Interference Coordination and Cancellation for 4G Networks

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ABSTRACT

This article provides an overview of contemporary and forward looking inter-cell interference coordination techniques for 4G OFDM systems with a specific emphasis on implementations for LTE. Viable approaches include the use of power control, opportunistic spectrum access, intra and inter-base station interference cancellation, adaptive fractional frequency reuse, spatial antenna techniques such as MIMO and SDMA, and adaptive beamforming, as well as recent innovations in decoding algorithms. The applicability, complexity, and performance gains possible with each of these techniques based on simulations and empirical measurements will be highlighted for specific cellular topologies relevant to LTE macro, pico, and femto deployments for both standalone and overlay networks.

INTRODUCTION

The growing demands on mobile networks to support data applications at higher throughputs and spectral efficiencies has driven the need to develop Orthogonal Frequency Division Multiplexing (OFDM) based 4th generation (4G) networks, including WiMAX and 3GPP Long Term Evolution (LTE). A key objective with respect to deployment of OFDM 4G networks is to utilize a frequency re-use of one (denoted by $N = 1$) or as close to $N = 1$ re-use as is practical. A frequency re-use of $N = 1$ implies that the base stations in cells transmit on all available time-frequency resource blocks (RBs) simultaneously. Due to transmit power limitations in mobile terminals, the constraint on the uplink link budget will necessitate the need for smaller cell sizes than is typically deployed for present 2nd generation (2G) and 3rd generation (3G) cellular systems. This requirement is driven by the need to meet targeted higher data rate throughputs for users not only near the base station, but also for cell edge users. The resulting interference limited system for $N = 1$ deployment will not achieve the full potential capacity that the LTE standard can support without the implementation at the base station and mobile terminal of one or more viable interference mitigation and/or cancellation techniques.

Interference cancellation and mitigation techniques have been investigated and deployed with varying degrees of success in terrestrial mobile networks for more than 20 years. Traditional approaches to interference mitigation between transmitted signals have focused on either ensuring orthogonality between transmitted signals in time, frequency as well as spatially, or by actively removing and canceling interfering signals from the desired signal if orthogonality between the desired signal and potential interferers cannot be achieved. In early 2G cellular systems such orthogonality was achieved primarily through static pre-planned allocations of radio resources. 3G systems introduced interference cancellation techniques based mostly on a combination of blind information gathering at a base station such as spectrum usage monitoring and coarse exchange of interference indicators such as the Rise over Thermal (RoT) indicator employed in the 3GPP2 1xEV-DO standard. Typically interfering signals have been estimated using blind detection and their estimates subtracted from the desired signals. Good overviews of historical approaches can be found in [1] and the references contained therein.

From a link perspective the downlink (DL) allows for a more tractable analysis since if the desired mobile terminal location is known, the distances to all potential interfering base stations can be easily determined based on the network geometry, and hence a probabilistic based estimate of the signal-to-interference-plus-noise ratio (SINR) can be calculated based on the channel fading conditions for the desired signal and the interfering signals. In addition to AWGN, both the desired signal and interfering signals will experience shadowing, which typically is log-normally distributed. Analysis of the uplink (UL) interference requires knowledge of not only the location of the desired mobile terminal under consideration, but also the relative locations of all potential interfering mobile terminals, for which both the locations of the interfering terminals, the number of potential terminals, and their spatial velocity will be random variables.

LTE offers the capability to provide a flexible dynamic inter-base station approach to interference coordination through the use of inter-base station signaling capabilities, including the use of UL reactive overload indicators (OIs) and proactive high interference indicators (HIIs) that provide bit maps of interference conditions on a per

RB basis. DL inter-cell interference coordination (ICIC) is supported through the use of DL relative narrowband transmit power (RNTP) bit maps providing a coarse power indication on a per RB basis.

The main body of the article is comprised of the next section providing an overview and analysis of existing interference mitigation and cancellation techniques that have been studied in the open literature and/or implemented in existing cellular systems. We then provide a comparison of the identified ICIC approaches for LTE along with implementation recommendations, followed by the conclusions in the final section.

