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Time-domain ICIC and optimized designs for 5G and beyond: a survey

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Abstract Time-domain enhanced inter-cell interference coordination (eICIC) is an effective technique to reduce the cross-tier inter-cell interference (ICI) in long term evolution (LTE)-based heterogeneous small cell networks (HetSCNs). This paper first clarifies two main communication scenarios in HetSCNs, i.e., macrocells deployed with femtocells (macro-femto) and with picocells (macro-pico). Then, the main challenges in HetSCNs, particularly the severe cross-tier ICI in macro-femto caused by femtocells with closed subscribe group (CSG) access or in macro-pico caused by picocells with range expansion are analyzed. Based on the prominent feature of dominant interference in HetSCNs, the main idea of time-domain interference coordination and two basic schemes in the eICIC standardization, i.e., almost blank subframe (ABS) and orthogonal frequency division multiplexing symbol shift are presented, with a systematic introduction to the interactions of these techniques with other network functions. Then, given macro-femto and macro-pico HetSCNs, an overview is provided on the advanced designs of ABS-based eICIC, including self-optimized designs with regard to key parameters such as ABS muting ratio, and joint optimized designs of ABS-based eICIC and other radio resource management techniques, such as user association and power control. Finally, the open issues and future research directions are discussed.

Keywords eICIC, almost blank subframe, joint optimized design, heterogeneous small cell networks, 5G and beyond

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1 Introduction

With the rapid development of wireless broadband communication networks and consumer electronics, the demand for mobile multimedia services becomes stronger and stronger, and mobile data traffic has increased exponentially in recent years [1]. It is expected that the fifth generation (5G) network will have to provide one thousand times higher capacity than the fourth generation (4G) network. To achieve such a capacity, various promising solutions have been proposed for future 5G systems [2, 3], such as striving for more spectra [4, 5], developing enhanced communication technologies with high spectral efficiency [6–8], and adopting heterogeneous cellular network architectures with dense wireless access nodes. In fact, a large increase in the number of access nodes has already been observed in recent years

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through the deployment of small cells, such as personal indoor access (femtocells), street outdoor coverage (picocells), remote radio heads (RRH), and relays, to meet the increasing demand for high throughput and ubiquitous coverage, especially in the indoor and hotspot scenarios. As an economic and effective solution to improve the network capacity, more and more small cells will be deployed in future mobile communication networks, constructing multitier heterogeneous networks (HetNets) with macrocells. To focus on the features of small cells, this review concerns heterogeneous small cell networks (HetSCNs).

Compared to homogeneous macro cellular networks (HomMCNs) with pseudoregular and static hexagonal topologies, the unplanned deployment of small cells in HetSCNs makes the network topology much more irregular. In addition, small cells could be flexibly turned on or off according to traffic requirements, which changes the network topology dynamically. As a result, classical inter-cell interference coordination (ICIC) schemes, such as reuse-n, fractional, or soft frequency reuse schemes employed in regular HomMCNs [9] could not be applied directly in HetSCNs. Moreover, the irregular topology of HetSCNs results in the proximity of numerous mobile stations (MSs) and base stations (BSs), and thus a large portion of the cells should be taken as the cell-edge, where the MSs experience poor signal-to-interference-and-noise ratio (SINR). Thus, inter-cell interference (ICI) becomes an even more serious problem in HetSCNs compared to conventional HomMCNs. As a consequence, owing to the irregular and dynamic topologies of HetSCNs, highly flexible and adaptive ICIC schemes should be designed.

From the perspective of inter-cell coordination, ICIC can be carried out in one or multiple radio resource domains, including the time, frequency, space, and power domains, to coordinate the resources used by cells and MSs. As different user association schemes result in diverse interference levels in HetSCNs, the ICIC schemes can also be jointly considered with user association. However, if there is no coordination in HetSCNs, cognitive radio can be employed in small cells for interference management. Small cells sense the spectrum usage of macrocells and change their working manner, such as the used channel, transmission power, and beam directions, to reduce the cross-tier ICI to an acceptable level, such that macrocells and small cells can coexist in a shared spectrum band. A number of surveys have been conducted focusing on ICIC and cognitive interference management for HetSCNs, including time-domain ICIC [10–12], frequency-domain ICIC [13–15], coordinated multipoint transmission and reception (CoMP) (i.e., space-domain ICIC) [16–20], power control [21], network-based and MS-based ICIC [22–24], user association and ICIC [25, 26], and cognitive interference management [27–29]. Moreover, the effect of performance-limited backhaul on ICIC is discussed in [30]. The main contributions of the existing surveys are summarized in Table 1.

Among the ICIC schemes, cognitive interference management [27–29] applies cognitive nodes with spectrum sensing functions, which increases the cost of small cell nodes and has not been accepted in standardizations yet. On the contrary, frequency reuse schemes [13–15] have been widely applied in the practical HomMCNs, because the network topology is quite regular and the ICI is predictable. Fractional and soft frequency reuse schemes are also studied in HetSCNs by allocating different frequency bands to macrocells and small cells to reduce the cross-tier and co-tier ICI. However, in long-term evolution (LTE)-based HetSCNs, frequency-domain ICIC schemes could only improve the performance of data channels (DCHs) by avoiding using the same resource as adjacent interferer cells, but fail to protect controls channels (CCHs), which use the same resource in all cells and carry critical information. Moreover, for space-domain ICIC schemes [16–20], such as coordinated multipoint (CoMP), its performance is limited or even vanishes in practical systems owing to the backhaul restrictions.

Time-domain ICIC is taken as one of the most promising ICIC schemes to employ for 4G and 5G systems, because it is convenient to implement and can effectively alleviate the ICI on both DCHs and CCHs. It has been observed that in HetSCNs, a dominant ICI is always observed in victim cells. The main idea of the time-domain ICIC is that the aggressive cell that causes the dominant ICI to victim cells avoids transmission in certain subframes, while victim cells schedule victim MSs with a high priority in these protected low-interference subframes. An almost blank subframe (ABS)-based time-domain ICIC scheme has been standardized by the third generation participate project (3GPP) in LTE-advanced (LTE-A) [31] as an enhanced ICIC (eICIC) scheme. Several surveys have been carried out on ICIC. For example, Ref. [15] mainly focuses on the frequency-domain ICIC and only provides a brief introduction on the

Table 1 Summary of existing surveys on HetSCNs

Categories	Survey papers	Contributions
Time-domain ICIC	[10]	Introduces the interference challenge in HetSCNs and the main idea of eICIC.
	[11]	Introduces the standardization work of eICIC in 3GPP LTE-A, including almost blank subframe (ABS), orthogonal frequency division multiplexing (OFDM) symbol shift, and power control.
	[12]	Introduces the main idea of eICIC, the coordination and signaling of system parameter settings related to eICIC, common reference signal (CRS) interference cancellation, and low-power ABS for eICIC.
Frequency domain ICIC	[13]	A survey of different fractional frequency reuse schemes for HetSCNs.
	[14]	A survey of various frequency-domain ICIC schemes with different enabling theories, such as game theory, graph theory, and machine learning, and different spectrum sharing principles.
	[15]	An overview of ICIC for macro-femto HetSCNs from the perspective of orthogonal channel and co-channel assignment.
CoMP	[16]	Introduces the standardization work of CoMP in LTE-A, including the CoMP scenarios in HomM-CNs and HetSCNs, CoMP transmission categories, and standardization for CoMP.
	[17]	A survey of BS coordination approaches in multicell network, including the downlink multicell beamforming and scheduling, and uplink coordinated scheduling and power control.
	[18]	Introduces the cooperative interference mitigation using CoMP in heterogeneous cloud small cell networks and provides performance evaluation of CoMP clustering schemes.
	[19]	Provides an overview of MS-side and network-side interference management techniques for 5G cellular networks, i.e., joint detection or decoding on the MS-side and joint scheduling on the network-side.
	[20]	A survey of CoMP clustering techniques for future cellular networks, including CoMP clustering algorithms based on self-organization (i.e., static, semistatic and dynamic) and aimed objective function (such as spectral efficiency and backhaul optimization).
Power control	[21]	Introduces the FFR in multilayer HetSCNs to reduce cross-tier interference and the joint optimization with power control.
Network-based and MS-based ICIC	[22]	A survey of ICIC techniques for HomMCNs from the perspective of network-based selective interference avoidance, including fractional frequency reuse, power control, and joint frequency and power allocation. It also provides a brief introduction on the interference scenarios and the main idea of eICIC for HetSCNs, including time, frequency, and power domain ICIC techniques.
	[23]	An overview of ICIC techniques for HetSCNs from the perspective of dominant interference mitigation, including a brief introduction of network-based time, frequency, and power domain resource allocation, and MS-based interference suppression and cancellation.
	[24]	An introduction of femtocell standardization and a survey of interference management techniques in femtocells, including MS-based interference cancellation such as successive interference cancellation and multiuser detection, and network-based interference coordination based on spectrum allocation, power control, and time hopping.
User association and ICIC	[25]	Introduces several user association approaches to load balancing in HetSCNs, and analyzes the effect of interference management, such as ABS-based eICIC, on load balancing.
	[26]	Summarizes the interference management challenges in multilayer networks, such as different user association schemes leading to diverse interference levels, and provides guidelines on joint user association and power control designs.
ICIC with backhaul constraints	[30]	Analyzes the coupling between backhaul constraints and ICIC, including user-cell association, interference management, multicell coordination, and dynamic spectrum access.
Cognitive interference management	[27]	A survey of cognitive interference management schemes in two-layer HetSCNs in which macrocells are noncognitive and femtocells are cognitive, including cognitive radio (CR)-enabled power control, frequency resource allocation, antenna beamforming, and joint schemes.
	[28]	An overview of how CR facilitates interference management in HetSCNs without any coordination. Introduces the CR-enabled interference mitigation approaches, including exploiting the orthogonality in the time-frequency and space domains, and interference cancellation via decoding techniques.
	[29]	A survey of using stochastic geometry models to analyze the performance of cognitive interference management performance in cognitive HetSCNs.

main idea of time-domain eICIC. Ref. [23] presents an overview on various ICIC schemes, including time, frequency, and power-domain ICIC. Again, the time-domain eICIC is only briefly introduced. Different from [22, 23], Refs. [10–12] focus on time-domain eICIC and provide an overview of its standardization in 4G networks. However, these surveys do not concern advanced designs of time-domain eICIC for 5G and beyond systems, such as joint time-domain eICIC and power control. This review aims to provide a comprehensive survey of time-domain eICIC standardization and advanced designs for future B4G mobile communication networks. First, it should be noted that the interference challenges in macro-femto and macro-pico HetSCNs are not the same; this paper provides an overview of time-domain eICIC schemes for macro-femto and macro-pico HetSCNs, as opposed to existing studies [14, 16, 17, 19–21] that do not make a distinction between femtocells and picocells. Moreover, in future B4G mobile communication networks, multiple ICIC schemes may be used simultaneously to combat complex ICI, including MS scheduling, power control, and CoMP, which can be jointly optimized with eICIC to improve the system performance. These advanced joint schemes have not been addressed in existing work.

Because HetSCN has been widely taken as a main deployment of future 5G mobile communication networks, it is especially interesting to investigate ICIC schemes that are not only theoretically feasible, but also implementable and standardizable, such as the time-domain ABS-based eICIC in LTE-A. Owing to the spectrum scarcity, co-channel will be the main deployment scenario of HetSCNs in 5G and the ICI can be coordinated using eICIC. An extensive survey on the main idea of basic eICIC schemes; advanced designs including self-optimized eICIC schemes and joint optimized eICIC versions with other techniques such as user association, MS scheduling, power control, and CoMP; and open issues will provide insights on how to design an effective and implementable ICI management scheme for HetSCNs and also provide references to 5G.

