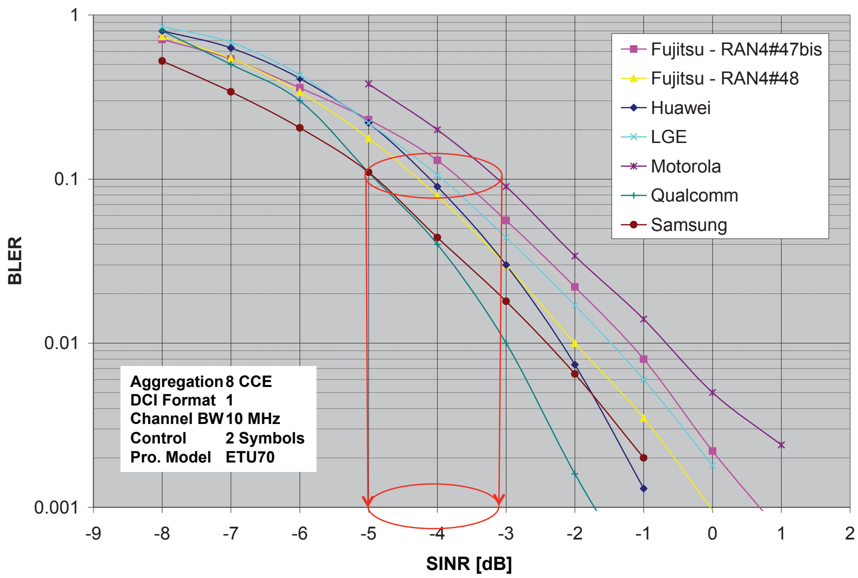
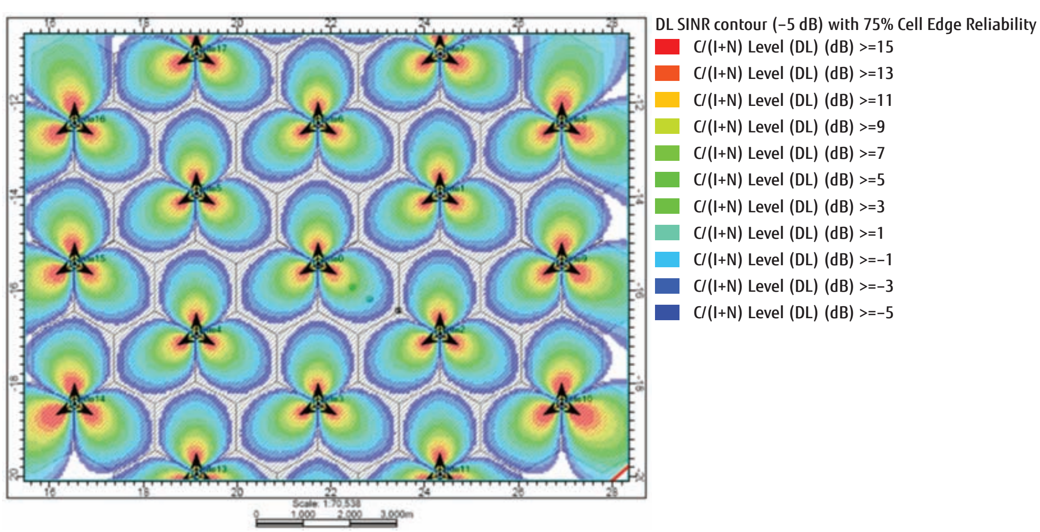


Figure 13: Comparison of PDCCH performance results from different vendors' simulations

Consider the best-case scenario, where SINR = –5 dB is needed to avoid RLF. How much area can contours of SINR = –5 dB cover for N=1 networks? Figure 14 shows the results from 3GPP-like modeling. One can see that even in such an idealistic network, under the best-case scenario SINR = –5 dB contours cannot reach the cell edge with 75% of cell-edge reliability.



