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Cochannel Interference Mitigation

Active and Passive Techniques

Rong Zhang and Lajos Hanzo

When aiming for achieving high spectral efficiency in wireless cellular networks, cochannel interference (CCI) becomes the dominant performance-limiting factor. This article provides a survey of CCI mitigation techniques, where both active and passive approaches are discussed in the context of both open- and closed-loop designs. More explicitly, we considered both the family of flexible frequency-reuse (FFR)-aided and dynamic channel allocation (DCA)-aided interference avoidance techniques as well as smart antenna-aided interference mitigation techniques, which may be classified as active approach. By contrast, in the class of passive approach, we considered a range of interference-aware receiver techniques, including both interference cancellation (IC) and interference suppression (IS) arrangements. We characterize the relationship of these techniques and list a range of open-research problems.

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Spectral- and energy-efficient wireless networks are typically designed to be capable of providing diverse

When aiming for achieving high spectral efficiency in wireless cellular networks, CCI becomes the dominant performance-limiting factor.

quality-of-service (QoS) guarantees while supporting time-variant network loads in diverse radio environments and network topologies. Among others, CCI is the most dominant impairment in wireless networks, especially in dense frequency-reuse scenarios. Broadly speaking, radio resource management may be deemed to be the system-level means of controlling the CCI [1], which involves controlling the wireless resources, such as the transmission power, the transmission rate, the channel assignments, and the handover. Based on recent contributions in both academia and industry, in this article, we consider various CCI mitigation techniques (see Figure 1) that may be categorized into the family of active and passive approaches, where the former class entails CCI mitigation techniques employed at the transmitter side, while the latter category subsumes the CCI mitigation techniques employed at the receiver side.

The active CCI mitigation techniques used at the transmitter side may be designed either with or without the aid of feedback information, resulting in the so-called open- and closed-loop solutions, respectively. For the sake of improving the attainable spectral efficiency as well as for mitigating the CCI of wireless system, it is wiser to exploit the channel fluctuation rather than to try and avoid it. This leads to the principle of opportunistic interference

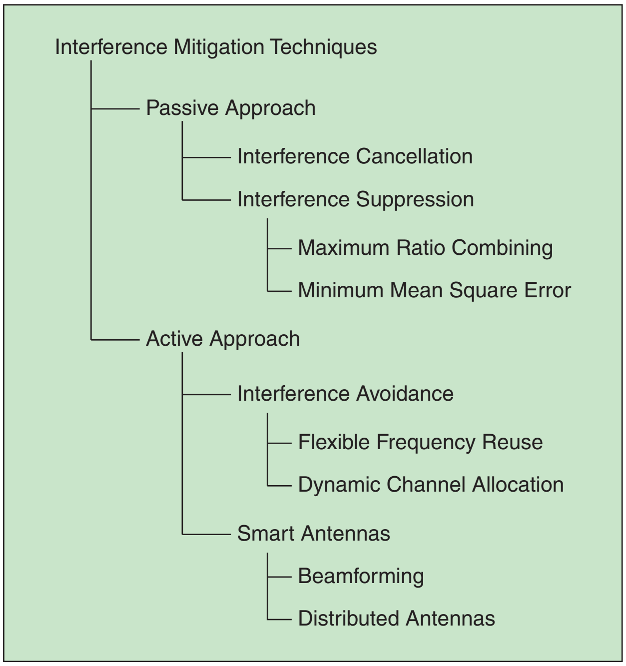

FIGURE 1 The family tree of CCI mitigation techniques.

avoidance, which employs the concept of FFR [2] and DCA [3], where the CCI is explicitly avoided prior to transmission during the network planning phase and constitutes an intrinsic element of resource management. Furthermore, multiple transmit antennas may be employed for both beamforming and transmit diversity. In beamforming, we improve the receiver's signal strength by creating a high antenna array gain in the receiver's angular direction. By contrast, provided that the transmit antennas are sufficiently far apart to experience independent fading, beneficial transmit diversity gains may be attained. These uncorrelated spatial channels may be constructed with the aid of so-called distributed antennas constituted by geographically separated base stations (BS) creating a so-called network multiple-input multiple-output (MIMO) system [4].

