Chapter 2
Heterogeneous Network Model and Preliminaries

2.1 A System Model for Heterogeneous Networks

A two-tier heterogeneous network model in LTE is studied throughout this book. As shown in Fig. 2.1, consider downlink communications in a heterogeneous cellular network with high transmit power macro evolved Node Bs (MeNB) and low transmit power small evolved Node Bs (SeNB) or relay nodes (RN). Each macro cell is divided into several sectors served by directional antennas. Within each macro cell sector, there are several SeNBs or RNs uniformly distributed. Denote the total number of macro cell sectors in the system as N_c and the number of uniformly deployed SeNBs/RNs in each sector as N_r. UEs are uniformly distributed in the network with an average of N_u active UEs in each sector. The SeNBs/RNs have full radio resource management (RRM) functionalities as well as data relaying capability. Decode-and-forward relaying scheme is assumed. A UE can be either associated with a MeNB or a SeNB/RN. Denote a UE associated with a MeNB as a M-UE and a UE associated with a SeNB/RN as a S-UE/R-UE. The communication link between a MeNB and a UE is termed as a direct link, the link between a SeNB/RN and a UE as an access link, and the link between a MeNB and a SeNB/RN as a backhaul link. The backhaul link could be wired or wireless, could be ideal or non-ideal with ideal backhaul featuring a typical transmission delay of several micro seconds while non-ideal backhaul featuring a transmission delay ranging from several milli-seconds to ten of milli-seconds. For the wireless backhaul, the backhual link could be out-of-band backhaul or in-band backhaul. With in-band backhual, the backhaul link shares the same radio resource as the direct/access link.

The total frequency band can be divided into several sub-bands with each sub-band being assigned to one of the UEs. Denote the frequency-domain channel gain on the fth sub-band at time t between the ith MeNB and the kth UE as $h^f_{k,0,i}(t)$, and between the jth SeNB/RN in the ith sector and the kth UE as $h^f_{k,j,i}(t)$. The channel gain counts both long-term path loss and shadowing and short-term fading due to

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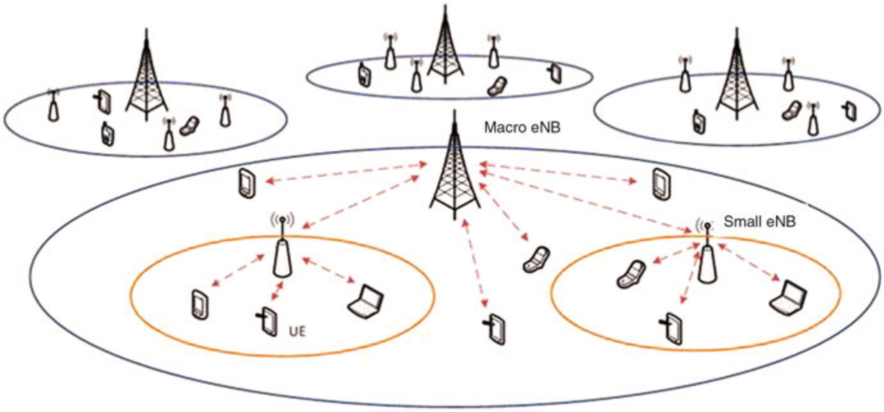

Fig. 2.1 A two-tier heterogeneous network model

multipath and mobility. The received signal-to-interference-noise-ratio (SINR) of the kth M-UE and kth S-UE/R-UE at the fth subband and tth transmission time slot can be evaluated respectively as

$$\mathrm{SINR}_{k,0,i}^{f}(t) = \frac{P_m^f |h_{k,0,i}^f(t)|^2}{\sum_{i' \neq i} |h_{k,0,i'}^f(t)|^2 P_m^f + \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} |h_{k,j,i}^f(t)|^2 P_p^f + N_0}, \quad (2.1)$$

and

$$\mathrm{SINR}_{k,j,i}^{f}(t) = \frac{P_p^f |h_{k,j,i}^f(t)|^2}{\sum_{i=1}^{N_c} |h_{k,0,i}^f(t)|^2 P_m^f + \sum_{i=1}^{N_c} \sum_{j'=1, j' \neq j}^{N_r} |h_{k,j',i}^f(t)|^2 P_p^f + N_0}, \quad (2.2)$$

where P_m^f is the transmit power density of the MeNB at the fth subband, P_p^f is the transmit power density of the SeNB/RN at the fth subband, and N_0 is the variance of the additive noise.