Different from existing studies in the literature, this review presents an extensive survey on the eICIC standardization and further advanced designs of time-domain eICIC schemes in LTE-based HetSCNs, including eICIC self-optimization and joint optimization with other ICIC schemes. The contributions of this paper are as follows. First, two important HetSCN scenarios in LTE and LTE-A networks, i.e., macro-femto and macro-pico scenarios, are described and the corresponding co-channel interference challenges are highlighted. Then, two main eICIC schemes proposed for LTE-A standardization, i.e., ABS and orthogonal frequency division multiplexing (OFDM) symbol shift, are introduced, with extensive illustrations of the impact of eICIC on other LTE-A functionalities, such as the multimedia broadcast multicast service single frequency network (MBSFN) mode, radio link failure (RLF) declaration, and carrier aggregation function. Next, an overview of advanced ABS-based eICIC designs is provided of macro-femto and macro-pico HetSCNs, on including self-optimized and joint optimized designs. The self-optimized ABS-eICIC is optimized with regard to key parameters of the scheme itself, such as the ABS muting ratio and which aggressors should mute. Moreover, because the ABS-eICIC is essentially a radio resource management scheme and radio resources are usually coupled among various schemes, it is necessary to jointly optimize eICIC with other radio resource management techniques, such as user association, MS scheduling, power control, and CoMP. Finally, this paper is concluded with a discussion of open issues in eICIC.

The rest of this paper is organized as follows. The basic configurations and main challenges of macro-femto and macro-pico HetSCNs are presented in Section 2. Then, two main eICIC schemes proposed for LTE-A, ABS and OFDM symbol shifting, are described in Section 3, including the impact of eICIC on other LTE-A functionalities. Next, various advanced algorithms for ABS-based eICIC are introduced in Section 4, including the self-optimized and joint optimized schemes. Finally, open research issues of eICIC are discussed in Section 5.

2 System description of heterogeneous small cell networks

2.1 Basic configurations

An example of a three-layered HetSCN is shown in Figure 1. The first layer is composed of macrocells,

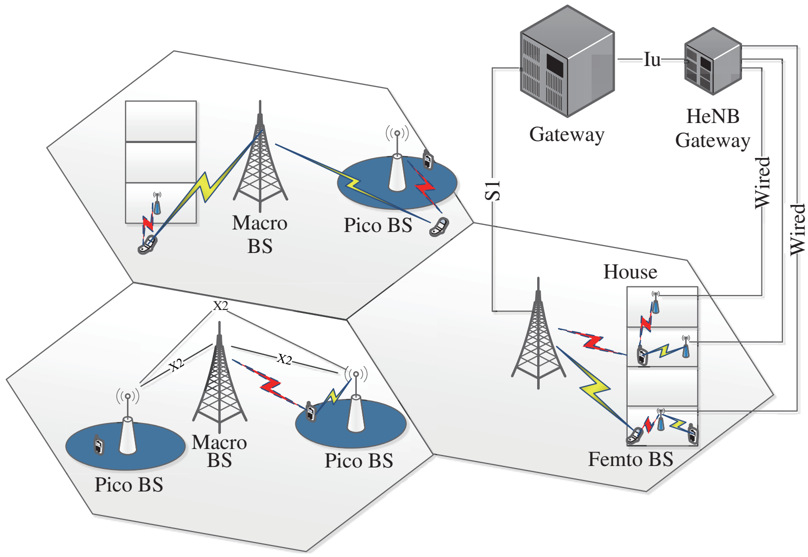

Figure 1 (Color online) Illustration of a HetSCN.

Table 2 Categories of small cells defined in LTE

Type of small cells	Backhaul	Access modes	Locations
Pico BS	Fiber (several microseconds latency) or wireless link	Open to all MSs	Placed indoors or outdoors Typically planned deployment
Femto BS	Digital subscriber line (DSL) or Cable (15–60 ms one way)	Closed subscriber group (CSG)	Placed indoors Consumer-deployed

which in practice are pseudoregularly and statically placed after careful cell planning and aim to provide wide area wireless access capability to all MSs. Irregularly placed picocells form the second layer, which are typically planned without cell planning but according to specific requirements such as providing multimedia services in stadia with high MS density. Finally, femtocells construct the third layer, which are deployed at home according to personal requirements of extremely high-speed wireless access. The properties of different small cells, including pico BSs (pBSs) and femto BSs (fBSs), are summarized in Table 2. Owing to the different demand and network deployment, macro-pico and macro-femto HetSCNs face different challenges.

2.2 Main challenges in HetSCNs

It is shown that the total system throughput of HetSCNs can be boosted significantly without any interference management techniques compared to HomMCNs [32–37], owing to the increased area frequency reuse. Take the macro-pico deployment as an example. When there are four outdoor picocells randomly deployed per macrocell and all MSs are randomly distributed in the network, the MS average throughput in the HetSCN can be twice as much as that in the HomMCN. However, the cell edge throughput, which is defined as the fifth percentile of MS throughput in the picocells of the HetSCN is reduced by 50% compared to that in HomMCNs [32]. This is because in HetSCNs, ICI is extremely serious owing to the overlapping deployment of macrocells and small cells, which becomes the main challenge.

In macro-femto scenarios, femtocells are deployed to enhance the indoor coverage of mobile cellular networks. The SINR of femto MSs (fMSs) is quite good because ICI from macrocells is weakened by the interior and exterior penetration loss. However, the macro MSs (mMSs) experience SINR degradation if fBSs exist nearby. Given a one-floor dual stripe in each sector of the macrocells with a 25% fBS deployment ratio, the SINR of the worst 5% mMSs and fMSs are below −18 dB and 0 dB, respectively [33], whereas in a HomMCN, the SINR of the worst 5% MS is below −3 dB. The SINR of mMSs is degraded in the macro-femto scenario, because femtocells are consumer-deployed and only MSs in the CSG are allowed

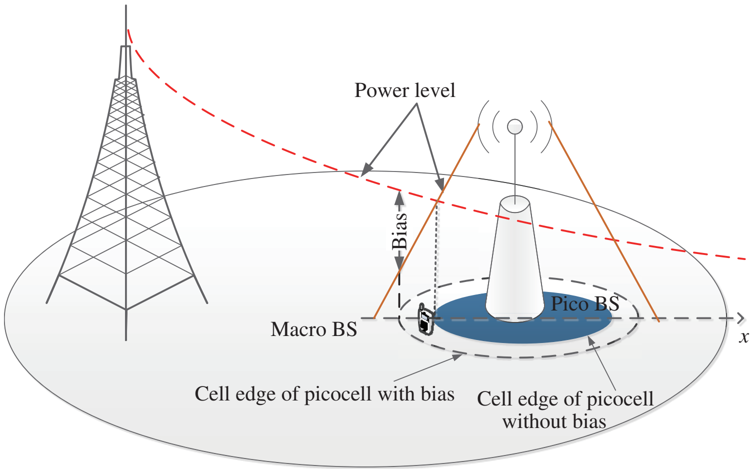

Figure 2 (Color online) Coverage of outdoor picocells with or without RE.

to connect to the fBS, which is totally different from HomMCNs, where MSs could connect to any cell that provides the strongest received signal power. Because mMSs in the vicinity of femtocells are not allowed to access the CSG cells, they will suffer severe downlink ICI from the CSG cells and this may result in coverage holes in macrocells. Moreover, for mMSs close to the edge of macrocells, their uplink transmission power is high, which causes severe ICI to nearby femtocells. The ICI between macrocells and small cells is called cross-tier ICI. Moreover, if many small cells are deployed in a building, i.e., the fBS deployment ratio is high, the ICI between small cells (i.e., co-tier ICI) could also be serious. Hence, in the macro-femto scenario, it is important to investigate ICIC algorithms that could alleviate the serious cross- and co-tier ICI, eliminate coverage holes, and improve the system capacity.

Different from the macro-femto scenario, in the macro-pico scenario, a significant challenge is how to offer high-load capability in outdoor picocells with severe ICI from macrocells. Note that picocells can be deployed to indoor or outdoor hotspots for coverage enhancing by balancing the load from macrocells. For indoor picocells, although their transmission power is much lower than that of macrocells, they could always provide stronger signals than macrocells in their coverage area, owing to interior and exterior penetration loss. Thus, load balancing can be easily achieved because indoor MSs tend to connect to picocells but not macrocells. However, for outdoor picocells, there is no penetration loss. Using conventional cell selection criteria, such as that based on the strongest reference signal receiving power (RSRP), MSs always select the BS providing the strongest signal power. Hence, the serving area of outdoor picocells may be small and only a limited number of MSs can be served, as shown in Figure 2. To improve the load balancing between outdoor picocells and macrocells, in addition to increasing the coverage of picocells by boosting their transmission power [38], a possible solution is to use range expansion (RE) with a biased RSRP cell selection criterion, whereby a bias is added to the RSRP value with several decibels for picocells and 0 dB for macrocells [31], such that more MSs are driven to select the picocell as the serving BS. However, the bias value can only vary within a few decibels, otherwise pico MSs (pMSs) in the RE area suffer high cross-tier ICI from macrocells and the coverage performance is degraded. With the same network setting in [32] as described before, the simulation results in [39] show that when the RE bias are 0, 8, and 16 dB, and the SINR of 5% pMSs are below −2, −8, and −16 dB, respectively. The SINR of the cell edge MSs in picocells thus decreases rapidly as the RE bias increases. Therefore, in the macro-pico scenario, it is important to investigate effective ICIC schemes that could mitigate the cross-tier ICI and enable outdoor picocells to offload efficiently. In the following context, outdoor picocells are concerned unless specifically noted otherwise.

In summary, for macro-femto and macro-pico HetSCNs, different dominant interferers exist, leading to severe cross-tier ICI. In macro-femto scenarios, the femtocells with CSG property are aggressors to the MSs of macrocells, whereas in macro-pico scenarios with RE, the macrocells with high transmission power are aggressors to the MSs of picocells. Fortunately, time-domain inter-cell resource allocation can

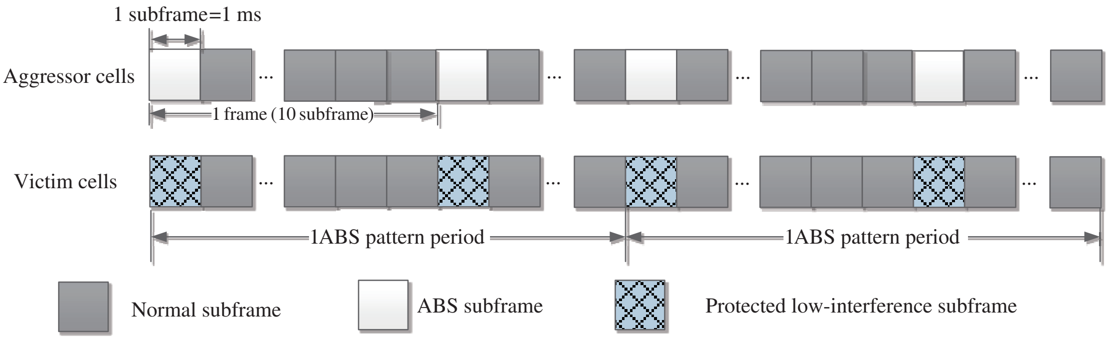

Figure 3 (Color online) Transmission with ABS configuration.

be used to reduce the dominant ICIs in both macro-femto and macro-pico HetSCNs.

3 Time-domain ICIC in LTE

As stated before, one prominent feature observed in the co-channel HetSCN is that there is always a major interferer, leading to a higher dominant-interference-ratio (DIR) than that in HomMCNs [10], which is defined as the ratio of the dominant inference to the sum of the rest of the interference experienced at an MS. It is expected that if the dominant interferers could be identified and then muted for a certain time, the performance of HetSCNs should be improved. Based on this idea, a time-domain eICIC scheme for co-channel deployment is developed for LTE-A in HetSCNs, and has been approved as a work item in 3GPP [40]. The basic principle is to coordinate the time-domain transmission of victims and aggressors, such that the ICI among different layers could be reduced and the overall system performance could be improved. There are mainly two types of time-domain eICIC schemes, i.e., ABS and OFDM symbol shift. The ABS approach is standardized in 3GPP for LTE-A release 10, whereas the OFDM symbol shift is not.