Contours of SINR = –5 dB cannot cover to the cell edge with 75% of edge reliability

Figure 14: Coverage contours of SINR=–5 dB under N=1 scenario

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One may wonder, if the contour of SINR = –5 dB cannot even reach the cell edge, how handover can ever be successful since it requires the PDCCH to perform beyond the cell edge?

The answer is, only under the "true N=1" scenario (i.e., all subcarrier frequencies are used in all cells), contours of SINR = –5 dB cannot reach the cell edge. However, in most other cases, the interference scenario in PDCCH is not a "true N=1." PDCCH has a way to mitigate co-channel interference from direct neighbors, as long as it is not fully loaded. It uses a scrambling mechanism in which the symbol quadruplets of the CCEs from each cell are shifted to different sub-carrier frequencies, or different symbols, to randomize and reduce the probability of collisions with direct neighbor cells, as shown in Figure 15. For details about PDCCH multiplexing and scrambling, please refer to [15].

The result is that the PDCCH's co-channel interference in most cases is closer to N=3 instead of N=1, as long as the loading on PDCCH is light so that most REs in the PDCCH control region are not occupied. On the other hand, if PDCCH from all cells are fully loaded, then the co-channel interference scenario will be in the region of N=1.

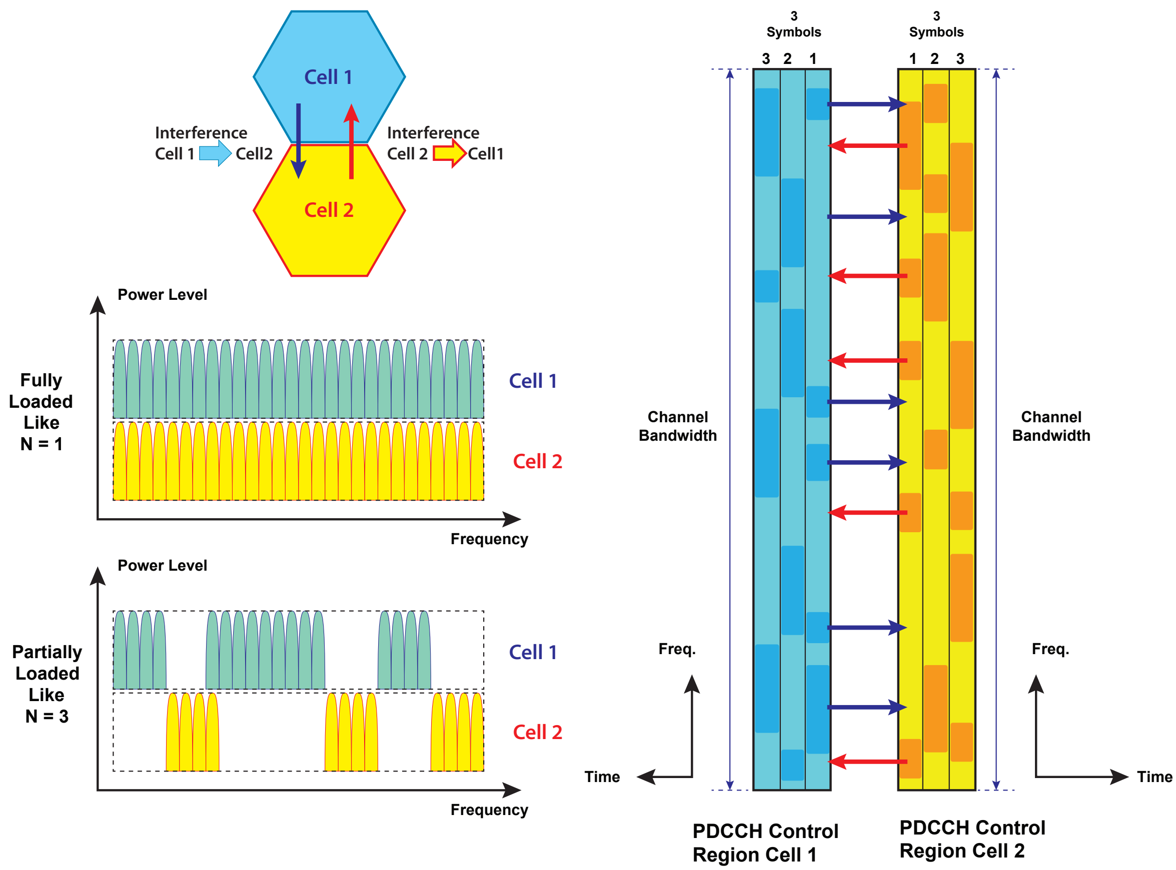

Figure 15: Interference scenarios for PDCCH (for illustration purposes only)