By contrast, according to the passive approach, the CCI mitigation techniques found in the literature were inspired by the concept of multiuser detection theory [5]. This implies that the CCI may be mitigated or perfectly eliminated by the joint detection of both the desired signal and of the interfering signal, provided that a sufficiently high degree of freedom is available in the system, where the achievable degree of freedom may be controlled by the choice and number of spreading codes, by multiple receive antennas and by appropriate channel codes. More specifically, a popular and particularly effective technique is constituted by the family of well-known IC arrangements [5], which aim for reducing the detrimental effects of CCI by partially or fully canceling it before making a final decision on the desired signal. Alternatively, linear detection algorithms, such as the classic maximum ratio combining (MRC) technique and the minimum mean square error (MMSE) technique [5], may also be used, both of which rely on the calculation of a linear detector weight vector, which eliminates the CCI component and at the same time enhances the desired signal component. Hence, they belong to the family of IS arrangements.

In the face of the limited-length reference list of this magazine, we have selected a range of survey-type papers for the readers' convenience, aiming to provide a pointer for all the most dominant techniques related to the topic of CCI mitigation. Instead of detailing each individual technique in great depth, we focus our attention on revealing their relationships in a hierarchical manner and on introducing them in the required depth.

The remainder of this article is organized as follows. In the "Overview of Closed-Loop Interference Mitigation Techniques" section, we provide a top–down view of the class of closed-loop CCI mitigation techniques. In the "Active Interference Mitigation Techniques" section, the family of active CCI mitigation techniques is introduced. In the "Passive Interference Mitigation Techniques" section, we discuss the subclass of passive CCI mitigation techniques, and, finally, we conclude our discourse in the "Conclusion" section.

Overview of Closed-Loop Interference Mitigation Techniques

Let us first reveal the relationship between the various CCI mitigation techniques employing closed-loop designs. At the highest level of the network planning phase, the total bandwidth is assigned on a long-term basis to different networks, where the traffic load may also be balanced among the different networks, provided that the network operator has access to these diverse networks. Naturally, these operations require internetwork coordination. Once the network planning phase was completed, the FFR attempts to efficiently distribute the available spectrum among cells by taking into account the CCI and network load, which is achieved by intercell coordination. The channels available within each cell are then dynamically allocated by considering different system design parameters, such as the received signal to interference plus noise ratio (SINR). Once the subset of rejected versus accepted channels was determined, the scheduler assigns the eligible channels to the users based on different design criteria. Our discussions are based here on the ubiquitous orthogonal frequency-division multiple access system employed in a cellular downlink (DL) scenario, where the minimum resource block that may be used for closed-loop channel allocation and scheduling has to be explicitly defined. In the Third-Generation Partnership Project's (3GPP) long-term evolution (LTE) [6], this minimum resource block consists of seven orthogonal frequency-division multiplexing (OFDM) symbols and 12 subcarriers. This time-frequency resource allocation is followed by sophisticated spatial processing, which jointly mitigates the CCI among the adjacent cells with the aid of feeding back the channel information estimated by each receiver, which may be exploited by transmit beamforming. Alternatively, the distributed antenna concept may be exploited for achieving a transmit diversity gain even in the absence of any channel information. The feedback information used for a closed-loop design, such as the channel state information (CSI) and/or channel quality information (CQI), usually represent the quantized version of the channel estimates of the previous DL transmission measured at the receiver side in a frequency-division duplex system [7]. At the receiver side, these channel estimates and any other synchronization information estimates, such as carrier synchronization, frequency synchronization, and time synchronization, are further subjected to advanced IC- or IS-aided detection, namely to passive CCI mitigation techniques.

CCI IS THE MOST DOMINANT IMPAIRMENT IN WIRELESS NETWORKS, ESPECIALLY IN DENSE FREQUENCY-REUSE SCENARIOS.

Active Interference Mitigation Techniques

FFR-Aided Interference Avoidance

Motivation of FFR

The basic principle of cellular systems is to partition a geographical area into nonoverlapping cells, each served by a single BS, where the same frequency may be used by several cells, provided that these cochannel cells are geographically separated to ensure that the interference generated among each other is attenuated to an acceptable level by taking advantage of the path loss. As seen in Figure 2, in the traditional frequency-reuse scenario B associated with the classic frequency-reuse factor of