3.1 Almost blank subframe

3.1.1 *Basic idea*

The basic idea of the ABS approach is to coordinate the subframe utilization across different cells in the time domain. As shown in Figure 3, the ABS pattern period is composed of several frames. In each period, a number of subframes are configured as ABSs in an aggressor cell, where only necessary control signals such as common reference signals (CRSs) are transmitted to ensure backward compatibility, but no data signals are transmitted [41]. In other words, the aggressors are almost muting in the configured ABSs. Therefore, the MSs suffering serious ICI in the victim cells can be scheduled with high priority to transmit in the protected low-interference subframes, i.e., ABSs. The ABS pattern period is 40 ms for frequency division duplex (FDD) mode and 20, 60, or 70 ms for time division duplex (TDD) mode with different uplink and downlink configurations. The available ABS patterns in real systems are limited. It has been approved in the standardization that the baseline patterns with muting ratio 1/8 (bitmap: [10000000, ...]), 2/8 (bitmap: [11000000, ...]), and 3/20 (bitmap: [1000010000 1000000000, ...]) are for FDD, and the baseline patterns with muting ratio 1/10 (bitmap: [0000000001, ...]) and 2/10 (bitmap: [0000011000, ...]) are for TDD [42]. Other patterns such as 3/8 and 4/8 for FDD, 2/6 and 5/10 for TDD are feasible when the load in victim cells is heavy. The detailed bitmaps can be found in [43].

The procedure of ABS configuration is as follows. First, via the coordination among the aggressor and victim cells, such as exchanging the MS measuring report and load information of each cell, the ABS muting ratio, i.e., the ratio of subframes configured as ABSs, is determined by one aggressor (or victim) BS. Then, this BS will transform the ABS muting ratio to a corresponding ABS pattern available in real systems. For instance, if the calculated ABS muting ratio is 2/19, the approximated ABS pattern with

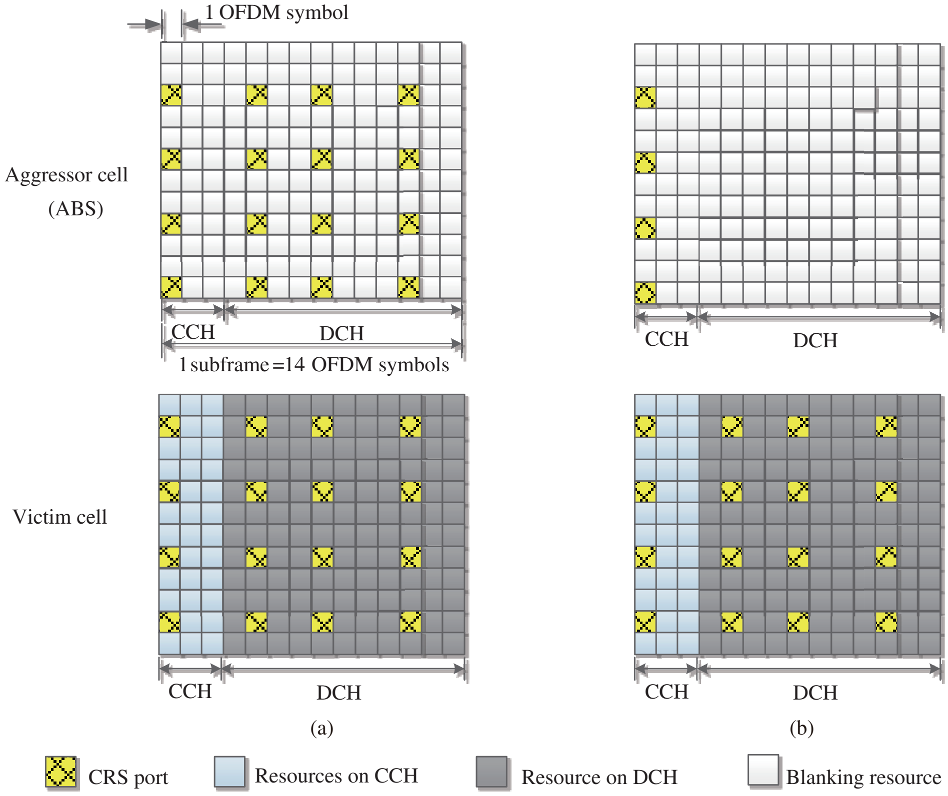

Figure 4 (Color online) ABS configurations with (a) normal and (b) MBSFN subframes.

a muting ratio of 1/10 will be selected. Then the corresponding ABS pattern and its bitmap will be informed to other BSs, so that they can schedule MSs to transmit (or mute) on ABSs according to the ABS pattern to reduce cross-tier ICI. As a baseline, the ABS patterns are transmitted via X2 signaling for picocells and via operation administration and maintenance (OAM) configuration for femtocells. Note that the ABS pattern defining which subframes are configured as ABSs may vary from period to period. To adapt to changes in the load and channel conditions, the ABS ratio, or equivalently, the ABS pattern, should be adjusted periodically or event-triggered. The ABS ratio updating period must be a multiple of the ABS pattern period.

3.1.2 *Interference from CRS*

As shown in Figure 4(a), in aggressor cells, even though some normal subframes are configured as ABSs, the CRS still causes severe interference to the signal on the same time-frequency resources in victim cells. Usually, adjacent cells use different CRS formats to avoid CRS co-channel interference. Thus, the CRS in the aggressor cell causes interference to the CCHs and DCHs in victim cells. In order to reduce the interference from CRSs in aggressor cells, on one hand, powerful signal processing techniques can be employed, such as the space-alternating generalized expectation-maximization algorithm with a maximum-a-posteriori criterion proposed in [44] and interference signal reconstructed method proposed in [45]. On the other hand, the CRS interference to DCHs can be avoided by configuring MBSFN subframes as ABSs, whereby the CRS is transmitted only on CCHs and DCHs are totally blank, as shown in Figure 4(b). According to the simulation results in [46], considering the overall average throughput in the HetSCN and in picocells, the performance of MBSFN approach is better than that of normal ABS mode, because the interference suffered in the picocells is reduced. However, if MBSFN subframes are used for multimedia broadcast and multicast service (MBMS), they cannot be configured as ABS subframes by the aggressors.

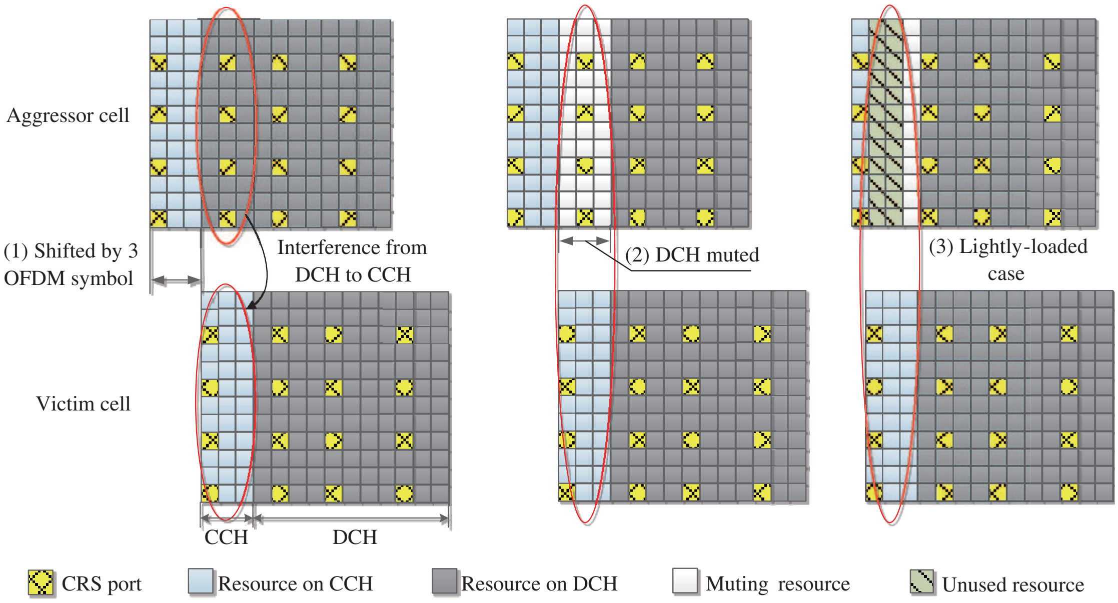

Figure 5 (Color online) OFDM symbol shift with data channel muting.

3.1.3 *Impact on radio link measurement*

In LTE networks, the RLF declaration is based on the signal measurement, which is obtained by averaging the received SINR over a certain period. For both the normal ABS and MBSFN approaches, cell edge MSs in the victim cells suffer much lower interference on ABS subframes than that on non-ABS subframes. Therefore, large SINR fluctuation can be observed in the measured link and it may cause an unnecessary and incorrect RLF declaration [47–49]. In addition, this large fluctuation in the channel quality also presents challenges for the BSs to conduct accurate link adaption and configure flexible channel state information (CSI) feedback. In order to avoid unnecessary RLF declarations, this problem has attracted much research interest in the channel quality indication (CQI) measurement, including aperiodic CSI reporting issues for eICIC (e.g., on which subframes MSs perform CQI measurement [50] and how MSs report CSI [51]) and SINR estimation during ABS and non-ABS subframes (e.g., discrete Kalman-filter-based SINR estimation [52] and Gray-model-based SINR estimation with poor known information [53]).

3.1.4 *Configuring CCH and DCH on ABS*

Usually, on ABS subframes, both the CCH and DCH are blank. This is because the role of the CCH in a subframe is to inform MSs on which time-frequency resources in this subframe they can transmit or receive data. For MSs only supporting Releases 8 and 9, if the CCH is blank, the DCH certainly cannot carry data. However, for MSs supporting Release 10, the CCH information can be obtained from the previous subframes via cross-subframe scheduling or from the primary carrier via cross-carrier scheduling in carrier aggregation scenarios. In these cases, the DCH of ABS subframes could still possibly carry data instead of being blank to improve the spectral efficiency. Obviously, the cost is the interference introduced by the data on the DCH.

3.2 OFDM symbol shift

Aimed at mitigating CCH interference, the OFDM symbol shift scheme is proposed [54]. First, to prevent the overlap of CCHs between macrocells and small cells, the subframe boundaries of victim and aggressor cells are shifted by a number of OFDM symbols. Then, the resource element muting strategy is employed to mitigate the ICI on the victim cell CCHs caused by the DCH of the aggressor cell. As shown in Figure 5, in all cells, the CCH occupies three OFDM symbols. At the first step, the subframe boundaries are shifted by three OFDM symbols to avoid the overlap of CCHs in different layers. Second, to avoid serious ICI from the aggressor DCH to the victim CCH, the aggressor cell mutes the three OFDM symbols overlapped with the CCH of victim cells. This means that 27.27% (3/11) of the resources is wasted in the aggressor cell. This waste can be mitigated in lightly loaded cases, when not all CCH resources are used to transmit control information and maybe one or two OFDM symbols are shifted and muted. In this way, the amount of wasted resources is reduced. However, extra interaction and coordination between the aggressors and the victims are needed to share the amount of CCH resources to be used. Note that the OFDM symbol shift approach can only mitigate the interference on the CCH, whereas the interference on the DCH still exists. To reduce the interference on the DCH, apart from the DCH symbols overlapped with the CCH of victim cells, other symbols in aggressor cells can also be configured as ABSs.

3.3 Effectiveness of eICIC

The eICIC based on time-domain resource allocation has been shown to be effective to mitigate the ICI in HetSCNs and improve the system performance.