Figure 16 shows the coverage of the contour SINR = –5 dB for N=3. Because for N=3, the direct neighbors do not cause co-channel interference, one can see that the contour of SINR = –5 dB can go much farther beyond the cell edge. This means that PDCCH will probably not have cell-edge performance issues, as long as the loading level on PDCCH is light so the out-of-cell interference scenario is more like that for N=3 instead of N=1.

This leaves one important question: what will produce heavy load on the PDCCH? This depends on the type of data traffic; some traffic types tend to load traffic channels more than control channels; other types of data models will load control channels more than traffic channels.

- When the network is supporting a small number of high data-rate users (e.g., FTP, video streaming), it loads the traffic channels much more than the control channels. Because of the small number of users per cell, the control channel is lightly loaded. This is likely to be the case for initial LTE deployments.
- The PDCCH's load will become heavy if there are a large number of low-rate users in the cell, such as the case for VoIP deployment. A large number of low-rate users tends to heavily load the PDCCH and lightly load the traffic channels. For VoIP, the overall capacity limit is due to the PDCCH capacity limit. This is the case even with semi-persistent scheduling [16].

N=1/3, Composite Coverage of DL SNR Countour (–5 dB) with 75% Cell Edge Reliability

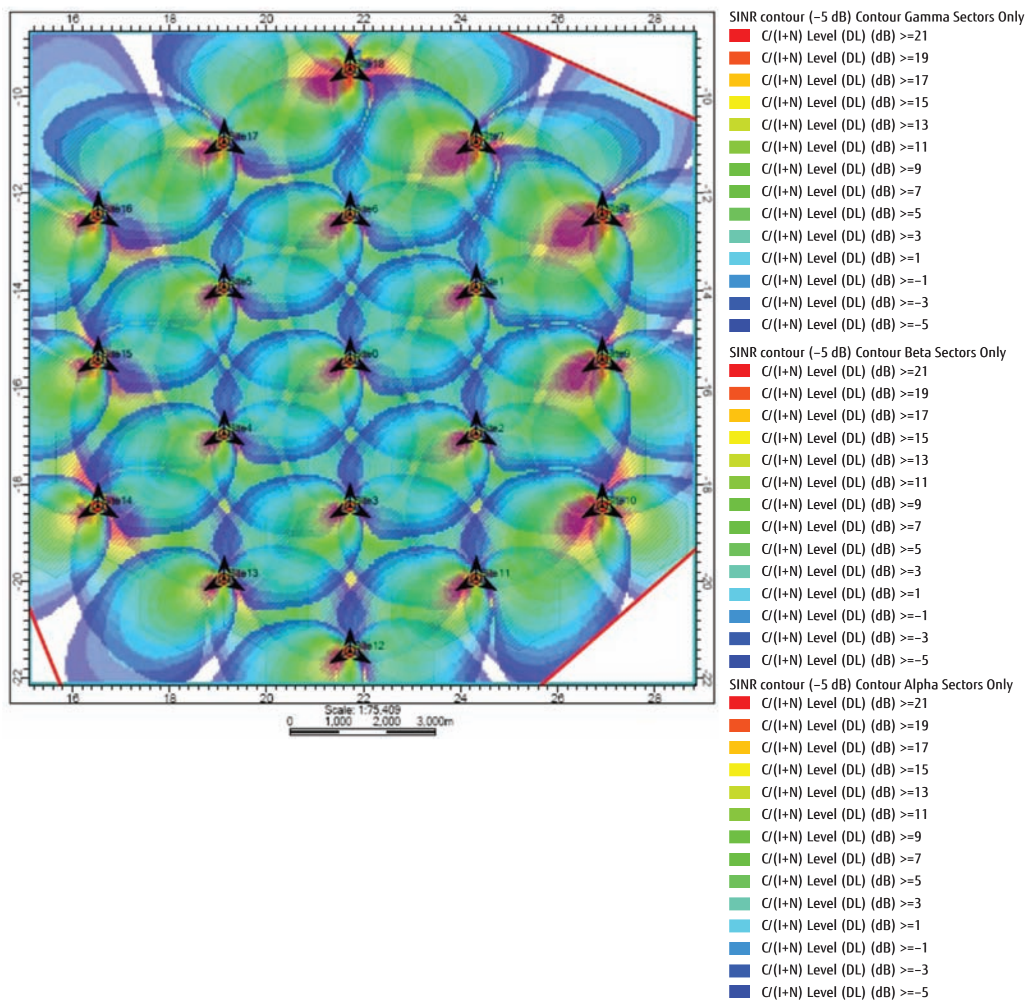

Figure 16: Coverage contour of SINR = –5 dB under N=3 scenario

Cell-edge performance issues due to PDCCH will become worse after massive deployment of VoIP, which tends to heavily load the PDCCH. Figure 17 shows one simulation result of probability of PDCCH collision as a function of the loading level.