The data rate in terms of bit/s/Hz for the kth UE received from the jth SeNB/RN in the ith cell on the fth radio band at time t can be calculated using Shannon formula as

$$R_{k,j,i}^f(t) = \log\left(1 + \mathrm{SINR}_{k,j,i}^f(t)\right). \quad (2.3)$$

Data rate $R_{k,0,i}^f(t)$ can be similarly obtained as

$$R_{k,0,i}^f(t) = \log\left(1 + \mathrm{SINR}_{k,0,i}^f(t)\right). \quad (2.4)$$

2.2 Mobile Associations in Heterogeneous Networks

A mobile association scheme decides the network node for a UE to connect with. In homogeneous networks, best-power based mobile association is often applied [1,2], where the kth UE is associated with the node $\mathcal{N}_{(j*,i*)}$ that it receives the highest power from, i.e.,

$$(j^*, i^*)_k = \arg \max_{i \in \{1,\cdots,N_c\}, j \in \{0,1,\cdots,N_r\}} (P_{k,j,i}|h_{k,j,i}|^2), \tag{2.5}$$

where $P_{k,j,i}$ is the corresponding node transmission power. In heterogeneous networks, due to the transmit power disparity between a MeNB and an SeNB/RN, most of the UEs will be associated with the MeNBs if the best-power based association scheme is used. The SeNB/RN utilization will be low and the advantage of using SeNB/RN in improving the spectrum efficiency and coverage of the network could not be fully exploited. To balance the traffic load between the MeNBs and the SeNBs/RNs, range-expansion based association scheme has been proposed, which uses a bias to compensate the power difference between MeNBs and SeNBs/RNs [2], so that more UEs can be associated with SeNBs/RNs. In the range expansion based mobile association, the kth UE is associated with the best node $\mathcal{N}_{(j*,i*)}$.

$$(j^*, i^*)_k = \arg \max_{i \in \{1,\cdots,N_c\}, j \in \{0,1,\cdots,N_r\}} (|h_{k,j,i}|^2/\delta_{i,j}), \tag{2.6}$$

where $\delta_{i,0} = 1$ and $1 < \delta_{i,j} < (P_m/P_p)$, for $j > 0$. $\delta_{i,j}$ value specifies the coverage of the macro and small cells. A small $\delta_{i,j}$ leads to a large coverage region of the small cell while a large $\delta_{i,j}$ value leads to a small coverage region of the small cell. In extreme cases, $\delta_{i,j} = 1$ corresponds to path-loss based mobile association and $\delta_{i,j} = (P_m/P_p)$ corresponds to best-power based mobile association. Figure 2.2 illustrates the different mobile association schemes.

Range-expansion based mobile association scheme can effectively expand the coverage range of small cells and therefore improves the overall system spectrum efficiency. However, with a fixed bias value, the coverage range of small cells are kept fixed. It cannot be adapted to the traffic load at small cells and therefore is less flexible and not able to fully exploit the capacity of the small cells. Mobile association schemes have been studied in heterogeneous networks for a mixed deployment of macro eNBs and small relay nodes in [3–8]. In Chap. 3, a load-balancing based mobile association scheme is presented for the two-tier heterogeneous network model in this book. The presented scheme adapts mobile association according to the macro and small cell load condition. The load-balancing based mobile association is shown effectively to improve the network spectrum efficiency as compared to best-power based and range-expansion based mobile association schemes.