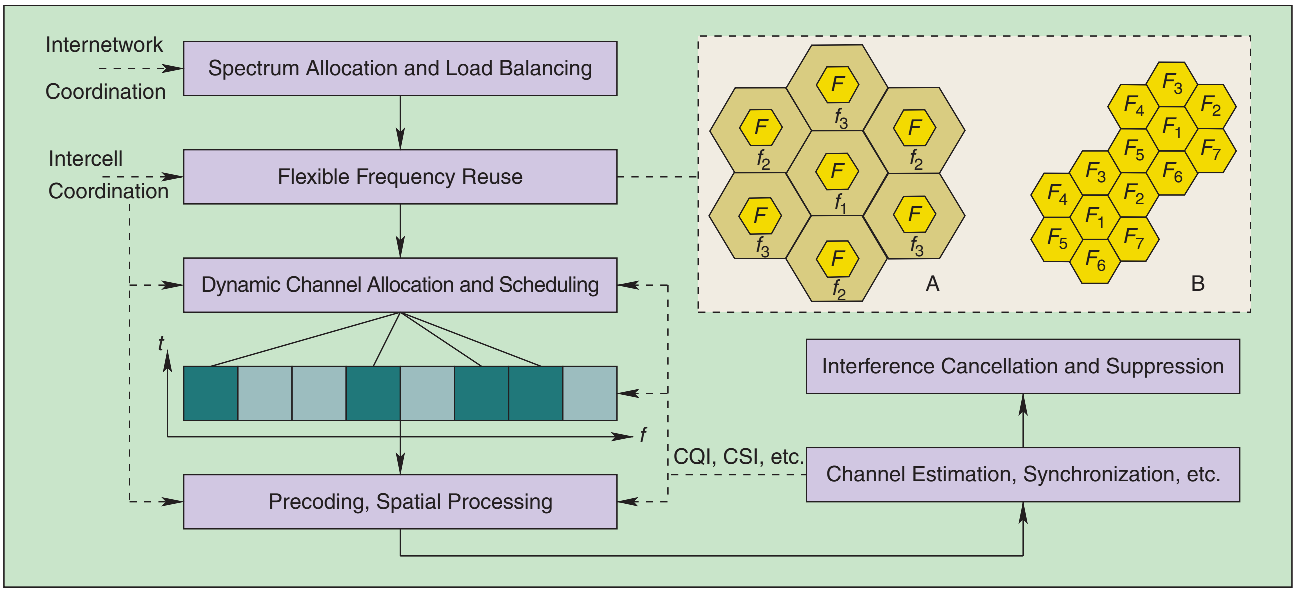

FIGURE 2 The top-down view of close-loop CCI mitigation techniques.

SPECTRAL- AND ENERGY-EFFICIENT WIRELESS NETWORKS ARE TYPICALLY DESIGNED TO BE CAPABLE OF PROVIDING DIVERSE QUALITY-OF-SERVICE (QOS) GUARANTEES.

seven, the same frequency is reused by geographically separated cells, while the adjacent cells have frequency bands that are orthogonal. This results in the well-known design tradeoff between having a low CCI and a high spectral efficiency.

Operation of FFR

To strike an attractive tradeoff, various standards opted for adjusting the reuse factor of the frequency resources across cells by implementing different reuse zones in each cell based on the received broadcast channel (BCH) signal level [2]. Conceptually, the FFR involves the following consecutive operations.

First, each traffic cell has to be divided into several zones, where the practical rule of thumb is to divide the cell into an inner cell-center zone having access to the entire frequency band F in conjunction with a reuse factor of unity and the outer cell-edge zone having access to the portion of the entire frequency band F. These sets of frequency bands may be referred to as cell-edge frequency bands f, as seen in Figure 2, for the FFR scenario A, where the cell-center frequency bands F is reused in every cell, while the cell-edge frequency bands have a reuse factor of three associated with $f_1 \cap f_2 \cap f_3 = \emptyset$. Second, the coverage area of the different zones has to be defined, where the BCH signal level determines the boundary between the inner zone and outer zone, which has to be accurately adjusted by the power control, taking into account the propagation conditions, the CCI, and the network load of each cell. This process takes place by mutual negotiation among the different cells, which requires the coordination and exchange of additional information among the cells. The next task is the determination of the cell-edge frequency bands, which may be performed either in an adaptive or in a nonadaptive manner. In the adaptive regime, the set of best resource blocks is allocated to the cell-edge frequency bands based on the estimates and feedback of CQI, while in the nonadaptive regime the cell-edge frequency bands are predefined. Finally, after allocating the specific cell-edge frequency bands, they may be associated with the cell-edge users relying on diverse allocation policies. The simplest policy is to evenly distribute the cell-edge frequency bands among the cell-edge users, while a slightly more sophisticated regime allocates the cell-edge frequency bands exclusively to the first N cell-edge users, whereas the rest of the cell-edge users may occupy out-of-band subcarriers, which enjoy priority for the cell-center users.

Being a closed-loop technique, the FFR arrangement requires the knowledge of both the CCI and CQI over the entire bandwidth, where the former may be acquired from the handover process, while the latter may be extracted from the link adaptation algorithm. Furthermore, the partitioning of different frequency-reuse zones is implemented during the network planning phase, and it is a one-off process. Hence, the FFR technique does not require additional feedback signaling.