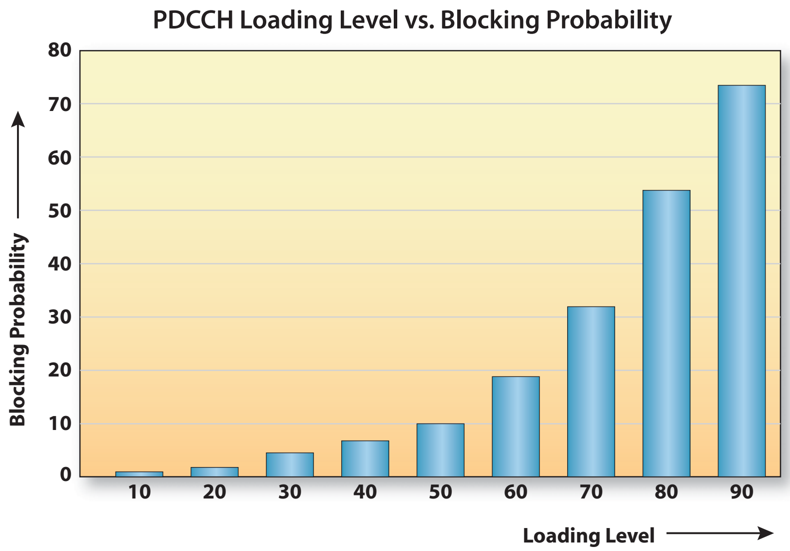

Figure 17: CCE collision probability increases with the PDCCH loading level

When PDCCH is fully loaded, scrambling can no longer avoid collisions with the neighbor cells. As a result, the interference scenario will be more like N=1, the service area of SINR = –5 dB will shrink, and cell-edge performance will become worse.

Inter-Cell Interference Coordination (ICIC)

A spread-spectrum system (like CDMA or UMTS) can work under very negative SINR because of the large processing gain for low data rates; soft handoff also helps tremendously. LTE air-link cannot work under the same negative SINR conditions, and does not support soft handoff. The industry recognized these cell-edge challenges, and responded by creating ICIC. Essentially, ICIC reduces the co-channel interference cell-edge users experience from direct neighbor cells, by increasing the cell-edge SINR values.

Traffic Channel ICIC

Although the scheduler has many dimensions to work with, the frequency and power domains are the main areas traffic-channel ICICs work with [17], [18]-[20].

In the frequency domain, the scheduler has the freedom to allocate any RB frequencies within the channel bandwidth. Working in the frequency domain is easy for traffic channels because the UE can easily find scheduling information from PDCCH, thus RB frequencies can be dynamically allocated. ICIC can allocate different RB frequencies to cell-edge users in different cells to avoid or minimize co-channel interference with direct neighbors. Furthermore, LTE defines a few mechanisms to measure or notify direct neighbors of the out-of-cell interference levels on each RB (HII, OI, RNTP) [21].