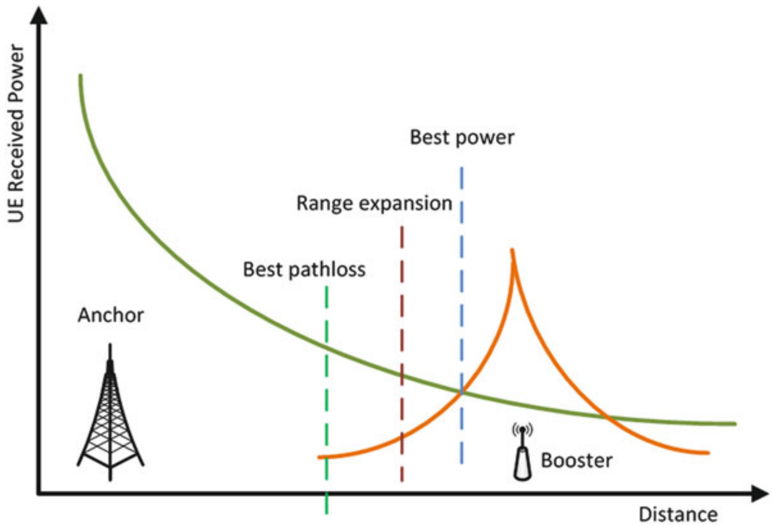

Fig. 2.2 Illustration of different mobile association schemes

2.3 Enhanced Inter-cell Interference Coordination in Heterogeneous Networks

Range expansion based or load-balancing based mobile association schemes expand the coverage range of small cells and improve the overall network spectrum efficiency. However, the UEs located at the edge of small cells would suffer from high interference from the MeNB. Proper interference management schemes can be used to mitigate the interference for cell edge UEs and improve the spectrum efficiency [9]. Inter-cell interference coordination (ICIC) is proposed in addressing the interference problem. By ICIC, proper resources coordination is conducted among interfering eNBs such that some of the eNBs give up some resource for the benefit of the other eNBs. The resource coordination can be done in time, frequency or spatial domain. Figure 2.3 demonstrates two examples of ICIC in time domain and frequency domain, where the MeNB reserves some of the subframes in time domain and resource blocks in frequency domain for use by the SeNB/RN.

In LTE Rel-8/9, ICIC is implemented among MeNBs to coordinate resource allocation in the frequency domain. Different frequency reuse options can be applied such as hard frequency reuse, fractional frequency reuse and soft fractional frequency reuse. To illustrate the different frequency reuse options, we use the example as shown in Fig. 2.4. By hard frequency reuse, the whole spectrum band is divided into subbands F_1 and F_2 with each subband being used by one of the cells. Hard frequency reuse completely eliminates the inter-cell interference, at the cost of reduced spectrum efficiency. By fractional frequency reuse, the frequency subband F_1 is used by both cells while the frequency subbands F_2 and F_3 are used by one of the cells,

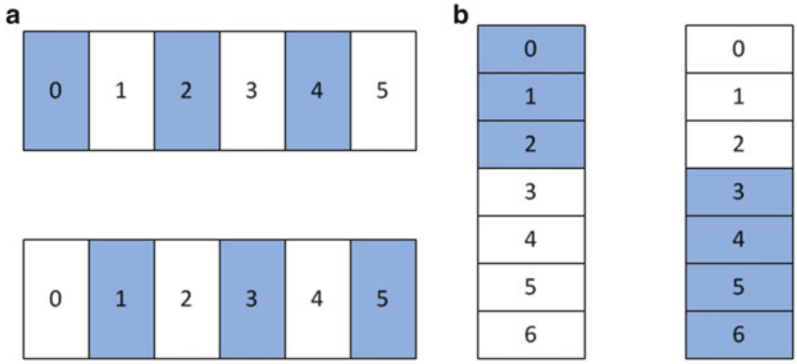

Fig. 2.3 Time domain and frequency domain frequency reuse. (**a**) Time domain resource coordination between macro and pico eNBs. (**b**) Frequency domain resource coordination between macro and pico eNBs

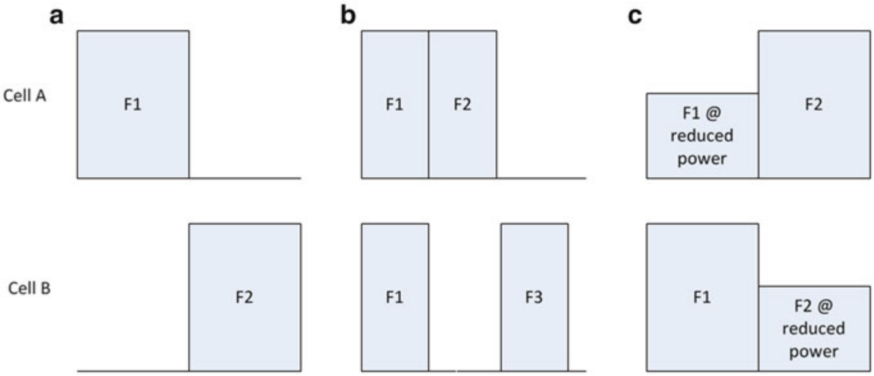

Fig. 2.4 Illustration of different frequency reuse schemes in frequency domain. (**a**) Hard frequency reuse. (**b**) Fractional frequency reuse. (**c**) Soft fractional frequency reuse