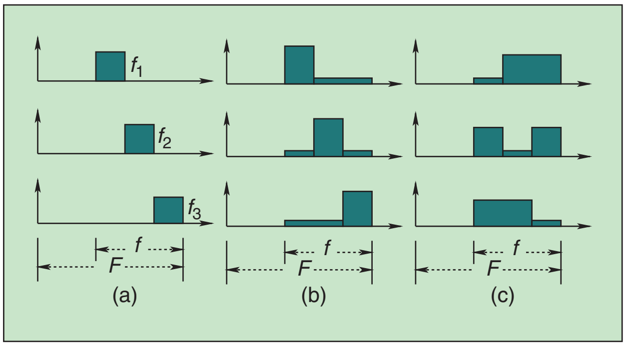

FIGURE 3 Three power coordination approaches in cell-edge frequency bands, where F denotes the total frequency bands, and f denotes the cell-edge frequency bands, having frequency-reuse factor (a) 3, (b) 3, and (c) 3/2.

Types of FFR

The DL transmit power assigned to the cell-edge frequency bands of different cells is also typically coordinated to create a set of subbands benefiting from a low interference level. This may be achieved using three different approaches, as illustrated in Figure 3 and discussed below. The most straightforward approach is to employ three subbands that are orthogonal to each other and assigning the full transmit power to the resultant fraction of 1/3 of the entire cell-edge frequency band as seen in Figure 3(a). As a result, the CCI can be totally avoided at a cost of having a factor of three at the reduced cell-edge frequency bands. The second approach is allowing the transmitter to have access to the entire cell-edge frequency bands but arranging a specific set of subbands to transmit at an increased power, while radiating in the remaining subbands at a commensurately reduced power and keeping the total transmit power unchanged as seen in Figure 3(b). On the other hand, in the third approach as seen in Figure 3(c), a specific set of subbands transmits at a reduced power, and the remaining subbands transmit at full power, which reduces the total transmit power. The latter is slightly different from the first two approaches in the sense that it facilitates the employment of soft frequency reuse. For example, the first approach has a reuse factor of three, the second approach has a reuse factor of three since 2/3 of the cell-edge frequency bands are restricted in power, and 1/3 has an increased power. Finally, the third approach has a reuse factor of 1.5, where 1/3 of the cell-edge frequency bands is restricted in power, while the rest of the band is allocated the full power.

DCA-Aided Interference Avoidance

Motivation of DCA

When assuming a unity-frequency-reuse-based cellular arrangement, DCA may be used for interference avoidance. The easiest technique of channel allocation is that of allocating a set of channels permanently to each cell without any channel information feedback. Alternatively, the simple average of the long-term channel information may be used, resulting in the so-called static channel allocation. However, because of the dynamic arrival of data in packet switched networks as well as owing to the time-varying nature of the wireless environment, the optimal channel allocation that is capable of maximizing the spectral efficiency becomes a function of time. Hence, the above-mentioned low-complexity static channel allocation ignores the time-varying nature of the wireless propagation environment and is incapable of adapting in diverse scenarios of fluctuating network loads. By contrast, DCA, which facilitates cross-layer design [8] and allocates the channels to each cell on a temporary basis by taking into account the traffic load fluctuations, its geographic distribution pattern as well as the channel variation and the CCI [3].

Types of DCA

The DCA may be operated under both centralized and distributed control [3]. To elaborate a little further, as seen in the Figure 4(a), the optimum centralized DCA involves interactions between the different cells and a central controller, where the BS of each cell executes the local decisions, while the central controller carries out joint decision. Based on the prevalent CCI statistics and the cell-throughput requirements, each cell produces a tentative list of channels ranked by their SINRs, which may be further classified into different grades of channels. Naturally, the simplest classification is constituted by enabling the adequate channels while disabling the inadequate ones. These local decisions of all the cells involved are then forwarded to the central controller, which is responsible for the joint decisions based on its own algorithm, where one of the basic design objectives is to find the set of cells and channels that can tolerate mutual interference so that the aggregate throughput is maximized. However, in the optimum centrally controlled DCA, the associated channel allocation time and signaling requirement is quite significant, which leads to the development of suboptimum distributed arrangements as seen in the Figure 4(b), where the BS of each cell receives feedback information from all cochannel users and makes decisions locally, i.e., without any BS coordination via a central controller. The distributed DCA arrangement requires a reduced allocation time and signaling overhead. Furthermore, the additional benefit of scalability may be gleaned, which simply implies that the distributed DCA arrangement may be employed in diverse network topologies.