As shown in Figure 1, in macro-femto scenarios, the mMS close to a fBS experiences dominant interference from the fBS and coverage holes may occur in the macrocell. This problem can be solved by eICIC via the identification of interfered mMSs and aggressor femtocells, and then muting the aggressor femtocells. It should be noted that a femtocell is an aggressor only if there are mMSs interfered by it. Ref. [55] presents throughput performance evaluations for the ABS-based eICIC in macro-femto scenarios with different muting implementation methods. Given a six-floor dual stripe in each sector of the macrocells with the fBS deployment ratio of 0.1, the simulation results show that if all the fBSs are simultaneously muted for two subframes in each frame, the average throughput of mMSs can be improved by 21%, whereas the average throughput of fMSs is degraded by 20% compared to that without eICIC. If only aggressor fBSs that have victim mMSs nearby are muted, the average throughput of mMSs can be improved by just 9.5%, whereas the degradation in the average throughput of fMSs is reduced to 7% compared to that without eICIC. It can be observed that the performance of mMSs is improved because the ICI from femtocells to mMSs totally vanishes or is reduced by muting all fBSs or aggressor fBSs. However, the muting strategy causes significant throughput loss in femtocells, because some subframes are muted at fBSs. Moreover, the mMS throughput gain of the all-fBSs-muted method is larger than that of the method in which only aggressor fBSs are muted, and the fMS throughput loss is also larger. Therefore, it is necessary to balance the performance improvement in macrocells with the performance degradation in femtocells. It can be seen that the performance improvement in macrocells comes from less ICI from femtocells and the fMS throughput loss comes from a lack of transmission in some subframes for fBSs. Schemes such as power control, which can minimize the ICI from fBSs to nearby mMSs, may be useful to work jointly with eICIC to achieve a better tradeoff between the performance improvement in macrocells and performance degradation in femtocells. A joint eICIC and power control optimization scheme is proposed in [56] and its main idea and performance are summarized in Subsection 4.1.3.

Moreover, as shown in Figure 2, in macro-pico scenarios with RE, the pMSs in the expanded coverage area of picocells experience dominant interference from macrocells, which can be mitigated via muting the transmission of the macrocell using ABS. Given a scenario with four picocells randomly deployed per macrocell and 2/15 MSs randomly distributed in the hotspots, the simulation results in [57] show that by muting all the even subframes in macrocells, the whole system throughput could be improved by 31.8% compared to that without ABS when the RE bias is 12 dB. Moreover, it is observed that when there is no ABS, RE is not desirable with any bias. This is because when the RE bias is increased, more MSs will be offloaded from macrocells to picocells in the expanded area. In this case, these pMSs will experience severe ICI from mBSs. The overall system throughput degrades if no ABS is configured. Whereas with ABS, the dominant interference can be mitigated, thereby improving the throughput. However, an excessively large RE bias is not desirable, because the received useful signal strength of a cell-edge pMS is weak owing to the long propagation distance, and the throughput will decrease even with ABS. Thus, when ABS-based eICIC is applied, an optimal RE bias exists to maximize the overall system performance. In [57], the optimal RE bias value is 12 dB. Therefore, with ABS-based eICIC, picocells with RE could provide larger

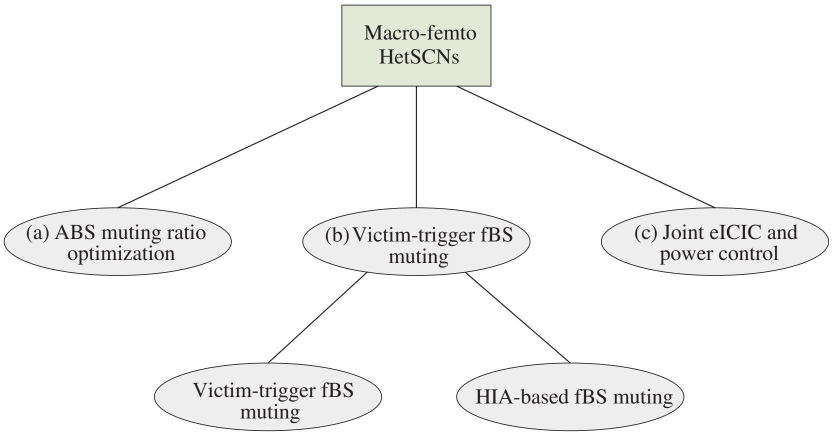

Figure 6 (Color online) Categories of advanced eICIC designs for macro-femto HetSCNs.

cell range expansions with a considerable performance improvement compared to that without ABS. In addition, offloading from macrocells with RE becomes more meaningful with ABS, because the pMSs in the expanded area can be scheduled in protected subframes to avoid serious ICI from macrocells. The optimal RE bias will change with the setting of the ABS muting ratio. For a certain ABS muting ratio, an optimal RE bias can be found. The theoretical analysis of the system performance with RE bias and ABS-based eICIC has been provided in [58] and the joint optimization of the ABS muting ratio and RE bias has been studied in [58–60]. Their main idea and insights are reviewed in Subsection 4.2.3.

4 Optimized design for eICIC in 5G and beyond

The mechanism of eICIC has been standardized in LTE-A and its effectiveness has been verified. However, there is still much work to do to fully understand eICIC and its impact on other communication schemes. On one hand, eICIC itself should be optimized with regard to key parameters, such as on which resources the aggressors should mute, i.e., ABS muting ratio; how aggressors should mute, i.e., fBS muting in macro-femto scenarios and low-power ABS in macro-pico scenarios; and which MSs are victims, i.e., MS partitioning. On the other hand, ABS-based eICIC is essentially a radio resource management scheme. Because the use of resources in communication systems is usually coupled among various schemes, such as eICIC and user association, a joint optimized design is necessary to achieve a good system performance.

4.1 Macro-femto eICIC designs

In macro-femto HetSCNs, femtocells are aggressors that deny access to nearby mMSs owing to the CSG property. Hence, to deploy ABS-based eICIC in this scenario, there are two key parameters to decide. The first is on which portion of resources the aggressors should mute. The second is which aggressors should mute. As shown in Figure 6, in literature, the existing advanced eICIC designs on ABS muting ratio optimization deal with the first parameter, whereas those on fBS muting concern the second parameter. Moreover, ABS muting can be taken as a special power control scheme that sets the transmission power of aggressors to zero when necessary. Therefore, it is natural to jointly investigate ABS-based eICIC with power control.

4.1.1 *ABS muting ratio optimization*

Assuming that all aggressors should mute, this research concerns on which portion of resources they should mute. In macro-femto HetSCNs, femtocells are aggressors and ABSs are configured in femtocells to protect the transmission of mMSs. In practical systems, the ABS ratio configuration is usually fixed to an empirical value for the ease of network operation. However, the fixed ABS ratio setting is not optimal with respect to the system performance. Although the performance of victim mMSs can be improved owing to the muting interferers, the resource utilization in the aggressor femtocells is reduced with the existence of ABS subframes. Therefore, in order to improve the system performance, the setting of the ABS muting ratio should take both the performance loss of aggressor cells and the improvement in the overall system performance into consideration. In order to obtain a good balance between the system throughput and MS fairness, an optimized design for the ABS muting ratio is proposed in [61], which can be used in both macro-femto and macro-pico scenarios. The objective is to maximize the system proportional fairness (PF) throughput for HetSCNs, i.e., a sum logarithmic utility, given by

$$U = \sum_{i} \log\left(T_i\right) = \sum_{i=1}^{N_v} \log\left(T_{v,i}\right) + \sum_{i=1}^{N_n} \log\left(T_{n,i}\right) + \sum_{i=1}^{N_a} \log\left(T_{a,i}\right), \tag{1}$$

where N_v and $T_{v,i}$, N_n and $T_{n,i}$, and N_a and $T_{a,i}$ are the number and throughput of victim MSs, normal MSs in the victim layer, and all MSs in the aggressor layer, respectively. The MS throughputs T_i are determined by the ABS muting ratio, proportions of MSs transmitting in protected and normal subframes, and channel capacity in protected and normal subframes. For example, the throughput of victim MS i, $T_{v,i}$, is expressed as

$$T_{v,i} = m \cdot \alpha \cdot r_{\mathrm{vp},i} + n\left(1-\alpha\right) r_{\mathrm{vn},i}, \tag{2}$$

where α is the muting ratio, m and n are the fraction of ABS and non-ABS resources allocated to this victim MS, and $r_{\mathrm{vp},i}$ and $r_{\mathrm{vn},i}$ are the channel capacities of the victim MS transmitting on ABS and non-ABS subframes, respectively. The optimal ABS muting ratio can be obtained by maximizing the utility function (1). In particular, if it is assumed that victim MSs can only transmit on ABSs and other MSs can only transmit on non-ABSs, the optimized muting ratio α can be derived as $\frac{N_v}{N_v+N_n+N_a}$, which is only related to load parameters.

4.1.2 *fBS muting schemes*

This type of research concerns which aggressors or fBSs should mute. In [61], all femtocells have to mute on ABS subframes. However, some femtocells are not aggressors if there are no mMSs nearby. The unnecessary muting in non-aggressor femtocells will lead to low subframe utilization in these femtocells.

Victim-trigger fBS muting. A victim-trigger eICIC scheme has been proposed in [62] to mute only aggressor fBSs. In this scheme, victim mMSs identify the aggressor femtocells and trigger them to mute. First, a victim MS tracking method is designed, where the victim states of mMSs are marked and unmarked according to their average SINR levels. When the SINR of a mMS degrades to a predefined minimum SINR level, it is marked as a victim. Then, victim mMSs send the interfering information to their serving mBSs, which will successively trigger the corresponding interfering fBSs to activate the ABS mode in descending order with respect to the received signal strength at the victim MS, until the SINR of the victim MS reaches the target value. When the SINR of the victim mMS increases to a given threshold and it is marked as a normal MS, the interfering fBSs are triggered to deactivate the ABS mode. In this way, the victim state of all MSs can be marked and their corresponding interfering fBSs are triggered to the ABS mode. Given a macrocell with a radius of 500 m and 40 CSG femtocells as well as 10 mMSs uniformly distributed in the coverage of the macrocell, for a fixed ABS ratio of 1/8, the throughput decrease in femtocells of the victim-trigger eICIC in [62] is much less than that obtained by muting all the fBSs in the aggressor layer.

Note that various forms of coordination are needed in this victim-trigger eICIC scheme, i.e., the coordination between mBS and its serving mMSs to track the victim state and report the interfering fBSs, and the coordination between mBS and fBS to activate or deactivate the ABS mode. The victim-trigger eICIC scheme relies on the backhaul latency performance owing to the signaling interaction between the mBS and fBS. If fibers are used for the backhauls of fBSs, the coordination latency could be several tens of milliseconds.

Another aggressor fBS identification method that does not rely on the backhaul is proposed in [63], whereby fBSs detect the uplink transmissions (e.g., reference signal) from mMSs to proactively obtain the victim mMS information. A mMS is most likely to be a victim if it is close to a fBS and it will increase its uplink transmission power. Thus, the SINR detected at the aggressor fBS is high. Then, the aggressor fBS will activate the ABS mode. In this way, the backhaul requirement posed by the victim-trigger scheme in [62] can be reduced.

In addition to the SINR tracking, the RSRP measurement can also be employed to identify victim MSs. If the strength of the RSRP from one fBS at a mMS over its useful signal strength from the serving mBS is larger than a predefined threshold, the fBS is identified as an aggressor and the mMS is marked as a victim [55].

Note that the ABS muting ratio is fixed and predefined in the victim-trigger scheme in [62], which is not optimal with respect to the network performance. Therefore, the optimization of the ABS muting ratio in [61] can be applied in this victim-trigger-aware scheme.

HIA-based two-Step fBS muting. In macro-femto scenarios using the victim-trigger scheme [62], all aggressor fBSs should be muted simultaneously on all ABS subframes. However, for a victim mMS j, it suffers strong interference (or dominant interference) only from the nearby aggressor fBS, whereas the interference caused by other aggressor fBSs is negligible. Therefore, if only the victim mMS j is transmitting and other victim mMSs are not, only the nearby aggressor fBS needs to be muted. Therefore, if the data transmission of victim mMSs with a certain aggressor fBS can be separated from those of other victim mMSs with another aggressor fBS on different ABS, it is unnecessary to set the same ABS muting ratio for all the aggressor fBSs.