respectively. In this way, the frequency band F_1 can be used in serving the UEs at both cell centers while the subbands F_2 and F_3 can be used in serving the UEs at the edge of each cells. As the cell edge UEs are the most vulnerable to the interference, such scheme can effectively protect the cell edge UEs while improve the spectrum efficiency. By soft fractional frequency reuse, frequency bands F_1 and F_2 are used by both cells with cell A transmitting at a lower power at F_1 while cell B transmitting at a lower power at F_2. Cell A serves its inner cell UEs at F_1 and cell edge UEs at F_2 while cell B serves its inner cell UEs at F_2 and cell edge UEs at F_1. As the inner cell UEs often has good channel quality, it can still achieve a good data rate when served by a reduced DL transmission power. At the same time, the reduced eNB transmission power will cause less interference to the UEs at the edge of the neighboring cell. Soft fractional frequency reuse effectively alleviates the interference for cell edge UEs while maintains a high spectrum efficiency.

In LTE Rel-10, with the introduction of heterogeneous networks, UEs at the edge of small cells would suffer from high interference. Control channel is the most vulnerable to such macro-small interference as the control payload is typically distributed across the entire bandwidth and thus cannot be protected by the frequency domain based ICIC. As a result, UEs at the small cell edge would experience coverage holes on their control channel signals. To overcome this issue, enhanced inter-cell interference coordination (eICIC) has been proposed in LTE-Rel 10 [10]. Time domain interference coordination is applied with the introduction of almost-blank subframes (ABSF) [10]. During the ABSF, the interfering eNB does not transmit user data, but may transmit system broadcasting and reference signals, therefore the term "almost blank". The residual interference can be canceled by interference cancellation schemes at the receiver side. Resource coordination schemes have been studied in time, frequency, and power domains in a heterogeneous LTE relay network in [9] and [11]. An optimal fractional frequency reuse and power control scheme has been proposed that can effectively coordinate the interference among high power and low power nodes. In Chap. 4, an optimization framework for interference management with fractional frequency reuse is presented for the two-tier heterogeneous network model.

2.4 Intra-cell Cooperation in Heterogeneous Networks

ICIC/eICIC improves cell-edge UE performance by proper interference management. For heterogeneous networks with small coverage range expansion, a UE at the edge of a small cell would receive comparable signal quality from SeNB/RN and MeNB. It is therefore possible to enhance the cell-edge UE performance by applying intra-cell coordinated multiple point (CoMP) joint transmission from MeNB and SeNB/RN.

In LTE Rel-11, three kinds of CoMP schemes have been adopted, namely, coordinated scheduling and beamforming (CS/CB) CoMP, joint transmission (JT) CoMP, and dynamic point selection (DPS) CoMP. Figure 2.5 demonstrates the different CoMP schemes. In CS/CB, the two eNBs simultaneously transmit to their

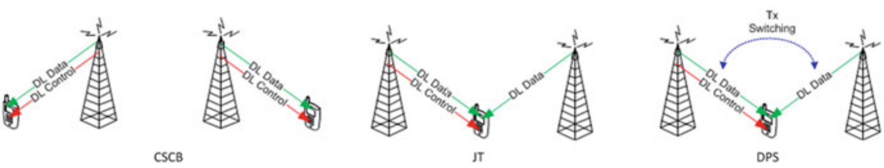

Fig. 2.5 Illustration of CoMP scheme options

Step 1: MeNB sends scheduling and data information to SeNB/RN.	Step 2: SeNB/RN decides the UEs that need to be cooperatively served with the MeNB and sends the corresponding scheduling information to MeNB.	Step 3: MeNB and SeNB/RN send data to the C-UEs according to the schedule determined in Step 2.	Step 4: each C-UE sends ACK/NACK information back to its associated SeNB/RN.