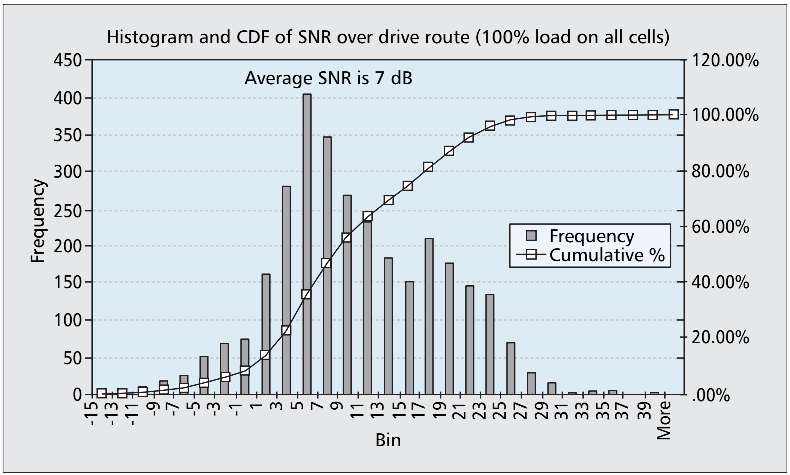

Figure 1. *Typical measured SINR distribution for a deployed LTE system in an urban environment.*

Overview of ICIC Techniques

The challenge with deploying a static $N = 1$ frequency re-use OFDM system in an interference limited environment is that for a fully loaded deployment, significant regions of coverage will experience negative SINR levels, resulting in gaps in the deployed coverage, irrespective of the inter-cell distance. Figure 1 illustrates a typical SINR distribution for 100 percent loading, as measured in an urban LTE trial deployment with nine cells. It can be seen that on the order of 15 percent of users will experience negative SINR, with some users experiencing negative SINR levels of –10 to –15 dB. It should be noted that in a fully loaded interference limited cellular deployment the severity of the SINR degradation will be highly dependent on the average path loss exponent. For a cellular deployment with a fixed inter-cell distance, high path loss propagation environments with path loss exponents up to a 5th or 6th order will experience less overall interference than deployments with lower path loss exponents, since potential interfering signals from neighboring cells will be more greatly attenuated in the former case. Even though there will be significant SINR variation depending on the propagation environment, in order to robustly deploy an LTE OFDM system one will have to mitigate the inevitable negative SINR coverage regions that will exist.

The following sections provide an overview of a number of techniques to address the potential SINR coverage holes, including power control, both static fractional frequency reuse (FFR) and adaptive fractional frequency reuse (AFFR), AFFR with tiering, intelligent SINR based scheduling, opportunistic scheduling and access techniques, multiple-input multiple-output (MIMO), and space division multiple access (SDMA) antenna techniques, as well as beamforming. Note that these techniques can be based on both intra and inter-base station communication approaches.

Power Control

Historically power control has been employed in cellular systems to minimize near-far dynamic range effects by constraining the UL power to be received with a constant power level at the base station. Such an approach, while not optimal from an aggregate throughput or spectral efficiency perspective, assures fairness to cell edge users. Recent investigations for 4G propose a compromise approach by controlling the power to compensate for a fraction of the path loss, as opposed to the full path loss for cell edge mobile terminals ([2] and the references therein). Use of fractional power control in interference limited environments has been shown to provide improvements in aggregate sector throughput on the order of 20 percent over traditional power control for scenarios employing inter-cell distances of 500 m to 1 km and a bandwidth of 10 MHz. For deployment scenarios with a small inter-cell distance (ISD) on the order of 500m, fractional power control also shows an increase in 5 percentile cell edge throughput on the order of 10–15 percent over traditional power control. However for larger macro cells with ISDs on the order of 2 km, the gain in aggregate throughput is traded off against a small loss in cell edge user throughput on the order of 20–30 percent [2]. It should be noted that although theoretically optimal power control approaches such as water filling can provide higher aggregate throughput gains, this is typically achieved at the expense of fair cell edge throughput.

Moving beyond the intra-eNodeB power control algorithms described above, power transmitted to or from a mobile can be optimized from a network inter-base station or macro diversity perspective. This approach can be applied in combination with relay networks. It is possible to define a number of distributed power control scheduling algorithms optimized for cell edge user throughputs, aggregate network throughputs, and max-min fairness, as well as intermediate variants such as proportional fair share (PFS) or harmonic mean fairness [3]. The PFS and min-max algorithms have shown potential gains of 30-80 percent. Note that unless otherwise specified, performance results quoted in this article are based on the 3GPP simulation methodology typically with ISDs of 0.5 to 2 km and log-normal shadowing with a standard deviation of 7–8 dB.