ACCORDING TO THE PASSIVE APPROACH, THE CCI MITIGATION TECHNIQUES FOUND IN THE LITERATURE WERE INSPIRED BY THE CONCEPT OF MULTIUSER DETECTION THEORY.

Types of Scheduling

Apart from the DCA, which may be referred to as a long-term interference avoidance technique updated on a time basis of hundreds of milliseconds, dynamic channel scheduling may be considered as having an additional short-term interference avoidance measure operating on a slot-by-slot basis of milliseconds. Hence, the system becomes capable of accurately capturing and accommodating the channel quality variations and exploiting the so-called multiuser diversity technique of [9], which simply assigns the slots to those users, who experience a good channel quality.

There are three widely employed scheduling schemes, namely the standard round robin (RR) scheduling, the classic maximum-throughput scheduling, and the compromise scheme of proportional fair scheduling [9]. In the basic RR scheduling operating without any feedback of the CQI, the channel resources are shared among all users, where the channel quality variations are not exploited, and, hence, no multiuser diversity may be harnessed. The maximum-throughput scheduling requires the feedback of CQI and assigns the channel resources to the users having high CQI values. Hence, it is efficient in terms of maximizing the throughput but tends to neglect the support of users experiencing bad channels, i.e., sacrificing fairness.

To strike an attractive tradeoff between the total throughput and the achievable fairness, the so-called proportional fair scheduling was proposed, which has been found effective in terms of striking a balance by assigning the channel resources to specific users according

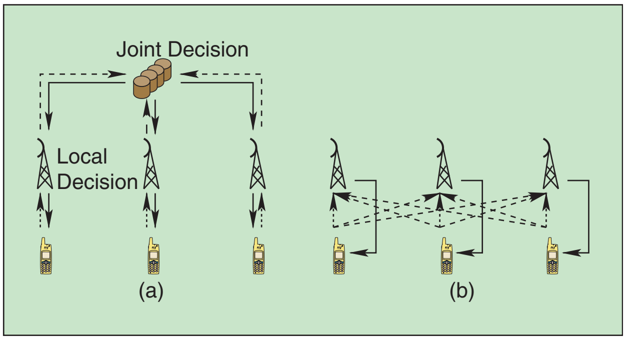

FIGURE 4 (a) The centralized and (b) distributed DCA, where dashed lines denote feedback transmission and solid lines denote DL transmission.

ONCE THE SUBSET OF REJECTED VERSUS ACCEPTED CHANNELS WAS DETERMINED, THE SCHEDULER ASSIGNS THE ELIGIBLE CHANNELS TO THE USERS BASED ON DIFFERENT DESIGN CRITERIA.

to the ratio between the potentially achievable throughput and the already achieved throughput. In its simplest guise, the proportional fair scheduling tends to assign channel resources to those users who will have a substantial contribution to the total throughput but have not contributed a lot at the time of observation.

This idea relies on the design methodology that both the channel allocation and scheduling has to take into account the network load encountered. When the network load is low, achieving the maximum total aggregate throughput is desired, while when the network load is high, ensuring the maximum possible number of satisfied users is opted for.

Smart Antenna-Aided Interference Mitigation

Beamforming

An efficient smart antenna-aided interference mitigation technique is constituted by the so-called beamforming [10], which transmits a narrow beam toward the desired user instead of transmitting in the conventional omnidirectional fashion or in a sectorized manner. It is capable of reducing the interference imposed on users of the system, particularly benefiting the cell-edge users. Hence, the classic beamforming technique is sometimes also referred to as interference alignment.

Beamforming techniques may be further classified into two types, namely nonadaptive and adaptive beamforming, where both types require the feedback of partial or full CSI. Adaptive beamforming techniques adapt the antenna weights according to diverse optimization criteria by exploiting the channel knowledge. A particularly beneficial adaptive beamforming technique is the well-known eigenbeamforming, where the antenna weights are chosen to be the eigenvector of the largest eigenvalue of the spatial MIMO channel's covariance matrix. On the other hand, the so-called beam-switching technique transmits using the best-oriented beam of a number of preselected beams, where the values of each array-weight vectors are a function of the beam direction as well as of the antenna element's position. In a typical 120° sector generated by a uniformly spaced linear array having four antenna elements, a total of eight beams may be created, where the adjacent beams are evenly spaced by an angle of 13°. Then the index of the best beam vector resulting from the maximum mean channel gain measured at the receiver is signaled back to the transmitter, where the channel gain is averaged over a certain time period, a set of carriers, and over the spatial domain constituted by the receive antennas, depending on the accuracy of the CSI feedback as well as on the affordable feedback bit rate. The combination of more advanced opportunistic transmission and beamforming techniques may attain a further performance enhancement in multiuser environments [11]. As a further design option, the concept of beam hopping may be invoked to intelligently avoid directional interference [12].