Working in the power domain is also relatively easy, as fast power control is performed on the UL anyway. Also, the DL power level on selected RBs can be changed, for example, power boost for cell-edge users. Figure 18 shows two examples of traffic channel ICIC algorithms. The figure on the left shows an example for frequency-domain ICIC: frequency allocations for cell-edge users are restricted to about 1/3 of total channel bandwidth in order to avoid co-channel interference with direct neighbors; cell-center users can use the full bandwidth. The figure on the right shows an example of ICIC that works on both frequency domain and power domain: cell-edge users use one-third of the bandwidth but higher power; cell-center users use full bandwidth but lower power.

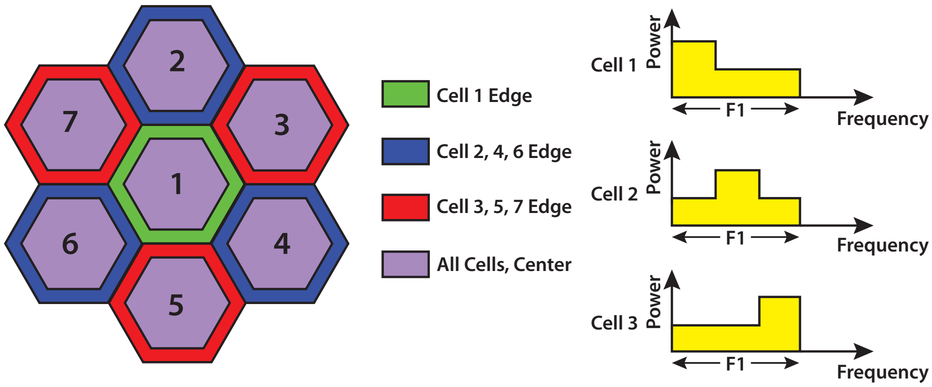

Figure 18: Schematic diagram of various traffic channel ICIC solutions, showing ICIC in frequency domain (left) and ICIC in frequency and power domains (right)

ICIC on PDCCH?

The existing traffic-channel ICIC algorithms will not directly work on PDCCH, because PDCCH has a very different channel structure and is much less flexible. First of all, the scheduler does not have the freedom of trying to avoid co-channel interference by dynamically restricting the PDCCH bandwidth as it does with traffic channel RBs. Secondly, there are no X2 messages that support ICIC on PDCCH, at least not in the current release.

CCE-based power boost is one way the scheduler can play in the power domain.

- CCE aggregation level can be 1, 2, 4 or 8 (CCE-1, CCE-2, CCE-4 or CCE-8). The higher the aggregation level, the more robust it will be. However, high aggregation levels also use more PDCCH resources. Therefore, cell-center users will use CCE-1 or CCE-2; users located somewhere in the middle will use CCE-2 or CCE-4; cell-edge users will always use CCE-8.
- CCE-based power boost can boost up the transmit power level on CCE-8, which can potentially increase the signal level on CCEs for cell-edge users.

How effective is the CCE-based power boost? Cells in a network can be in one of the following three scenarios:

- **Coverage-limited environment:** The cells are spaced very far apart from each other. Examples are rural and highway cells. Typically the signal levels near the cell edges are already very low; as a result, the out-of-cell interference levels are also very low. For coverage-limited environments, one can approximate using the formula below:

$$SINR = \frac{S}{n + I} \approx \frac{S}{n} = \text{SNR}$$

In this case, boosting the signal power enhances "S," and thus improves SNR since thermal noise is just a constant. So CCE-based power boost is effective in a coverage-limited environment.

- **Interference-limited environment:** The cells are packed very close to each other. Examples are dense suburban, urban or dense urban with small cells. Typically the cell-edge composite signal level is very high, but the out-of-cell interference level is also very high. As a result, the cell-edge SINR is still poor. For interference-limited environment, one can approximate using the formula below:

$$SINR = \frac{S}{n + I} \approx \frac{S}{I} = \text{SIR}$$

In this case, CCE-based power boost will not be effective, because when signal power is boosted up, the out-of-cell interference level is also increased, and as a result the SIR is not improved. Generally, when cell-edge power level is already very high, boosting the power further will not help.