Hence, a novel two-step optimal resource partitioning scheme is proposed in [64]. The goal of this scheme is to maintain the performance of macrocells while improve the performance of femtocells by reducing the muting ratio of each aggressor femtocell compared to the victim-trigger scheme. Assume that the victim mMSs are all scheduled on ABSs and the normal mMSs are all scheduled on non-ABSs. At the first step, the time-domain resource partitioning is performed between the victim and normal mMSs to maximize the macrocell PF throughput (i.e., the first and the second items of (1)) and the optimal ABS muting ratio can be obtained as $\beta_{\rm all} = \frac{N_v}{N_v+N_n}$. At the second step, the victim mMSs report their aggressor fBSs to a central unit, which groups adjacent victim mMSs with the same aggressor fBSs to from several high-interference areas (HIAs). Then, the ABS resources obtained according to $\beta_{\rm all}$ are orthogonally allocated to the victim mMSs in each HIA with the goal to maximize the summed PF throughput of all victim mMSs. After the optimization, an optimal muting ratio β_h can be obtained for HIA h. Then, an aggressor fBS will mute only when the victim mMSs in the same HIA are scheduled. This leads to a reduced ABS muting ratio for each aggressor fBS, while the effective ABS muting ratio in the macrocell can still be guaranteed.

Given a macrocell with the radius of 500 m and 40 CSG femtocells uniformly distributed in the coverage of the macrocell, six mMSs are randomly located nearby femtocells and the other six mMSs are randomly located in the macrocells. With a maximal ABS ratio restriction of 3/8, the simulations show that the throughput of the macrocell with the HIA-based two-step fBS muting is close to that with the victim-trigger scheme, whereas the throughput of femtocells with the HIA-based scheme is improved by 44% compared to that with the victim-trigger scheme.

4.1.3 *Joint eICIC and power control*

In macro-femto scenarios, appropriate power setting of fBSs, i.e., power control [65–67] is also effective to mitigate the interference experienced by mMSs while maintaining the throughput of fMSs. The fBS power control will adjust the total transmission power of a certain fBS, which is uniformly distributed in each resource block. In fact, ABS-based eICIC can also be taken as a specific power control scheme that sets the transmission power to zero on ABS subframes. Therefore, it is natural to employ fBS power control schemes with eICIC jointly, which can improve the MS outage performance [68] or the system throughput [56] compared to only applying eICIC or fBS power control.

In [68], it is shown that even with the fBS power control scheme based on path loss, there are still nearly 30% of indoor mMSs whose average SINR is below -10 dB. Therefore, a joint power control and eICIC scheme is proposed, whereby these victim indoor mMSs are scheduled with priority in ABS subframes in priority and other mMSs are served in non-ABS subframes with power control at fBSs. With 80% of mMSs deployed indoors and a fixed ABS muting ratio of 0.5 at fBSs, it is verified by simulation that the mMS outage probability of the fBS power setting scheme with ABS could be reduced by half compared to that of the fBS power control scheme without ABS.

Note that the fBS transmission power and ABS muting ratio in [68] are fixed, which are not optimal. Thus, a joint fBS power control and eICIC optimization method is proposed in [56] to maximize the fMS throughput while satisfying the minimum throughput requirement at victim mMSs. Considering a simplified macro-femto network with one fBS and one mBS, each with one fMS and one mMS, the MS throughput is given by

$$T = N_{\rm ABS}r(0) + (N - N_{\rm ABS})r(P), \tag{3}$$

where N is the total number of subframes in an ABS period, $N_{\rm ABS}$ is the number of ABS subframes in an ABS period, and $r(0)$ and $r(P)$ are the MS rates when the transmission power of the fBS is 0 and P, respectively. This differs for victim mMSs, normal mMSs, and fMSs. To maximize the above throughput with the mMS rate requirement constraint and the integer ABS subframe number constraint, this joint optimization of fBS transmission power and ABS muting ratio is nonconvex. It has been proved in [56] that when the integer constraint of ABS subframe number is relaxed, the optimal solution is either power control or ABS-based eICIC individually, which reveals that the joint scheme is not needed in this case. When the integer constraint of ABS subframe number is considered, it is proved that the optimal solution is always the best of three cases, i.e., power control without eICIC, or eICIC without power control with a rounding up or down ABS subframe number. Using the scheme without eICIC as a baseline, the fMS performance loss of the joint eICIC and power control optimization scheme in [56] can be reduced by 50% compared to that of the non-joint eICIC.

5G and beyond systems will also adopt macro-femto HetSCNs to increase network capacity. To support the advanced optimized eICIC schemes [56, 61–64, 68] in 5G and beyond systems, there is no need for new signaling, because existing signaling can be used to convey the load of each cell and track the victim state. However, a central unit is needed to determine the optimization of the ABS muting ratio or the joint optimization of eICIC and power control.

4.2 Macro-pico eICIC designs

In macro-pico HetSCNs, macrocells are aggressors to the MSs offloaded from macrocells to picocells with cell range expansion (CRE). ABSs can be configured in macrocells to protect the transmission of the victim pMSs. Therefore, to employ ABS-based eICIC in this scenario, the following problems should be solved. The first is on which portion of resources the aggressors should mute, i.e., the ABS muting ratio optimization. The second is how to group MSs in picocells into victim and normal MSs, i.e., MS partitioning. The third is how to set the CRE bias such that MSs in macrocells can be partially offloaded to picocells. Furthermore, these problems need to be jointly considered with other schemes, such as user association and CoMP. The existing advanced eICIC self-optimizations and joint designs with other schemes in macro-pico are outlined in Figures 7 and 8, respectively.

4.2.1 *eICIC self-optimizations*

(1) ABS muting ratio optimization. Given a CRE bias, the MS association to macrocells or picocells can be determined. Then, pMSs are partitioned into normal pMSs and victim pMSs. With the known MS association and MS partitioning results, the optimal ABS muting ratio to maximize the system PF throughput can be obtained as that in macro-femto scenarios [61]; refer to Subsection 4.1.1. Note that the CRE bias setting and MS partitioning have strong impacts on the optimal value of the ABS muting ratio, which should be optimized jointly and will be further discussed later.

Usually, for macro-pico HetSCNs, ABS is only configured in macrocells to reduce ICI to victim pMSs. However, the mMSs near the boundary of picocells also suffered ICI from picocells. Thus, the authors in [69] propose to employ ABS in both macrocells and picocells. Assuming that victim MSs can only transmit on ABSs and other MSs can only transmit on non-ABSs, the throughput of a MS can be obtained

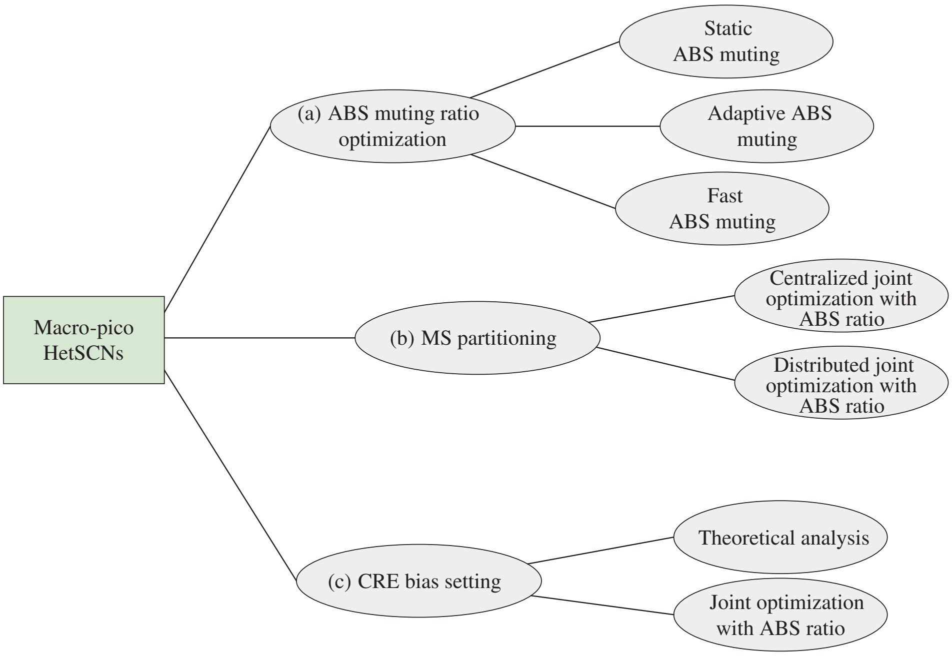

Figure 7 (Color online) Categories of eICIC self-optimizations for macro-pico HetSCNs.

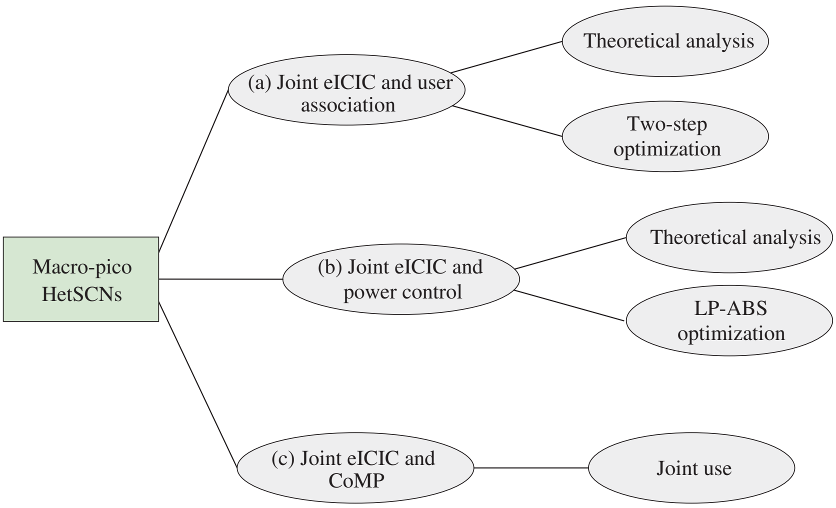

Figure 8 (Color online) Categories of joint eICIC and other ICIC schemes designs for macro-pico HetSCNs.

as a function of the ABS muting ratio of picocells and macrocells, depending on its type, i.e., a normal mMS, victim mMS, or pMS. Then the optimal ABS muting ratio for picocells and macrocells can be obtained by maximizing the system weighted product throughput utility via convex optimization tools.

• Adaptive ABS muting. In practical networks, the network load is time-varied owing to the MS mobility and traffic dynamics. As MSs move, the channel gain changes, which leads to different SINR levels of MSs or even reselection of the serving BS. Thus, the MS state, i.e., victim, normal, or aggressor, changes, which finally results in variations in the numbers of victim MSs, normal MSs in the victim layer, and all MSs in the aggressor layer. Moreover, various service types and packet sizes, dynamic arrival and departure of traffic packets, and even dropping of packet transmission also result in load variations. Therefore, in such dynamic HetSCNs, the optimal ABS muting ratio should be adaptively updated in response to the variations in network load and channel condition, which is known as dynamic eICIC [70–72].

In [70], a simple periodic adaptive eICIC scheme is proposed. At the start of every ABS period (such as 1 s or 1 min), given a current operating ABS ratio, the network evaluates the performance gain with a step-increased or reduced ABS ratio based on the varying channel information of MSs. Then, the network chooses the ABS ratio that provides the larger throughput. Compared to the eICIC scheme with a fixed ABS muting ratio of 1/4, the cell edge throughput of the adaptive eICIC can be improved by 15%.

In [71], given a network snapshot, the optimal ABS muting ratio is first derived for both full buffer (with infinite packet size) and non-full buffer traffic (with finite packet size). Then, dynamic eICIC can be designed according to the network dynamics, including MS mobility and traffic dynamics. This reveals that for the full buffer traffic, MS movements have strong impacts on the ABS ratio updating, and the system performance improves as the ABS ratio updating period gets smaller. For the non-full buffer traffic, the ABS ratio updating is closely related to the network load, i.e., the packet size and arrival rate. At low load, the average packet queue length is reduced compared to static eICIC, whereas at high load, the dropping rate of data transmission is reduced.

Instead of using a universal ABS ratio for all aggressor cells in the network [71], a dynamic ABS control scheme is proposed in [72] to adapt to the dynamic loads and interference states in different cells, whereby the ABS ratio is jointly optimized with MS scheduling in each victim cell. It assumes that MSs in any cells that suffer interference from other cells are victims, and ABS can be configured in each aggressor cell to protect the transmission of victims. First, the MSs in each macrocell and small cell are partitioned to interference-limited as noise-limited MSs. The interference-limited MSs are preferred to be scheduled on protected ABS subframes. Therefore, the ABS configuration can be jointly optimized with the MS scheduling, which is modelled by a probabilistic reasoning problem to maximize the network PF utility. This joint optimization problem can be decomposed into two subproblems, i.e., ABS configuration optimization with a given MS scheduling and MS scheduling optimization with a given ABS configuration, which can be independently solved by convex theories. Compared to the eICIC with a fixed ABS ratio of 1/8, the throughput of interference-limited mMSs and pMSs can be improved by approximately 150% and 70%, respectively.