Static Fractional Frequency Reuse

Fractional frequency reuse (FFR) involves partitioning the usable spectrum into a number of subbands and assigning a given subband to a cell in a coordinated manner that minimizes inter-

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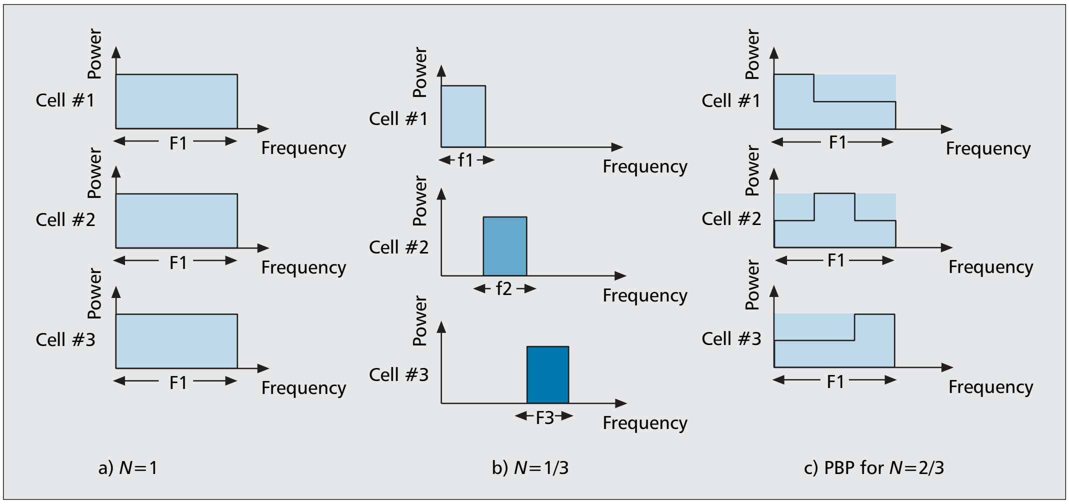

Figure 2. *Adaptive FFR modes: a)* N = *1; b)* N = *1/3 and; c) PBP for* N = *2/3.*

cell interference. For example, for an $N = 1/3$ FFR re-use pattern, each cell would be assigned a subband spanning 1/3 of the available spectrum. Basic $N = 1/3$ FFR results in an improvement in SINR due to reduced interference levels; however, due to a reduction in available BW, the aggregate throughput is typically about 75–80 percent of the aggregate throughput of an equivalent system employing $N = 1$ reuse. However, due to the improvement in SINR, any coverage gaps for cell edge users can typically be mitigated, although total cell edge user spectral efficiency compared to $N = 1$ performance does not typically improve significantly. It should also be noted that use of FFR in an LTE OFDM system will reduce the available number of RBs that can be scheduled and hence the peak throughput, potentially impacting the possible quality of service for high bandwidth applications.

Adaptive Fractional Frequency Reuse

Further improvements in SINR can be achieved by adapting the FFR assignments based on interference levels, as well as scheduling users with a given subband based on channel quality measurements (CQI) fed back from the mobiles [4]. An AFFR implementation can be based on the notion of Power Bandwidth Profiles (PBPs). Figure 2a–c illustrates allocations of bandwidths for $N = 1$, static $N = 1/3$, and PBPs for an $N = 2/3$ FFR scheme, respectively. As illustrated in Fig. 2c, the difference in power spectral density within a given PBP is defined as the power split (PS). For the example considered here the power split is 3 dB.

Table 1 provides a summary comparing the throughput of 10 MHz LTE deployments employing $N = 1$ re-use, $N = 1/3$ re-use, and AFFR with $N = 2/3$. It can be seen that the sector throughput of AFFR is close to $N = 1$ and both outperform $N = 1/3$ by close to 30 percent. AFFR also improves cell-edge user throughput over $N = 1$.

The process of adapting the FFR operation comprises a number of steps based on moving between the $N = 1$, 1/3, and 2/3 reuse modes as defined in Fig. 2. Each base station would begin in, for example, mode 1 (i.e., $N = 1$ re-use) and maintain a record of throughput levels, coverage and or interference problems through use of a channel quality indicator (CQI) and handover feedback from the mobiles it is serving. If a base station in mode 1 detects a problem (for example, the number of users at the cell edge with data to transmit/receive exceeds a certain threshold) then the scheduler for that base station can transition to employing mode 2 (i.e., $N = 2/3$ reuse) and send a message to neighboring base stations to transition to use of mode 2. Note that for an LTE deployment this signaling can be accomplished over the X2 interface between base stations (i.e., eNodeB's). If a neighbouring base station is already using mode 2 or higher no further action by that base station is necessary. Each base station will keep track of which neighboring base station made the request and the requested mode of operation.