- This phenomenon is the so-called "cocktail party effect:" in a cocktail party with high noise level in the background, it does not improve audibility if everyone increases their voice level; it just creates a higher level of background noise.
- Unfortunately, an interference-limited environment is the area where help is most needed. Call drops happen most frequently in small cells, especially calls placed from fast-moving vehicles.

- **Environments somewhere between interference-limited and coverage-limited:** The cells are neither very close nor very far from each other. Examples are most light suburban cells. As long as both "I" and "n" terms are not negligible in the SINR equation, boosting the signal level will help somewhat, but this is not as effective as the situation for coverage-limited environments. The degree of effectiveness depends on the magnitude of "I"versus the magnitude of n; the higher the ratio of I/n, the less effective it will be, and vice versa. Because most times I > n, so the main issue here is that the gain achieved from CCE-based power boost may not be sufficient to handle the worst-case scenario.

Figure 19 shows the achieved cell-edge SINR gain as a function of "interference to noise ratio" (I/n), for a fixed 6 dB power boost. Assume that initially the SINR = –5 dB. One can see that if there is almost no interference (I/n < –20 dB), a 6 dB power boost results in almost 6 dB SINR gain. On the other extreme, if interference is high (I/n > 20 dB), a 6 dB power boost results in practically no gain on cell-edge SINR. In fact, as long as I > n, the SINR gain from power boost is small.

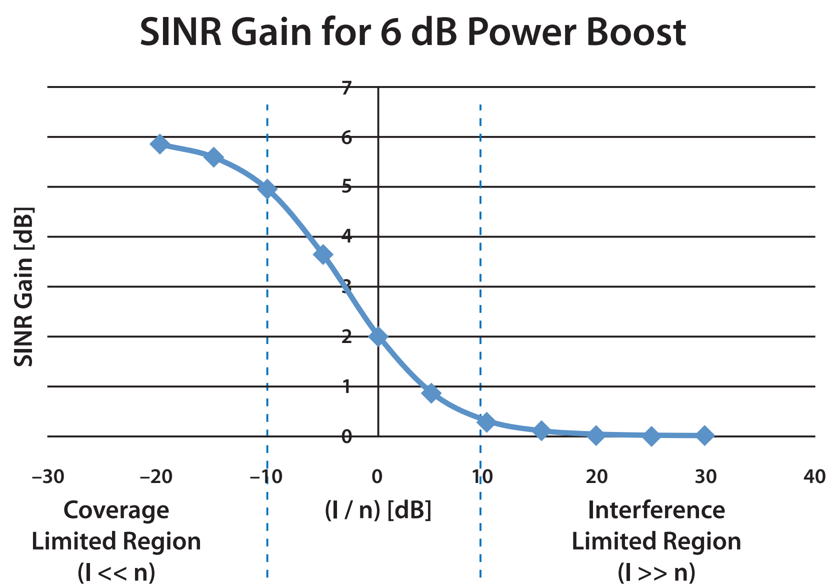

Figure 19: Cell-edge SINR gain achieved due to a 6 dB power boost, as a function of I/n

It is clear that an effective method is needed to enhance the cell-edge performance for interference-limited environments. Also, for most suburban cells, it is helpful to have a method that can produce higher gain than the CCE-based power boost.

High-Level Discussions of ICIC on PDCCH

LTE-Advanced (3GPP Release 10) supports new features like carrier aggregation and cross-carrier scheduling [22], which can be used to avoid co-channel interference on PDCCH. However, there are still some issues. First of all, LTE-Advanced will not be deployed until many years from now. Secondly, even after it is deployed, one still faces the issues of legacy terminals that do not support carrier aggregation and cross-carrier scheduling. Therefore, solutions are still needed for the current (Release 8), and future (Release 9) systems.