The adaptive eICIC [70–72] can improve the system performance with network dynamics. This should be emphasized in the standardization of 5G, where the traffic dynamics are particularly prominent. However, the coordination overhead is high to update the optimized ABS ratio periodically.

• Fast ABS muting. Ideally, the ABS muting pattern should be adapted instantaneously to follow the fluctuations in the traffic and the channel conditions, such as on a timescale of one subframe, i.e., 1 ms. In dynamic eICIC schemes [70–72], according to the 3GPP standard, the updating period of the optimal ABS ratio must be a multiple of the ABS pattern period (e.g., at least 40 ms for FDD). If the ABS ratio should be updated, the current ABS pattern period with the outdated ratio must be completed before the new ratio can be used in the next period. Thus, a fast eICIC muting scheme is proposed in [73], which can adjust the ABS ratio on a subframe (1 ms) basis. Different from the standardized ABS that only defines a limited number of ABS patterns and a subframe is fixed to be an ABS or normal subframe, a new configurable subframe is introduced in the fast ABS pattern, which can be flexibly set as an ABS or normal subframe. Hence, the ABS ratio can be quickly adjusted by setting the next configurable subframes without waiting for the beginning of the next ABS period. Given an average offered load of 30 Mbps, compared to the eICIC with slow ABS muting ratio adaptation every 40 ms, the fast eICIC can improve the cell edge throughput by 37%.

Based on the work in [73], the authors of [74] evaluate the performance of fast eICIC in realistic networks by considering load-aware BS-MS association and allowing a different ABS ratio in each aggressor macrocell. Using load-based and throughput-based BS-MS association, the fast eICIC scheme in [73] is applied in every macrocell based on the local load condition. Given a realistic network topology and 3GPP simulation assumptions in [75, Annex A], the simulations show that compared to the static eICIC with RE-biased association, the cell-edge throughputs of the fast eICIC with load-based and throughput-based association can be improved by 30% and 65%, respectively, given an offered load of 280 Mbps.

It should be noted that the millisecond-level fast eICIC decisions require frequency signaling exchanges over nearly ideal backhauls for multicell coordination. Hence, the fast eICIC scheme is not applicable in current 4G networks. However, it may be employed in 5G and beyond systems with centralized architectures [75], in which the signal processing of all BSs is concentrated at one unit.

(2) Joint ABS muting ratio and MS partitioning optimization. The target of MS partitioning is to determine which MSs in picocells are victim pMSs and should transmit on ABSs while the others are normal pMSs and should transmit on non-ABSs. One simple solution is to make all pMSs transmit on ABSs and all mMSs transmit on non-ABSs, such that the transmission of picocells and macrocells use different resources in the time domain and cross-tier ICI is completely avoided. However, it is shown in [54] that given the ratio of available resources in macrocells and picocells to be 1:1, the throughput performance of this orthogonal scheme is 30% worse than that of the co-channel scheme, owing to the low resource efficiency of orthogonal transmission in different layers. Other possible eICIC solutions are to schedule victim pMSs on ABSs and normal pMSs on non-ABSs. These MS partitioning strategies are only based on victim MS identification and are easy to control. However, it should be noted that not all MSs being scheduled on ABSs must be victims. For example, normal MSs requesting a high-performance service can also be scheduled on ABSs to maximize the overall performance.

It is known that the MS performance is determined by not only the SINR level, which is related to MS partitioning, but also the available resource, which depends on the ABS muting ratio. Thus, to achieve the best performance, the MS partitioning should be optimized jointly with the ABS muting ratio [76,77]. Assuming that the ABS muting ratio is the same for all the cells, the PF utility of victim and normal pMSs in a picocell j and the PF utility of mMSs in a macrocell k can be obtained as $U_{v,j}$, $U_{n,j}$, and $U_{n,k}$, respectively. Then, the utility of each victim cell or the whole system can be designed as the product [76] or sum [77] of $U_{v,j}$ and $U_{n,j}$, or $U_{v,j}$ and $U_{n,k}$. Because the joint optimization involves a set of binary variables for MS partitioning and a continuous variable for the ABS muting ratio, it is nonconvex and difficult to solve. There are two types of solutions for this problem.

• Centralized iterative joint optimization. An iterative scheme is introduced in [76], in which the ABS muting ratio and MS partitioning are adjusted in turn to approach a near-optimal solution in macro-pico scenarios. A central controller is needed to coordinate the joint optimization. First, the ABS muting ratio is set to any possible value and broadcasted to each cell by the central controller. Then, each picocell could perform optimized MS partitioning with the given muting ratio, aiming to maximize the picocell utility given by the product of $U_{v,j}$ and $U_{n,j}$. Lagrangian theory is introduced to facilitate the MS partitioning and the marginal benefit (throughput) difference of a pMS being scheduled on non-ABSs or ABSs is derived by taking the Karush-Kuhn-Tucker condition. According to each pMS's marginal benefit difference, they are sorted in descending order. The first i pMSs will be arranged on non-ABSs and the rest on ABSs. Then, the optimal partition of the sorted pMSs can be found by testing i from zero to the total number of pMSs. It is noted that either victim or normal mMSs could be scheduled on ABSs if they can achieve a higher gain on ABSs than on non-ABSs. Given the MS partitioning, all macrocells and picocells could calculate the achievable channel capacities on ABSs and non-ABSs, and report these values to the central controller. Then, by maximizing the system utility, i.e., the product of the utilities of each cell, an optimized ABS muting ratio is obtained at the central controller. This optimized ABS muting ratio is broadcasted to every cell and the iterative approach continues until the ABS muting ratio converges.

Given a scenario with two randomly deployed picocells, 25 MSs uniformly distributed in each macrocell, and a RE bias of 9 dB in picocells, it is shown that up to 24% gain in the overall throughput can be achieved by the proposed scheme in [76], compared to that with a fixed ABS muting ratio of 0.3 and a simple MS partitioning arranging the worst 30% of MSs in terms of the SINR on ABSs.

• Distributed DP-based joint optimization. To avoid the requirements of a central controller and frequent information exchange, a distributed dynamic programming (DP)-based scheme is proposed in [77] to jointly optimize the MS partitioning and ABS muting ratio. At the first step, for ABS muting ratios valued from 0 to 1 with a step of 0.1, each macrocell calculates the cell utility and each picocell performs MS partitioning to maximize the cell utility, i.e., the sum of $U_{v,j}$ and $U_{n,j}$. For a given ABS muting ratio, the optimal MS partitioning can be obtained via a global search with a complexity of $O(2^K)$ or a DP method with a complexity of $O(K^2)$, where K represents the number of MSs in a picocell. At the second step, the optimal utilities of the picocells and macrocells for each ABS muting ratio are exchanged among all the pBSs and mBSs. With all the utility information, a common optimal ABS muting ratio can be found in each BS, which could maximize the system utility. Given a scenario similar to that in [76], the simulations show that the overall throughput can be improved by 31.5% with the proposed scheme in [77], compared to the orthogonal scheme with the resource ratio of 3:7 for picocells and macrocells.

Comparing the centralized scheme proposed in [76] and the distributed scheme proposed in [77], it can be seen that a central optimization decision unit is needed in [76], which can be easily realized in the future centralized architecture for 5G and beyond, whereas the distributed optimization [77] requires frequent signaling exchange among BSs to share the cell utility of each ABS ratio.

(3) Joint ABS muting ratio and RE bias optimization. In macro-pico scenarios, the setting of the RE is critical to the system performance. As stated before, ABS working with RE can effectively reduce the cross-tier ICI suffered by MSs in the RE area. Usually, a larger RE bias enables better offloading and needs a higher ABS muting ratio to provide sufficient ABS resources for victim range expansion MSs. However, a higher ABS muting ratio certainly decreases the resource utilization in macrocells. Hence, the ABS muting ratio and RE bias should be jointly optimized to achieve the best system performance and provide high-quality load balancing.

• Theoretical analysis. In [58], the effects of RE bias setting and ABS ratio on the SINR and rate coverage are analyzed. Based on the RSRP measurements, MSs are partitioned into three categories, including mMSs, pMSs without bias, and pMSs in the RE area. Assume that the mMSs and pMSs without bias can only be scheduled on non-ABSs, and pMSs with bias can only be scheduled on ABSs. The SINR and rate coverage of a typical MS are related to the association probabilities and their closed forms are derived using stochastic geometry theory. It can be seen that the SINR distribution of MSs is related to the setting of the RE bias, but independent of the ABS ratio, because the received signal and interference power for SINR calculation are determined by the RE bias. The rate distribution of MSs, which depends on the channel capacity and available resources, is related to the setting of both the RE bias and ABS ratio. The simulations show that without ABS, the SINR coverage (the probability of SINR larger than 0 dB) decreases as the RE bias increases. With ABS, an optimal RE bias exists for both the SINR and rate coverage. Theoretically, given an ABS ratio or a RE bias, the optimal RE bias or ABS ratio can be obtained. However, it is difficult to derive the optimal ABS ratio and RE bias jointly in theory. Therefore, joint optimization algorithms should be designed.

• TDM-based global resource allocation. Aiming to maximize the system weighted PF throughput, a novel joint ABS muting ratio and RE bias optimization algorithm is proposed in [59], which transforms the joint optimization problem into a resource allocation problem. First, the RE bias optimization is formulated as a MS association problem. Note that if a MS is associated to a pBS or a mBS, this pBS or mBS has to allocate an ABS or non-ABS resource to the MS. Therefore, the MS association can be obtained from the resource allocation problem, i.e., ABS and non-ABS resource allocation in picocells and non-muted resource allocation in macrocells. Next, because the ABS muting ratio is defined as the ratio of the ABS subframes time to the ABS pattern period, this ratio can be obtained from the time-domain multiplexing (TDM)-based resource allocation problem, i.e., the ABS and non-ABS resource allocation. Hence, the joint optimization of the RE bias and ABS muting ratio is formulated as a TDM-based resource allocation problem. Because this resource allocation problem is NP-hard, a two-step suboptimal algorithm is proposed [59]. Given an 8.9 km^2 real macrocell deployment with 10 picocells manually embedded in carefully chosen locations, MSs are randomly distributed with a density of 450 MSs/km^2 and MS hotspots are created in four of these picocells with a doubled MS density. The simulation results show that the proposed scheme in [59] can improve the cell edge throughput by nearly 40% compared with the eICIC with a fixed ABS muting ratio of 15/40 and a RE bias of 15 dB.

• ADMM-based TDM resource allocation. Compared to [59], in which the optimization variables in the joint problem are resource allocation indicators, the ABS ratio and RE bias are optimization variables in [60]. The joint optimization problem is converted to a general form consensus optimization problem with regularization and solved by an alternating direction method of multipliers (ADMM) algorithm. The simulation results show that the algorithm in [60] can outperform the algorithm in [59] by 1.34% in system utility with a running time of only 1.14% of that in [59]. Hence, Ref. [60] provides a low-complexity solution for the joint ABS ratio and RE bias optimization.

• Dynamic TDD transmission. Ref. [59, 60] are based on the regular LTE FDD transmissions. In beyond 4G or 5G networks, dynamic TDD transmissions may be employed, which dynamically change the uplink and downlink (UL/DL) transmission in each subframe. Ref. [78] considers ABS ratio and RE bias optimization in dynamic TDD transmissions, where the dynamic TDD configurations must be optimized together and cross-tier UL/DL ICI should be considered.