Spatial Techniques

Gains due to SDMA and MIMO implementations in OFDMA systems have been extensively researched, and a full suite of MIMO and SDMA techniques are currently defined in the LTE standard, including spatial multiplexing, cyclic delay diversity (CCD), and space frequency block coding (SFBC) on the DL and multiuser MIMO (MU-MIMO) on the UL. The gains of these techniques have been well established through simulation [5] as well as trial implementations. Throughput gains from MIMO in actual implementations have been shown to approach the theoretical maximums for uncorrelated spatial paths (i.e., a 2 times throughput gain for 2×2 MIMO and a 4 times throughput gain for 4×4 MIMO).

Network MIMO

The notion of network MIMO involves transmission of multiple spatial paths to or from a mobile from multiple base stations. On the DL, multiple base stations can transmit one or more MIMO paths to a mobile, whereas on the UL, the transmission by a mobile can be received by one or more base stations. In its simplest form comprised of a single path from each respective base station to a mobile, network MIMO takes on the form of macro diversity. With respect to the UL, the notion of network MIMO can also be combined with the notion of MU-MIMO and interference cancellation to allow mobiles in adjacent cells to be assigned the same RBs, thus improving overall system spectral efficiency. Receiver algorithms such as dirty paper coding can also be employed in combination with network MIMO to improve overall efficiency. One of the challenges with network MIMO implementations is the latency for exchange of information between base stations. In the current Release 8 of the LTE standard, the minimum X2 latency for exchange of information between base stations is 20 msec, whereas RBs are typically assigned on a 1 msec subframe basis, making real time processing of interference cancellation data from adjacent base stations unfeasible.

	$N = 1$	FFR PS = 3 dB	FFR PS = 6 dB	$N = 1/3$	AFFR
Sector Tput (Mb/s)	8.01	7.92	7.79	6.11	7.89
5%-ile Cell-Edge User Tput (kb/s)	286	313	352	292	312
10%-ile Cell-Edge User Tput (kb/s)	311	362	395	368	357

Table 1. *Comparison of* $N = 1$, $N = 1/3$, *and AFFR throughputs in a 10 MHz LTE system.*

Interference Regeneration and Cancellation Techniques

The notion of interference cancellation (IC) is well known and was seriously proposed more than 20 years ago for commercial implementations. The basic concept is to regenerate the interfering signals and subsequently subtract them from the desired signal. Typically this involves storing the received signal in a sample buffer. From an implementation standpoint, it is simplest to cancel signals whose modulation symbols are *a priori* known at the base station (e.g., reference symbols) since the IC process can avoid data demodulation and decoding. The most advanced forms of IC with the largest capacity gains require cancellation of interference from data signals as well.

It is feasible to implement IC in OFDMA systems such as LTE. Although IC techniques can be applied to both downlink and uplink of LTE, due to complexity considerations, IC is considered mainly as a technique for the UL and implemented in the base station receiver. IC techniques can be used to cancel both intra-cell and inter-cell interference. For effective cancellation of inter-cell interference, inter-cell communication is essential. The current version of the LTE standard supports non-real time IC through the X2 interface, which provides inter-base station communication. IC techniques can also be used for canceling interference from MU-MIMO (also referred to as Virtual-MIMO) configurations in the LTE uplink, for which two or more users are scheduled with the same set or overlapping set of physical RBs for uplink transmissions. The simultaneous transmissions could interfere with each other, resulting in degraded SINR performance, and consequently, less than the expected spectral efficiency improvement for MU-MIMO.