Although the current standard does not give specifics on how to do ICIC on PDCCH, any proposed ICIC algorithm must comply with the current standard. Proposals requiring changes of standard will take too much time and effort to implement.

Physical resources in the LTE downlink have three dimensions: time, frequency and power. Therefore, these are the dimensions with which the ICIC algorithms can work.

Time Domain

In the time domain, note that for FDD system, the H-ARQ process uses an 8 ms time structure (Figure 20).

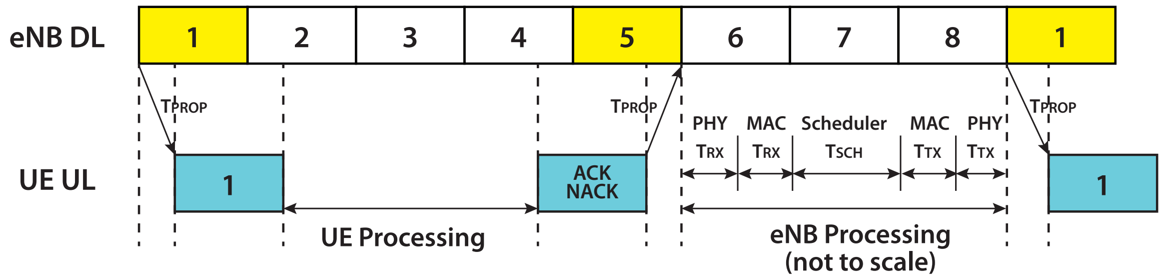

Figure 20: H-ARQ timing for FDD

For TDD frames, the H-ARQ timing structure varies depending on the DL and UL allocation. Any ICIC algorithm working on the time dimension must comply with the H-ARQ timing structure.

Power Domain

CCE-based power boost is one simple solution that works on the power domain. However, due to its simplicity, it has the drawback of causing extra out-of-cell interference at the same time, which makes it ineffective in an interference-limited environment. A more intelligent algorithm could be designed to enhance the signal level without simultaneously increasing out-of-cell interference. If this algorithm could reduce the out-of-cell interference at the same time as increasing the signal level, that would be even more effective.

Frequency Domain

As mentioned previously, most traffic-channel ICIC algorithms work in the frequency domain. This is not only because this type of solution is very effective under interference-limited environments. It is also very easy to implement a dynamic frequency allocation algorithm, since the UE can easily find the allocated RB frequencies from PDCCH. The X2 messages defined for traffic ICIC are another reason.

PDCCH is not that flexible. As a control channel, it contains the scheduling and RB frequency allocation information for traffic channels. But there is no signaling mechanism to tell the UE where to find the CCEs if CCEs were to “jump around” dynamically to avoid co-channel interference. UEs must perform blind detection to find CCEs. Also, currently there is no X2 message to support ICIC in PDCCH.

Therefore, a more intelligent algorithm is needed to work in the frequency domain. It is possible to work on other dimensions and/or other parameters which have indirect effects in the frequency domain, thereby reducing the collision probability, and thus reducing the co-channel interference on PDCCH.

Pros and Cons

The cellular environment can be coverage-limited, interference-limited or somewhere in between. ICIC algorithms can work in the time domain, power domain, frequency domain or a combination of these. Different kinds of algorithms have different degrees of effectiveness in different types of environment.

Interference-Limited Environment

The main issue here is "too much interference" rather than "not enough signal." Therefore, the most effective solution for this type of environment is to reduce or remove co-channel interference, not to increase the signal level.

Therefore, ICIC algorithms that work in the time or frequency domains will likely be more effective. If the contribution of co-channel interference from direct neighbors can be removed, the cell-edge SINR gain can be 10 dB or more, for a fully loaded system, as shown in Figure 21.

Algorithms working in the power domain can also produce significant SINR gain, but the key here is to reduce the out-of-cell interference, rather than boosting the signal level.

Coverage-Limited Environment

The issue in coverage-limited environments is indeed one of "not enough signal." Since there is not much out-of-cell interference in this type of environment, algorithms trying to remove or reduce out-of-cell interference will have no effect. Power boost is the most effective solution.