Assume that dynamic TDD transmissions is only employed in small cells. First, to avoid the main cross-tier UL/DL ICI, it is proposed that small cells can only conduct downlink transmission in the DL subframes in macrocells and perform dynamic TDD transmission in UL and ABS subframes in macrocells. Given an ABS period, the proposed ABS muting ratio and RE bias optimization algorithm performs an exhaustive search to find the optimal ABS number that minimizes the average traffic demand density difference in each macrocell and picocell. For each ABS number, mMSs are partitioned into two groups based on their SINR in descending order: the first group is in macrocells and the rest offloaded to picocells. Given any MS partitioning option, the optimal dynamic TDD UL subframes can be found to minimize the average UL and DL traffic demand density difference in each picocell. The corresponding CREs for each picocell can be obtained based on the RSRPs of the offloaded MSs. With the information of the dynamic TDD subframe number, MS partitioning, and ABS subframes number, the average traffic demand density difference in each macrocell and picocell can be calculated. Thus, the optimal ABS muting ratio and RE bias can be determined. The simulations show that compared to the static TDD with ABS muting ratio and RE bias optimization, the proposed scheme in [78] can achieve a better system DL throughput performance with low and medium loads, whereas for the system UL throughput, the performance is worse than for the static TDD case with medium and high loads, owing to cross-tier and co-tier UL/DL ICI.

In 4G, MSs access the network based on the strongest received signal or RE-biased cell selection criterion. Employing the joint optimization of the ABS ratio and RE bias, the optimized ABS ratio and RE bias may change when MSs arrive or depart. Then, each small cell will broadcast the new optimized RE bias to MSs, with which cell edge MSs judge whether they have to handover to another cell. Moreover, it can be seen that the existing work on the joint optimization of the ABS muting ratio and RE bias are all from the perspective of global optimization. A central unit is needed to gather the channel information of all MSs and perform the centralized optimization, which can be realized in 5G and beyond systems with centralized architectures. In particular, the scheme in [78] can be employed in 5G and beyond systems with dynamic TDD or UL/DL decoupling configurations.

4.2.2 *Joint eICIC designs*

(1) Joint eICIC and user association. With different user association schemes, MSs may associate to BSs that do not provide the strongest received power. This will result in diverse interference levels in HetSCNs. For example, MSs associated to BSs providing weaker received power may suffer dominant interference from the BS providing the strongest received power. In this case, eICIC can be used with these novel user association schemes and ABSs can be configured at the dominant interferers to reduce ICI.

• Theoretical analysis. In [79], with ABS-based eICIC, a channel access-aware user association scheme is proposed to maximize the available resources and the spectral efficiency is derived. For a newly arrived MS, the channel access probability is calculated for every BS, which is defined as $\frac{1}{U_c+1}$, where U_c is the number of served MS in the concerned cell. Then, each MS selects the BS providing the largest channel access probability biased RSRP with which to associate. Given an ABS ratio, the average spectral efficiency of a newly arrived MS is analyzed based on the derivation of the association probability to mBSs in non-ABS and pBSs in ABS or non-ABS, cell load, and signal and interference statistics. Given a HetSCN with seven macrocells and 200 small cells, the channel access-aware user association scheme can obtain a much more balanced load than the strongest and biased RSRP association schemes. The average spectral efficiency of the newly arrival MS is also higher than those of the strongest RSRP and biased RSRP association schemes for any given ABS ratio.

• Joint optimization. The user association has a strong interplay with the ABS muting ratio. Once MSs change their associated BSs, the ICI varies and the optimal ABS ratio is different. To achieve a better overall system performance, the user association and ABS ratio should be optimized jointly. Refs. [80–85] study the user association and ABS ratio optimization jointly to achieve the best system utility: minimizing the outage probability [81], maximizing the system PF throughput [80, 82, 83, 85], and maximizing the system max-min weighted throughput [84]. However, the joint optimization problem is nonconvex and NP-hard with 0-1 association and continuous ABS ratio optimization variables.

Because the available ABS ratio is finite in real systems, Ref. [81] proposes a Hungarian matching algorithm to achieve the optimal user association for each given ABS ratio. Defining a "path" as one MS associating to a BS with satisfied quality of service (QoS), a new path may have a negative impact on other existing paths associating to the target BS, because it has to share the radio resource with other MSs in the same cell and may decrease the QoS of other MSs. Thus, some of the existing paths to the target BS may be disabled. On the contrary, it has positive impact on other existing paths associating to the source BS, because its radio resource can be used by other MSs. The Hungarian matching algorithm is to add and alter paths between MSs and BSs to maximize the path number between BSs and MSs. Then, through a brute-force search over all the candidate ABS ratios, the optimal ABS ratio can be found. Given a macro-pico HetSCN specified in 3GPP [75], it is shown that using the scheme proposed in [81], the MS blocking ratio is much lower than that of eICIC with a fixed RE bias of 6 dB and ABS ratio of 0.3.

Refs. [80, 82–85] all propose to solve the joint problem by a two-step optimization method. Given the user association vectors, the ABS ratio optimization problem is tractable, and the optimized ABS ratio can be obtained by taking the derivative of the objective function as in [61]. Then, with the optimized ABS ratio, a Lagrangian-based user association is proposed in [82] to iteratively solve the combinational user association problem. Defining different utility functions, Refs. [80, 83–85] all propose a marginal utility-based user association to make MSs associate to a BS with the largest marginal utility. Given a scenario with two picocell clusters randomly distributed per macrocell, four picocells randomly located in each cluster, and 2/3 MSs distributed in the clusters, compared to the strongest RSRP user association without ABS, it is shown that the average throughput can be improved by approximately 20% using the proposed schemes in [80, 82]. Meanwhile, because the marginal utility in [80, 83–85] considers the performance loss of other MSs if an MS associates with a certain cell, the Jain's fairness of MS throughput can be improved by over 50% by [83, 84] and the system PF utility is always better than that of eICIC with a fixed RE bias and ABS ratio [80, 85].

Different from the joint optimization of the ABS ratio and RE bias, in the joint optimization of the eICIC and user association, macrocells and small cells must inform MSs individually as to whether they must handover to another cell, according to the optimized user association results. The MS handover is triggered by the network. Assume that MSs access the BS with the strongest received power initially. They are most likely to handover to another BS when they need to transmit data. A handover before data transmission will significantly decrease the QoS of real-time applications, with a handover delay of over 17.5 ms [86]. Thus, the QoS of MSs cannot be guaranteed and it is unacceptable for 4G networks. If a hypercell is virtualized over physical cells, MSs access this hypercell and all the resources belong to each BS can be scheduled by this hypercell flexibly. MS handover in the joint optimization of the eICIC and user association will be no longer needed. This might be supported in 5G centralized networks with cell virtualization management.

(2) Joint eICIC and power control. In macro-pico HetSCNs, as described in Subsection 3.1.1, the conventional ABS subframe in macrocells is almost muted except for some necessary control information, and it is denoted as zero-power ABS (ZP-ABS). However, this will decrease the spectral efficiency of macrocells with ZP-ABS subframes. Power control can be applied to ABS subframes, which are called low-power ABS (LP-ABS) in macrocells to allow mBSs to serve mMSs with good channel condition using a reduced transmission power, as long as the low transmission power in macrocell ABSs would not incur a high ICI to picocells [87]. Thus, the spectral efficiency of macrocells can be improved. In order to maintain the cross-tier ICI to picocells at an acceptable level, the power of LP-ABS should be optimized, or even the power of LP-ABS and the ABS ratio should be optimized jointly.

• Theoretical analysis for LP-ABS. Tractable performance analysis is developed for LP-ABS-based eICIC, considering the LP-ABS power setting, ABS muting ratio, and RE bias [88, 89]. The performance metrics of [88, 89] are coverage probability and MS capacity, respectively.

In [88], the coverage performance of the LP-ABS-based eICIC is derived. The numerical results show that for a macro-pico network with an average of five picocells per macrocell and a RE bias of 6 dB, when the ABS ratio is lower than 0.45, the coverage performance of the LP-ABS-based eICIC with 20 dB power reduction on the LP-ABSs is better than that of no eICIC. Then, its performance decreases as the LP-ABS ratio increases. Given a LP-ABS ratio and mBS transmission power reduction factor, an optimal RE bias exists to maximize the coverage performance, which increases with the mBS transmission power reduction factor.

In [89], the MS capacity is derived for the LP-ABS-based eICIC, where the mMSs (pMSs) with the SIR above a threshold ρ (ρ') are scheduled on LP-ABSs (non-ABSs) and the others are scheduled on non-ABSs (LP-ABSs). It is shown that given a LP-ABS ratio of 0.5 and a RE bias of 12 dB, the lower the transmission power on the LP-ABSs is, the higher is the optimal scheduling threshold ρ in macrocells. The optimal system summed throughput and summed PF throughput considering fairness of the eICIC with LP-ABS are higher than those with ZP-ABS.

• Joint optimization for LP-ABS. In [90], to maximize the total system throughput, a joint optimization scheme of the ABS power, ABS ratio, and user association is proposed, which is based on TDM resource allocation as in [56], and a suboptimal solution is provided. First, given an LP-ABS power and ignoring the combinational MS-BS association constraints in TDM resource allocation, the problem reduces to a linear programming one and is solved by the interior point algorithm. With the resource allocation results, the MS association and the ABS ratio can be obtained, and the ABS power can be optimized to select the power satisfying the minimum rate requirement of MSs. Then, with the updated ABS power, the resource allocation and ABS power are adjusted iteratively until the optimized ABS power converges. Given a scenario with two picocells per macrocell, and 2/3 MSs clustered located in picocells, it is shown that the proposed scheme in [90] outperforms the eICIC optimization with fixed LP-ABS power of 12 dB and ZP-ABS by 3.3% and 8.6% in terms of system throughput, respectively. It can be seen that the gain of LP-ABS optimization over the eICIC-only optimization is limited. This is because the mMS throughput on LP-ABS subframes is low, whereas the pMS throughput on LP-ABS subframes is reduced compared to that on ZP-ABS subframes. The tradeoff between the mMS throughput improvement and pMS throughput degradation on LP-ABS is not obvious with respect to the system throughput.

(3) Joint eICIC and CoMP. CoMP is an effective ICIC technique to reduce ICI via BS cooperation, especially for cell-edge MSs. The basic idea of CoMP is to avoid the ICI in adjacent cells via coordinated spatial-domain inter-cell scheduling or transform the interfering signals to desired signals via joint transmission among multiple BSs [91]. Usually, a universal ABS ratio and RE bias are commonly adopted by eICIC, which lead to different ICI levels among cells. CoMP can deal with the ICI via coordinated scheduling or joint transmission (JT). For example, on ABS subframes, rather than muting mBSs, mBSs and pBSs can cooperate to serve victim pMSs to reduce cross-tier ICI. On ABS or non-ABS subframes, CoMP can be used among pBSs to serve victim or normal pMSs to reduce co-tier ICI. Thus, it can be used with eICIC jointly to further reduce the co-tier and cross-tier ICI.

In [92, 93], ICIC schemes using ABS and CoMP selectively are proposed considering a simple HetSCN with one macrocell and one picocell. In [92], for each subframe, the scheduler decides to use ABS mode or CoMP mode by comparing the MS data rate satisfaction ratio achieved with different modes. Thus, the ABS ratio and ABS configuration are not fixed and change from time to time. In contrast, a fixed ABS ratio is used in [93] with known ABS configurations. Then, in each ABS subframe, the network selects ABS or CoMP mode which provides a higher system throughput for victim pMSs. In non-ABS subframes, pBSs and mBSs serve MSs independently using a non-CoMP mode.

In [94], CoMP is applied along with eICIC to further improve the performance of pMS in the RE area.

For eICIC with ZP-ABS, JT is applied among picocells in ZP-ABS subframes. For eICIC with LP-ABS, JT is applied among picocells or between picocells and reduced power macrocells in LP-ABS subframes. The performance of CoMP on the top of eICIC with ZP-ABS and LP-ABS is evaluated for HetSCNs. Given a RE bias of 9 dB, eICIC is applied for the MSs in the RE area with a bias less than 6 dB, and CoMP is applied for the MSs in the RE area with a bias larger than 6 dB. In the scenario of four picocells per macrocell and 2/3 MSs clustered in picocells, it is shown that the cell-edge performance of the CoMP with LP-ABS (reduced 6 dB on LP-ABS) is 135% better than that of the CoMP with ZP-ABS. This is because MSs in the RE bias mainly suffer severe ICI from macrocells and cross-tier JT can be used on LP-ABS to improve MS performance, whereas the performance gain of co-tier JT on ZP-ABS is limited.