The high-level architecture of a typical interference canceling LTE UL receiver at a base station with two receive antenna is shown in Fig. 3. UE_1 is the desired user and UE_2 to UE_n are the interfering users. Note that user equipment (UE) is the LTE equivalent term for a mobile and the subscript refers to the mobile number. Interfering users could arise from within the cell (intra-cell interference) or from outside the cell (inter-cell interference). Intra-cell interference scenarios include UEs purposely scheduled on the same RBs within the cell (MU-MIMO), or

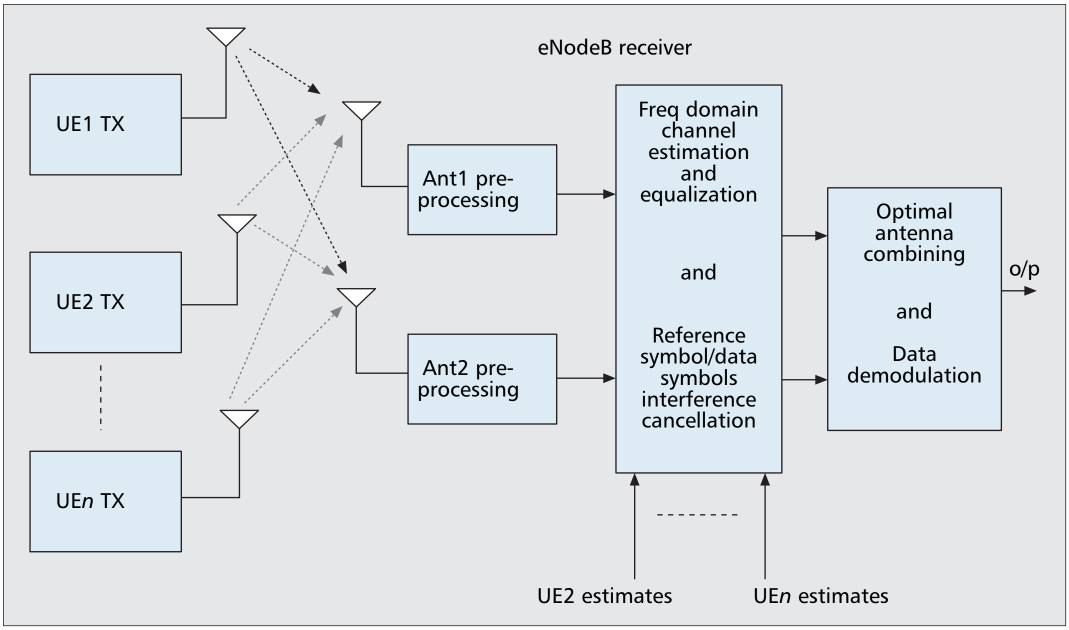

Figure 3. *High level view of interference canceling receiver at eNodeB.*

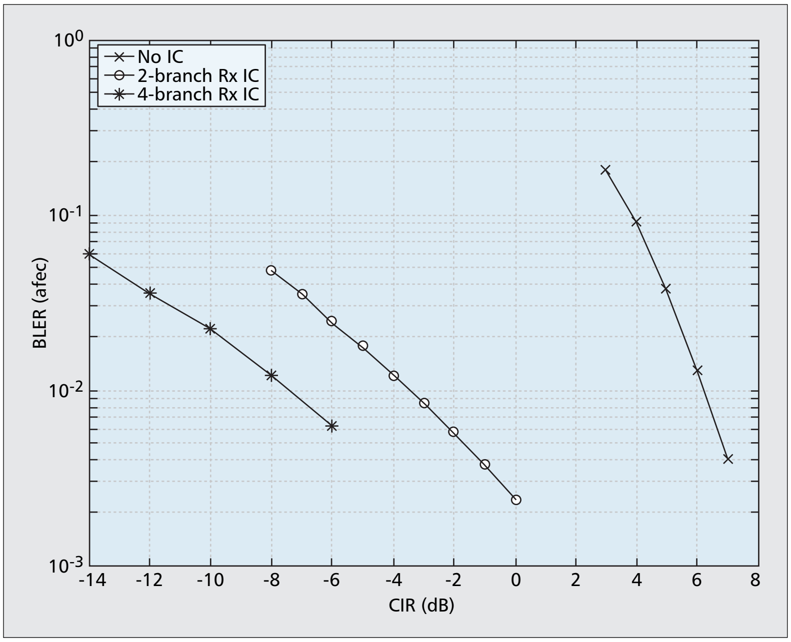

Figure 4. *: Interference cancellation performance with one major co-channel interferer (CCI).*

having UEs within a cell allocated with the same RB during an overload situation. Inter-cell interference scenarios typically involve UEs in neighboring cells being scheduled on the same RB.