Regardless, whether the adaptive or nonadaptive variant is employed, when transmitting directionally by exploiting the maximum equivalent channel gain, the received signal power and, hence, the SINR is enhanced, or alternatively, the transmitted power may be reduced, despite maintaining a certain received SINR. Hence, the interference imposed on the adjacent cells is reduced, and the overall interference level in the entire system is reduced.

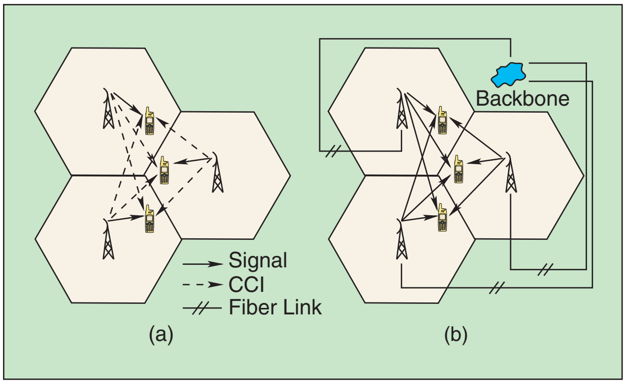

FIGURE 5 (a) Conventional single-cell transmission and (b) distributed antenna-aided multicell transmission.

Distributed Antennas

In contrast to the directivity exploited by the above-mentioned beamforming techniques, the benefits of transmit diversity may be harnessed by transmitting the same signal from different antennas, provided that they experience independent fading. Since the transmit power required for maintaining a certain error probability may be reduced as a benefit of transmit diversity, the interference imposed becomes low. Hence, the concept of distributed antennas was proposed [13] for ensuring that the antenna elements are sufficiently far apart to guarantee that the signals generated by each geographically separated antenna are uncorrelated. An additional merit of employing distributed antennas is the increased macrodiversity, which is particularly beneficial for the cell-edge users, who would otherwise suffer from high CCI levels. As seen in Figure 5, in contrast to the conventional single-cell transmission shown in Figure 5(a), where each user is served by its local BS only and suffers from CCI imposed by the adjacent cells, in the distributed antenna-aided multicell transmission characterized as shown in Figure 5(b), each user is served by several coordinated BSs and each BS jointly processes multiple users' information, which is shared in the networks' backbone via a high-speed, near-perfect optical fiber link. This leads to an equivalent distributed multiuser-MIMO system. There are three typical approaches of achieving transmit diversity in distributed antennas-aided systems, namely the employment of distributed space time block codes [14], distributed transmit beamforming-style precoding [4], and distributed cyclic delayed transmissions [15].

This concept leads to the so-called cooperative multipoint (CoMP) transmissions, which was formally proposed in the LTE advanced (LTE-A) project [16]. There are two different types of CoMP transmission, namely single-cell processing-based coordinated transmission and multicell processing (MCP)-based cooperative transmission, where the former scheme refers to classic CCI avoidance technique based on resource allocation and management, while the latter is constituted by the joint data transmission of multiple cells, mainly aimed at improving the throughput at the cell edge. In the latter, MCP requires the CSI of all the links to all supported mobile stations (MSs) at all the distributed transmitters (CSI-DTs) to facilitate DL precoding invoked at the BSs for combating the CCI at the BS's transmitter rather than at the MS's receiver. This philosophy potentially facilitates the employment of low-complexity matched filter MS receivers. To elaborate a little further, in the context of linear precoding, the design principle of classic beamforming [4] based precoding is that all cooperating BSs jointly transmit in their respective directions for the sake of maximizing a specific MS's received signal power, which is achieved at the cost of potentially imposing interference on all other MSs. By contrast, zero-forcing (ZF)-based precoding is capable of entirely eliminating the CCI imposed by joint multiple BSs-aided transmit preprocessing at the cost of noise amplification. Naturally, a linear precoding technique that combines the benefits of both the egoistic beamforming technique and of the altruistic ZF technique is desired. This may be achieved by block-diagonalization (BD) techniques [17] and signal-to-interference-leakage-plus-noise-ratio (SILNR) maximization techniques [18]. The former aims for creating a block–diagonal composite channel matrix, which corresponds to noninterfering individual links for all MSs. By contrast, the latter carefully balances the received signal power of the target MSs against the interference power imposed on the remaining MSs. Similarly to the ZF technique, the BD technique should also obey the classic dimensionality constraint, where the total number of BS transmit antennas should be no less than the total number of all the MS receive antennas. By contrast, the SILNR maximization technique offers a more flexible design.