The ABS ratio in real systems is periodically updated on a long timescale such as 1 s, 1 min, or 1 h, which is semistatic and cannot adapt instantaneously to traffic load or network topology changes with small cells turning on or off. User-centric CoMP can adapt to the traffic load or network topology changes flexibly on a short timescale. Thus, in [95], the optimized use of user-centric CoMP is studied on the top of static eICIC with fixed ABS ratio in ultra-dense HetSCNs to further reduce the cross-tier and co-tier ICI, where CoMP is applied among picocells in all subframes and is applied between picocells and macrocells only in non-ABS subframes. First, given an ABS muting ratio, the CoMP transmission is optimized, where a MS selection and BS clustering problem is formed with the goal to minimize the average unsatisfied data rate requests of MSs. Because this problem is NP-hard, a heuristic iterative algorithm is proposed. Then, the near-optimal ABS ratio is obtained by a global search. Given a HetSCN with one macrocell and 32 picocells, the average unsatisfied request of the proposed scheme in [95] is only 1/5 of that with only the ABS-based eICIC scheme.

It can be seen that the existing joint eICIC and CoMP designs are mainly limited to an alternative CoMP and eICIC scheme [92,93] or apply CoMP on the top of the eICIC to further reduce the ICI [94,95]. The joint optimization of eICIC and CoMP remains an open problem, and should be further investigated in future ultradense cellular networks (UDNs).

Because the ICI gets more complex in 5G and beyond systems with ultradense deployment, the advanced joint designs are more preferred. A central unit is needed for the joint optimization schemes [80–85, 90, 92–95], which can be realized in 5G and beyond systems with centralized architectures.

5 Open issues

eICIC is an effective technique for the interference management of LTE-based HetSCNs, including macro-femto and macro-pico scenarios, by muting the aggressor cells to protect the transmission of victim MSs. It is believed that eICIC will be further employed in 5G with advanced designs. Although eICIC has been widely investigated, there are still many open issues for 5G and beyond.

5.1 Tractable eICIC analysis

The existing studies on eICIC are mostly focused on standardization and performance optimization, but there is a lack of systematic performance analysis to provide insights for advanced eICIC design. Using stochastic geometry, the authors in [96] have derived a closed-form expression of the average dominant interferer and a semi-closed form expression of the minimum ABS number satisfying the minimum required MS throughput. Moreover, the authors in [97] have derived a closed-form expression of MS SINR distribution with any number of muted and non-muted interfering cells. These analysis methods may be extended to obtain some tractable eICIC performance analysis results.

5.2 QoS or QoE guaranteed eICIC

Consider the macro-pico scenario. With a large RE bias, the SINR of some pMSs in the cell RE area on ABSs may be lower than that of no RE, owing to the co-tier ICI in the pico layer. The quality of service or experience (QoS or QoE) of MSs will degrade when compared to those of no RE and no eICIC. Because the existing eICIC can only reduce the cross-tier ICI, joint cross-tier and co-tier eICIC schemes could be developed to guarantee the QoS or QoE. The QoS or QoE assessing indexes are summarized in [98], including the peak signal-to-noise ratio (PSNR) in video applications, delay, jitter or rate parameters in voice over Internet protocol applications, mean opinion score, and user satisfaction based on service cost. The design of utility functions for QoS- or QoE-guaranteed eICIC schemes can refer to the aforementioned assessing indexes. Moreover, the deployment of small cells in the eICIC-enabled HetSCNs could also be optimized with QoS or QoE requirements [99].

5.3 eICIC optimization with backhaul limitations

As shown in Section 2, current small cells are backhaul-limited and this limitation is even more serious for future 5G, which aims to provide a peak data rate of tens of Gbps. Therefore, it is desirable to explore the performance of the eICIC with backhaul constraints. For the macro-femto scenario, the backhaul delay is large and difficult to estimate, because since femtocells are generally connected to the gateway through DSL or cable, which belong to different telecom companies. Therefore, the eICIC scheme applied in the macro-femto scenario is usually static to avoid frequent exchanging of signaling. However, a static eICIC scheme cannot adapt to the variations in cell load and channel state. When dynamic interference coordination among fBSs and mBSs is considered, if the signaling delay caused by the backhaul (typically 15–60 ms one-way) is larger than the ABS updating period (e.g., 40 ms), the performance may be degraded. In order to avoid the interaction among mBSs and fBSs, advanced eICIC schemes such as fBSs proactive signal detection and subframe muting should be developed.

5.4 eICIC optimization in the emerging centralized network

One promising network architecture for 5G is the cloud-radio access network (C-RAN), which has a centralized baseband unit (BBU) pool and high-capacity low-latency fronthauls connecting each remote radio unit (RRU) with the BBU pool [100,101]. It has been shown in [102] that it is easier to employ eICIC in centralized mobile networks such as C-RAN, where all MS information, including channel measurement and traffic request, is collected by a central unit. The data transmissions of all RRUs are managed by this central unit so that the interaction among BSs is avoided. Thus, eICIC can be naturally realized in this centralized architecture with a joint multicell high-performance manager. It would be interesting to analyze the performance difference of eICIC in centralized networks with a near-ideal backhaul and conventional distributed networks with coordination via a non-ideal backhaul.

5.5 eICIC for 5G ultradense cellular networks

Current eICIC is mainly designed for cross-tier ICI coordination with a dominant interferer in different layers. Note that UDN would be one of the main features of 5G and beyond [103–105]. As the small cell density increases, the co-tier ICI in the small cell layer increases and there may exist more dominant interferers [106–108]. It is desirable to investigate the interference distribution as the small cell density increases, including the cross-tier and co-tier ICI. Moreover, it is also interesting to explore whether the existing eICIC could be extended to deal with multiple dominant interferers from both the cross-layer and co-layer. New interference management schemes should be developed by exploiting the features of the interference distribution in UDN.

In addition, in UDN, it is more important to investigate the joint optimization of eICIC and CoMP, owing to the extremely high and complex ICI in the network. Note that eICIC is to mute some BSs in certain subframes, whereas CoMP needs to group several BSs to coordinate for MSs. BS muting results in changes in network topology, which has impacts on the BS clustering. Thus, the BS muting and BS clustering could be optimized jointly to improve the system performance.

5.6 Interference coordination for 5G with new frame structure

In 5G and beyond systems, higher frequency bands including 3.5 GHz and above 6 GHz (e.g., millimeter wave (mmWave)) have attracted much attention as a possible solution to obtain more spectra. In order

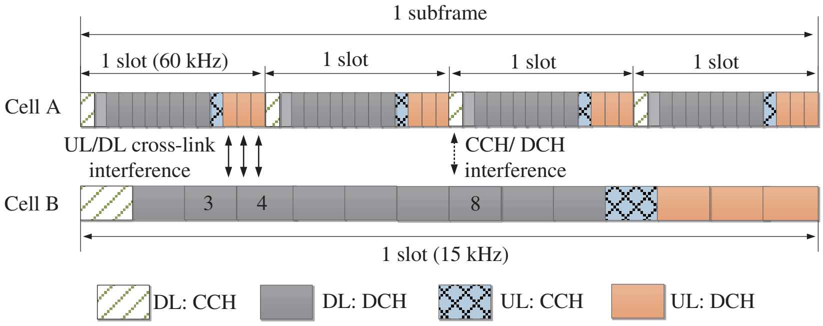

Figure 9 (Color online) Illustration of ICI caused by the 5G new frame structure.

to support a wide spectrum deployment with the sub-6 GHz band up to mmWave, 5G adopts multiple numerologies with subcarrier spacing ranging from 15 to 240 kHz [109]. Under a fixed setting of one slot with 14 symbols, a larger subcarrier spacing leads to a shorter slot duration. Moreover, in contrast to LTE frames, 5G adopts a self-contained frame structure in which the symbols in a slot can carry both UL and DL control and/or data signals. This new structure ensures faster feedback, because DL data and the corresponding ACK/NACK transmissions can be completed in a slot. As shown in Figure 9, with the new frame structure, ICI is more complex in 5G. For example, the DL DCH transmission in cell B incurs cross-link interference to the UL DCH signals in cell A, and the DCH transmission in cell B incurs interference to the CCH signals in cell A. To reduce the interference to cells A and B can use eICIC to mute some symbols, i.e., symbols 3, 4, and 8 in this example. It can be seen that because the symbol duration in cell B is four times that in cell A, more resources than needed are muted in cell B, which results in a waste. Therefore, more efficient interference coordination techniques should be designed for 5G with the new frame structure.

5.7 Interference coordination with UL/DL decoupling

Consider wireless communication with higher frequency bands, such as mmWave. It is well known that the wireless coverage performance is relatively poor for these high frequency bands, owing to the high path loss and weak diffraction ability. UL/DL decoupling has been proposed for 5G, whose main idea is to transmit UL and DL signals in lower (e.g., 1.8 GHz used by LTE) and higher (e.g., 3.5 GHz or mmWave) frequency bands, respectively [110]. The lower frequency band has better channel propagation condition and is used to achieve better coverage with limited transmission power at MSs. On the contrary, the higher frequency band is used to improve the network capacity in DL with a wider available spectrum. With UL/DL decoupling, co-channel interference occurs when the LTE and 5G uplink use the same frequency band such as 1.8 GHz at the same time. Because LTE has a higher priority to use in this frequency band, it is required that 5G cannot incur serious interference to LTE, especially to key LTE signals such as CRS. Therefore, if the symbols transmitting key LTE signals are known, 5G can use eICIC to mute the corresponding symbols to avoid high interference. Other techniques such as power control and beamforming should be considered.

5.8 Interference coordination for 5G and beyond with mmWave communications

mmWave communications with abundant spectral resources have been suggested for 5G and beyond to improve the network capacity, which could be applied in data transmissions for indoor hotspot, dense urban, macrocell, and backhaul transmissions for outdoor sBSs. In the indoor hotspot scenario with one cell in a room, the ICI is negligible owing to the poor radio propagation capability of mmWave. The inter-MS interference in the same cell can be mitigated via precoding techniques. In the dense urban, microcell, or sBS backhauling scenarios, mmWave communication usually works with the massive multiple-input and multiple-output technique jointly, to support a long-distance transmission by concentrating the energy in a certain direction via beamforming and allowing multiple links to communicate simultaneously. In this case, the interference among receivers (MSs or sBSs) with different locations is not severe as long as they can be distinguished by different beams. However, if receivers are close to each other or some are located in the beam direction of a target receiver, inter-receiver interference is serious. To reduce this type of interference, link scheduling in the time or frequency domains could be used, or advanced techniques such as nonorthogonal multiple access could be considered.

6 Conclusion

This paper presented a survey on time-domain eICIC for macro-femto and macro-pico HetSCNs from the perspective of standardization and advanced optimized and joint designs. It has shown that there is always a dominant interferer in HetSCNs, resulting in severe cross-tier ICI, and eICIC is an effective technique to reduce it by subframe coordination. Two basic eICIC schemes for LTE-based 4G systems, i.e., ABS and OFDM symbol shift, have been discussed in detail. Moreover, given macro-femto and macro-pico HetSCNs, the eICIC self-optimization with regard to key parameters such as ABS ratio has been reviewed. In addition, because the ABS-based eICIC is essentially a radio resource management scheme and the resources are coupled among eICIC and various schemes, joint designs are necessary between eICIC and many other schemes such as user association and power control. It has been demonstrated that the advanced self-optimized and joint designs could provide considerable performance gain over the basic schemes. These advanced schemes could be employed in 5G and beyond systems if centralized network architectures and additional signaling are available. Finally, from both the theoretical analysis and the perspective of 5G and beyond, the open issues of eICIC have been discussed. With tractable theoretical analysis, more insight might be provided for the design of advanced eICIC, especially for 5G-featured networks with serious backhaul limitations, centralized network architectures, and UDNs.

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