The first step in the interference cancellation receiver is the regeneration of the interference from UE_2 to UE_n, for which the signal and channel parameters of the interfering users need to be estimated. The base station receiver first acquires the information on the reference symbol (RS) sequences employed by interfering users UE_2 to UE_n and subsequently estimates both the channel gain and phase as well as the time delay estimates of the interfering signals from this RS information. With these estimates, the base station receiver can regenerate the interfering signals of UE_2 to UE_n and subsequently, subtract them from the received signal. If the channel estimates are accurate, the regenerated signal will be an accurate estimate of the actual interfering signal and the subtraction process can substantially cancel the interference from the signal of the desired user UE_1. It is therefore essential that accurate channel estimates, frequency offset estimates, time delay estimates, and received power estimates are available under all fading scenarios. Minimum mean squared estimation (MMSE) and maximum likelihood sequence estimation (MLSE) techniques are both viable channel estimation approaches. Note that the interference regeneration and cancellation steps need to be performed successively to realize the potential capacity and throughput advantages offered by this technique.

Figure 4 shows the possible improvement in block error rate (BLER) from employing both 2-branch and 4-branch MMSE interference cancellation in the presence of one major interferer. The modulation and coding scheme employed is QPSK with a coding rate of 1/2. The fading channel model is Pedestrian B with a speed of 3 km/h. It can be seen that the improvement from 2-branch MMSE-IC is about 9.5 dB at a BLER level of 1 percent, whereas the gain from a 4-branch MMSE-IC reaches 13.5 dB.

Intelligent Scheduling

In [6, 7] the performance of OFDMA frequency re-use schemes is analyzed with a particular emphasis on LTE. The simulated results of [7] claim that a frequency re-use scheme of $N = 1$ provides the best overall throughput for both the UL and DL; however, cell edge users are interference limited in the $N = 1$ reuse case resulting in approximately equal per user throughput at the cell edge. In [6] similar results are provided; however, cell edge throughputs are claimed to be maximized through a partial frequency re-use scheme in which different subbands within a cell have different transmit power limits. Gains of up to 20 percent in aggregate throughput are shown for partial frequency reuse, but with a potential penalty of up to 20 percent for cell edge users. It should be noted that the analysis does not take into account the effects of lognormal shadowing. In order to mitigate cell edge SINR degradation it is recommended that a partial frequency re-use scheme be employed.

Opportunistic and Organized Inter-Base station Access

Opportunistic or organized access can be implemented from a perspective of spectral, temporal or spatial re-use of scheduled RB's between base stations. The notion of opportunistic spectral access can be exploited both for hierarchal overlay systems such as femto overlays on a macro system as well as for spectral re-use within a single macro cellular network. For LTE macro networks, opportunistic access takes the form of dynamic channel allocation (DCA) at the base station to enable the assignment of the same RB's to multiple mobiles, thus increasing overall spectral efficiency. If DCA decisions at the candidate base station are undertaken independently of RB assignment decisions from neighboring base stations, the candidate base station must have a means to measure the level of interference in the candidate RBs. For time division duplex (TDD) systems, in which the channel is stationary across the frame of interest, the received signal subframe can be employed as an accurate estimate of the channel conditions for the transmit portion of the subframe. However, in frequency division duplex (FDD) implementations of LTE, a separate measurement of the transmit channel quality will need to be signaled through CQI feedback from the mobile.

Opportunistic beamforming and scheduling are relatively recent areas of investigation to achieve throughput and spectral efficiency gains in a cellular system [8]. For an OFDMA system such as the DL of LTE, multiuser diversity in the frequency domain can be exploited by intelligently scheduling mobiles during the peaks of the channel fading. The potential large CQI overhead to implement such a scheme can be minimized by forming the beams randomly based on clustered CQI feedback and scheduling a user on the instantiation of a beam within a high

SINR cluster. Simulation results from [8] show gains in aggregate throughput of up to 50 percent for opportunistic beamforming plus proportional fair share scheduling over a conventional equal gain beamformed system with round robin scheduling.

In [9] Hu *et al*. investigate the performance of organized beam hopping (OBH) between nodes in a multi-cellular environment. OBH is a technique to pseudo-randomly hop beams in an organized quasi-orthogonal pattern between base stations to maximize throughput by RB reuse while minimizing inter-base station interference. The performance of OBH is shown to be superior to opportunistic beamforming for all levels of mobile populations in a cell. Gains in spectral efficiency of 1 b/s/Hz by OBH over both opportunistic beamforming and coherent beamforming were demonstrated in [9]. Results were obtained through simulation of a cellular system comprised of cells with a 1 km cell radius, each having six beams per cell (i.e., 60 degree sectors). Although the potential performance improvements of OBH are compelling, a number of outstanding implementation issues remain, including contention and collision resolution methods for inter-base station beam selection as well as the ability of the OBH algorithm to adapt to varying mobile traffic patterns.