THERE ARE TWO DIFFERENT TYPES OF COMP TRANSMISSION, NAMELY SINGLE-CELL PROCESSING-BASED COORDINATED TRANSMISSION AND MULTICELL PROCESSING (MCP)-BASED COOPERATIVE TRANSMISSION

Passive Interference Mitigation Techniques

Although the above-mentioned active CCI mitigation techniques are capable of mitigating the CCI prior to transmission, nonetheless, they are prone to residual CCI effects experienced at the receiver side. This is particularly the case when the feedback information is inaccurate, owing to being noise contaminated, or outdated. In this case, the family of passive CCI mitigation techniques may act as a safeguard to further mitigate the effects of CCI.

Interference Cancellation

IC techniques are capable of iteratively canceling the interference at the receiver side, and, hence, the resultant signal becomes effectively noise limited. The IC arrangement may be classified as serial or parallel IC and may employ either hard- or soft-cancellation methods. Serial IC techniques are particularly effective when the difference between the signal power and the interference power is noticeable, since the detection of weak signals benefits from the cancellation of the reliably detected strong signal. By contrast, parallel IC performs better when the signal and interference power is similar. An inherent problem of both serial and parallel IC techniques is the so-called error-propagation phenomenon, which means that the errors in the already-detected signals propagate to the detection of the weaker yet-to-be detected signals, and the resultant system may be catastrophically affected. This is often the case, when the CCI is dominant, and the noise power is significant. As a powerful countermeasure, turbo IC receivers [19] are capable of eliminating the residual errors at each detection step by taking into consideration the improved confidence decisions of the channel codes.

Several assumptions are associated with the employment of IC techniques. Theoretically, they rely on the availability of a sufficiently high degree of freedom, since the desired signal should be differentiated from the CCI. The reliability of this desired versus undesired signal separation may be enhanced with the aid of a sufficiently high processing gain, which may be achieved by using direct-sequence spreading codes, multiple receive antennas, and low-rate channel codes. Practically, it requires that the CCI parameters, such as the CSI and the modulation and coding scheme (MCS), are explicitly signaled to or, alternatively, are estimated at the receiver side, which requires

IC TECHNIQUES ARE CAPABLE OF ITERATIVELY CANCELING THE INTERFERENCE AT THE RECEIVER SIDE, AND, HENCE, THE RESULTANT SIGNAL BECOMES EFFECTIVELY NOISE LIMITED.

a sophisticated design and imposes challenges on the pilot design. Furthermore, the time synchronization of the desired signal and CCI is a prerequisite, while having a sufficiently high turbo interleaver length and delay tolerance are also important design constraints in the context of soft turbo IC. Field measurement performed in the Universal Mobile Telecommunications System network revealed that there are typically no more than three simultaneous interfering signals near the cell edge. This discovery suggests that, indeed, the above-mentioned assumptions become realistic, and hence, the employment of IC techniques becomes feasible.

Interference Suppression

In the context of multiple receive antennas, different linear detection techniques may be employed to enhance the desired signal while suppressing the CCI. One of the classic techniques is the so-called MRC, which coherently combines the desired signals of multiple antennas and achieves receive diversity, provided that the fades of the different receive antennas are uncorrelated. It may also be considered as a receive beamforming arrangement, since the effective antenna pattern generated from the MRC weights effectively forms a beam toward the desired signal. By taking into account of the covariance matrix of the spatial interference, more advanced MMSE techniques may be designed. This technique allows the interference to be partially suppressed in the spatial domain. This implies that the effective antenna pattern created with the aid of the MMSE weights forms a beam toward the desired signal and a null in the direction of the interferers, resulting in the so-called null-steering. However, the calculation of the MMSE weights is more complex than that of the MRC weights, since the inverse of the spatial correlation matrix of the interference plus noise term is required, which involves estimating both the CCI power as well as the channel, hence imposing challenges on the multiuser channel estimation pilot design.

Figure 6 shows the cumulative distributed function (CDF) of the received SINR, when employing the different IS techniques introduced earlier, namely the MRC and the MMSE techniques. In our simulations, a total of 18 cochannel cells were modeled, where there were six tier-one cells and 12 tier-two cells. The simulation results were averaged over 100 runs of an OFDM system employing 1,024 subcarriers. An urban microcell environment [20] was assumed, where one transmit antenna and at most two receive antennas were used. During each simulation run, a total of ten users were randomly allocated within the central cell of interest, while they were independently allocated between different simulation runs. It can be seen in Figure 6 that the MMSE receiver achieves the best performance as a benefit of taking into account of the interference structure. By exploiting the knowledge of the signal energy received by multiple antennas, the MRC attains performance improvement over the single-receive antenna scenario while still being inferior to the MMSE technique.