Environments in Between the Two Extremes

In environments that fall between coverage-limited and interference-limited environments, both increasing the signal level and reducing out-of-cell interference will work. However, algorithms that can do both, i.e., simultaneously increasing signal and reducing interference will be most effective.

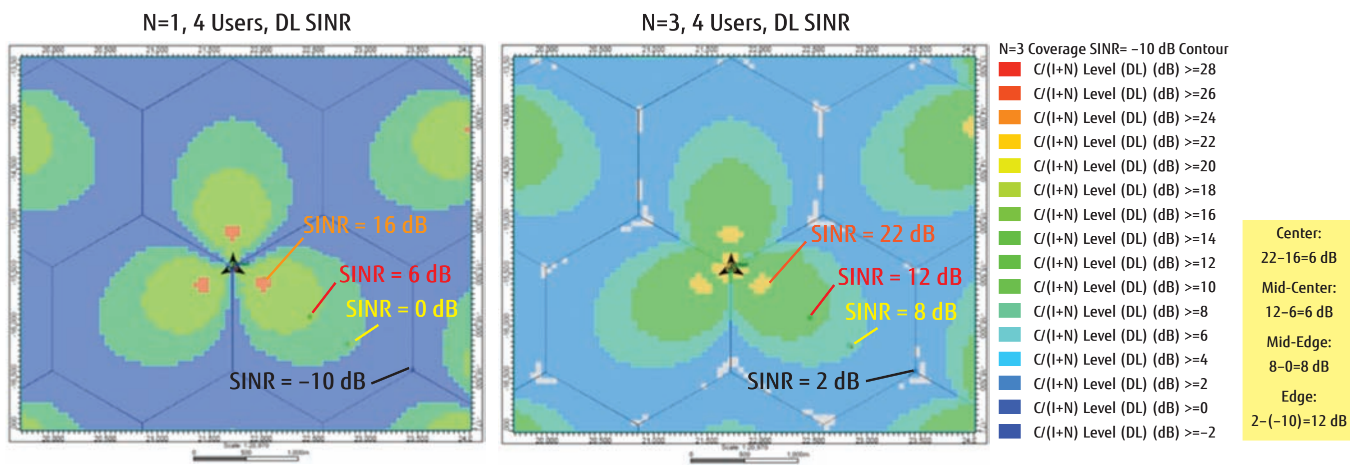

Figure 21: Cell-edge SINR improvement due to the removal of co-channel interference from direct neighbors (for interference-limited environments)

Summary

The main topic of discussion is that of interference-limited environments. If PDCCH becomes fully loaded, the cell-edge performance can be poor due to control channel issues. Handover failure often results from RLF, which is based on BLERs from PDCCH. The situation is even worse for high-speed vehicles in small cells. Therefore, traffic channel ICIC alone may not be sufficient to guarantee cell-edge performance.

ICIC can work on PDCCH to enhance the cell-edge performance. However, ICIC algorithms for PDCCH will be different from traffic channel ICIC due to the differences in channel structures and the fact that control channels are less flexible. Depending on the network environments, different ICIC algorithms will have different degrees of effectiveness. Therefore, it is best for an operator to use different algorithms in different situations such as rural/highway, suburban, urban or dense urban to produce the best results.

References

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Acronym	Description
BLER	Block Error Rate
DL	Downlink
EnodeB	Evolved Node B (LTE Base Station)
HII	High Interference Indicator
ICIC	Inter-Cell Interference Coordination
LOS	Line-of-Sight RF Propagation Condition
NLOS	Non-LOS Propagation Condition
OI	Overload Indicator
PDCCH	Downlink Physical Control Channel
RB	Resource Block
RE	Resource Element
RLF	Radio Link Failure
RNTP	Relative Narrowband Transmit Power
RSRP	Reference Signal Received Power
SINR	Signal-to-Interference & Noise Ratio
SIR	Signal-to-Interference Ratio
SNR	Signal-to-Noise Ratio
UE	User Equipment (LTE Terminal)
UL	Uplink

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