Recent Receiver Decoding Algorithm Innovations

Sphere and dirty paper decoding are two recent innovations in decoding algorithms that are potentially applicable to 4G systems. Sphere decoding is a technique of considerable interest based on its potential to provide close to a maximum likelihood (ML) decoding result at significantly lower complexity than a ML decoder. The basic concept is to search an N-dimensional hypersphere of some predefined radius R within the code space. The choice of the size of radius to search over is a trade-off between exponentially increasing search complexity as R increases, and a higher probability of an error in decoding as R decreases (i.e., the correct code point may not be inside the search radius). Recent analysis [10] has shown that the complexity of a sphere decoding algorithm at high SINR for 16- and 64-QAM modulations can be reasonably implemented with current processors. Furthermore, the performance of such an implementation is within 1 dB of a ML decoder assuming uncorrelated MIMO paths. If the MIMO spatial paths are correlated, the performance of the sphere decoder can degrade up to 5 dB depending on the level of correlation between the paths.

Dirty paper coding (DPC) is another technique that has received considerable attention recently as an approach to eliminate interference in systems for which joint decoding is not possible. The essence of the approach is to precode each transmission such that the desired signal is mapped into a known code space. The receiver will have knowledge of the precoding code space which can be employed to successfully decode the desired signal in the presence of interference using a trellis type decoder in combination with vector quantization. Recent research has shown that DPC combined with 2×2 MIMO can potentially achieve spectral efficiency gains of 0.8 b/s/Hz over 2×2 MIMO alone and 1.35 b/s/Hz for DPC over 4×4 MIMO [11]. DPC has also been shown to outperform frequency re-use schemes. One of the current challenges with implementing DPC is the complexity of the implementation. DPC requires an implementation of vector quantization at both the transmitter and receiver as well as an iterative type decoder, such as a Viterbi, turbo, or a successive trellis decoder. It order to achieve the full theoretical gain of DPC, the number of symbols per codeword has to be on the order of up to 10^4, resulting in prohibitively complex vector quantizers and decoders due to the exponential increase in complexity with codeword size.

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ICIC Performance Results

Based on the overview of ICIC techniques provided in the previous section, Table 2 provides a summary comparison of the various ICIC techniques from a perspective of performance, complexity, as well technology maturity and risk. The applicability of the technique to the LTE DL, LTE UL, or both is indicated in the leftmost column. Current mature approaches that should be considered as baseline features for initial UL and DL LTE deployments include power control, some form of FFR, preferably with adaptation, as well as MIMO. SDMA is also relatively mature and can provide significant aggregate capacity improvements for a small increase in complexity. Interference cancellation promises significant gains but is likely limited to the LTE UL due to processing complexity, and will require real-time exchange of information between base stations on the order of every msec to maximize the gain for an LTE system. Beamforming technologies such as opportunistic spectrum access and organized beam hopping show significant theoretical promise; however, as practical technologies for a deployed LTE system they are still unproven. Newer decoding approaches such as sphere decoding and dirty paper coding show considerable promise in terms of the gain they can provide; however, the processing complexity of these approaches will likely limit their use to the UL for the near future. Network power control and network MIMO are inter-base station techniques that seem viable as features for LTE ICIC evolution in the near future due to the potential performance gains and the feasibility of their implementation at the base station.

Conclusions

This article has provided an overview of techniques that can be employed to mitigate interference in 4G OFDM systems with specific relevance to LTE. Viable existing and possible future approaches have been reviewed, including the use of fractional power control, static and adaptive fractional frequency reuse, opportunistic spectrum access, intra and inter-base station interference cancellation, MIMO, SDMA, adap-