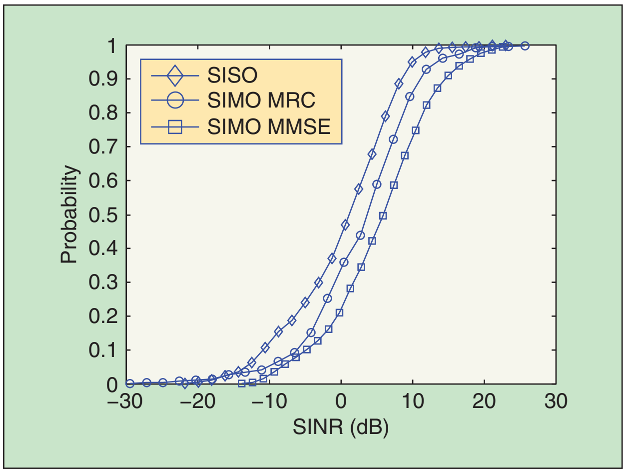

FIGURE 6 The CDF of received SINR when using different IS techniques. SISO: single-input single-output; SIMO: single-input multiple-output.

Conclusion

In this article, we discussed diverse CCI mitigation techniques by classifying them into different groups, where both active and passive CCI mitigation techniques were treated. Each of the techniques has its pros and cons, each tending to mitigate the CCI from different perspectives, and hence, an appropriate combination of these techniques has to be employed to jointly mitigate the CCI by taking into account the wireless channel's variation, the network load's fluctuation, and the users' diverse QoS requirements. The following problems constitute some of our future interest:

- *Asynchronous distributed antennas:* Although distributed antennas contribute toward achieving a high cell-edge throughput, the asynchronous nature of the signal transmitted from different BSs is critical, when relying on this concept [21]. This will either increase the complexity of the receiver or impose challenges on the multiuser pilot design at the transmitter side. This problem will become more obvious, when hybrid automatic repeat request is used, which ultimately affect the user's delay experience. This is particularly true for multimedia broadcast and multicast services, which constitute unidirectional point-to-multipoint services operated across the entire network, and hence, cell synchronization has to be ensured that distributed antennas are applied.

- *QoS-aided scheduling:* Although the proportional fair scheduling aims for maximizing the total throughput, while maintaining fairness, it gives little cognizance to the QoS. The users who suffer from bad channel conditions and strong CCI are more likely to face delivery delays, since they tend to experience higher queuing delays and hence potentially suffer from an increased packet drop probability. As a result, for bursty traffic patterns, the effects of delays has to be counteracted by allocating more channels in the short term to disadvantaged users while maintaining the fairness of the system in the long term. Hence, the QoS-enabled scheduling is of much importance [22].

Author Information

Rong Zhang (rz@ecs.soton.ac.uk) received his B.Eng. degree in communications engineering from Southeast University, Nanjing, China, in 2003 and his M.Sc. degree with distinction in radio frequency communications engineering and Ph.D. degree in wireless communications from the University of Southampton, United Kingdom, in 2005 and 2009, respectively. He was a system engineer with Mobile Communications Division of China Telecom and is currently a research fellow with the Communications Research Group, School of Electronics and Computer Science, University of Southampton. He was awarded a joint EPSRC and Mobile VCE scholarship in 2006. His research interests include cellular networks optimization, multiuser communications, multiantenna communications, and cooperative communications. He is a member of the IEEE and IET.

Lajos Hanzo (lh@ecs.soton.ac.uk) received his degree in electronics in 1976 and his doctorate degree in 1983. During his 34-year career in telecommunications, he has held various research and academic posts in Hungary, Germany, and the United Kingdom. Since 1986, he has been the chair for telecommunications with the School of Electronics and Computer Science, University of Southampton, United Kingdom. He has coauthored 20 books on mobile radio communications for John Wiley–IEEE Press. He has also published 955 research papers and book chapters at the IEEE *Xplore*. He has been awarded a number of distinctions. Currently, he is directing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by industry, the Engineering and Physical Sciences Research Council, United Kingdom, the European IST Programme, and the Mobile Virtual Centre of Excellence, United Kingdom. He is an enthusiastic supporter of industrial and academic liaison, and he offers a range of industrial courses. He is also an IEEE Distinguished Lecturer as well as a governor of both the IEEE ComSoc and the VTS. He is the acting editor-in-chief of the IEEE Press.

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