ICIC Option	Description	Implementation Complexity	Maturity and technical risk	Performance & Spectral Efficiency Improvement
Power Control (LTE UL & DL)	Regular power control and fractional power control	Scales linearly with increase in number of RBs available	Mature technology with known performance	Improvements of up to 40% in aggregate throughputs and 100% for cell edge users over scenario with no power control
Static FFR (LTE UL & DL)	Fixed assignment of subbands to each cell	Minimal complexity. Fixed assignment is preconfigured	Mature technology with known performance	Aggregate throughput loss of up to 25%. Small improvement in cell edge user throughput
Adaptive FFR (LTE UL & DL)	FFR assignment is adaptively updated based on the SINR in each subband	Scales linearly with the number of mobiles served at the base station. Requires exchange of SINR based metric between base stations	New technology. Dynamics and stability in a loaded network need to be validated	Up to 10 dB improvement in SINR levels. Can translate into spectral efficiency gains of up to 1 b/s/Hz
MIMO (LTE DL)	Use of multiple transmit and receive antenna. SFBC, STTD, CCD, and MU-MIMO	Complexity scales linearly with number of users. Exponential complexity with order of MIMO	Theory is well understood. Empirical trial results are available confirming potential performance gains	Potentially 2–4 times spectral efficiency improvement with 4×4 MIMO for uncorrelated spatial paths
MU-MIMO (LTE UL)	UL technique to assign the same RB to multiple mobiles in the same cell	Scales exponentially with number of mobiles simultaneously processed	New technology. Scheduling algorithms to select MU mobiles are still evolving	Theoretical improvement in spectral efficiency scales with order of MU-MIMO. Typically less than 2 in practice.
SDMA (LTE UL&DL)	Fixed beam partitioning of the cell	Minimal additional processing is required at the scheduler	Mature technology that has been deployed in 3G systems	Up to N times capacity improvement for N beams. Typically provides 2–4 times spectral efficiency improvement
Interference Cancellation (LTE UL)	Regenerate and subtract interfering signal from desired signal	Scales exponentially with number of mobiles served at the base station. Requires exchange of information in real time between base stations.	Algorithms are mature and understood. High cost of implementation will likely limit application to the UL	Gain of up to 2 b/s/Hz in the presence of a single strong interferer. Can potentially improve channel performance to that of AWGN if accurate channel estimation is available
Opportunistic Spectrum Access (LTE UL & DL)	BTS assigns resources only to subchannels with low power spectral density	High complexity. Exploits channel sounding. Additional HW is required in FDD systems. Suited to mitigate interference levels and strong interferers	New technology that has not been empirically evaluated	Gain of up to 50% in aggregate channel throughput or spectral efficiency
Organized Beamforming (LTE UL&DL)	Beams are pseudo-randomly hopped in a quasi-orthogonal manner	Scheduling complexity will increase exponentially relative to the number of mobiles serviced	New technology. Contention resolution and traffic pattern adaptability needs to be addressed	Improvements in spectral efficiency of up to 1 b/s/Hz
Sphere Decoding (LTE UL)	Based on a decoding search in an N-dimensional hyper-sphere	Complexity increases exponentially with the size of the search space	High cost of processing likely to limit application to the UL	Improvements of up to 1 b/s/Hz in fading environments
Dirty Paper decoding (LTE UL)	Precoding of signal mapped into a known code space	Complexity increases exponentially with the size of the search space and codeword size.	High cost of processing likely to limit application to the UL	Potential spectral efficiency gains of 0.8 to 1.35 b/s/Hz
Network Power coordination (DL)	Power control coordinated between base stations	Complexity increases linearly with the number of base stations. Requires exchange of power levels between base stations	New technology that has not been empirically evaluated	Potential gains in throughput or spectral efficiency of up to 80%
Network MIMO (DL)	MIMO implemented across multiple base stations	Complexity increases exponentially with the number of base stations and number of links. Will require exchange of information between base stations	New technology that has not been empirically evaluated	Gains are expected to be consistent with higher order diversity implementations

Table 2. *Summary of LTE ICIC options.*

tive beamforming, network MIMO, sphere decoding, and dirty paper coding. The applicability, maturity, complexity, and performance gains possible from each of these techniques have been summarized in this article. No single approach will in itself provide complete interference mitigation for an LTE implementation. However, it is expected that a combination of these approaches can be employed to provide a robust $N = 1$ reuse capability in a heavily loaded LTE deployment. In the short term a combination such as fractional power control and adaptive fractional frequency reuse based on scheduling in high SINR regions could form the basis of a robust LTE ICIC strategy. Longer term gains in ICIC performance could potentially be achieved through the use of inter-base station network based algorithms, including network MIMO, opportunistic and/or organized beamforming, and distributed power control, as well as coding strategies such as sphere decoding or dirty paper coding.

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Biographies

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