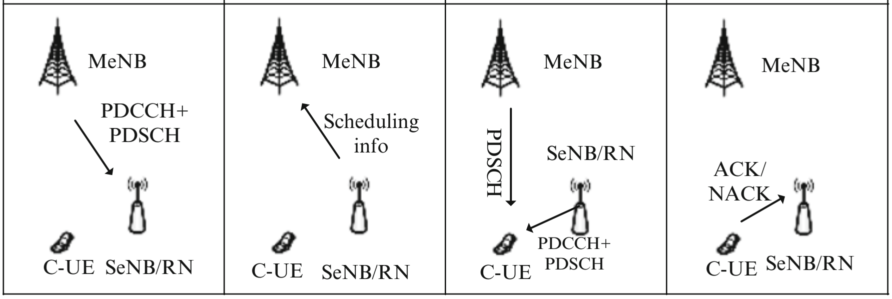

Fig. 2.6 The first intra-cell CoMP scheme

respective UEs in the same frequency resource in a coordinated way such that the mutual interference at the receiver side is minimized. In JT, each UE receives signals transmitted from both eNBs with one eNB acting as the master eNB responsible for both control and data channel transmission while the other eNB acting as slave eNB for conveying user data only. In DPS, the UE can select to receive user data from the eNB with the best channel condition, although the control signaling will remain to be received from its serving/anchored eNB.

Implementation of the above mentioned CoMP schemes assumes ideal wired backhaul between the eNBs in the CoMP set. For heterogeneous networks with wireless backhaul connection between macro and small eNBs, two possible implementations of intra-cell CoMP schemes are shown in Figs. 2.6 and 2.7. Refer to [12] for further details of the intra-cell cooperative communications in LTE systems.

In the first intra-cell CoMP scheme, there are both M-UE and S-UE/R-UE. Depending on the channel condition and available resources, MeNB can assist the communication between the SeNB/RN and some of the S-UEs/R-UEs by transmitting cooperatively with the SeNB/RN. Denote such UEs as cooperative UEs (C-UE). Figure 2.6 illustrates the intra-cell CoMP strategy for serving the C-UEs. Communications from a MeNB and an SeNB/RN to a C-UE take place in four transmission steps. In the first step, MeNB sends control and data information to SeNB/RN. Control information is sent via the physical downlink control channel (PDCCH) and the data information is sent via the physical downlink shared channel (PDSCH). In the second step, SeNB/RN decides whether to use cooperation or not for its associated S-UEs/R-UEs. If cooperation is needed, the SeNB/RN sends the corresponding scheduling and control information to the MeNB on the wireless backhaul. In the third step, upon receiving the scheduling information from the SeNB/RN, the MeNB arranges its transmission by sending data information to the

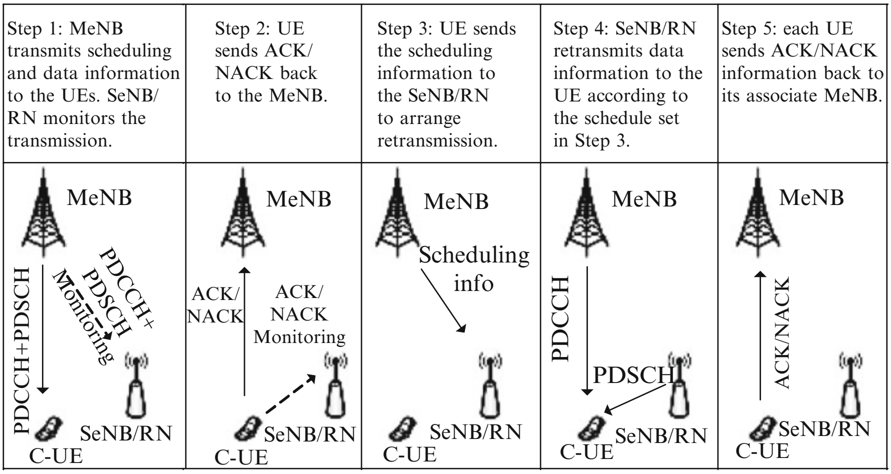

Fig. 2.7 The second intra-cell CoMP scheme

C-UE together with the SeNB/RN. With the received signals from the MeNB and the SeNB/RN, the C-UE decodes the information using joint decoding methods such as maximum likelihood (ML) decoding or maximum ratio combining (MRC) decoding. In the fourth step, the C-UE sends back ACK/NACK message to its associated SeNB/RN. In the first intra-cell CoMP scheme, the SeNB/RN creates a new cell with a separate cell ID distinct from the donor MeNB and appears to the UEs in the same way as a regular MeNB. Layer-3 functions are performed by the SeNB/RN.

In the second intra-cell CoMP scheme, UEs in the network are associated with the MeNB with some of them being served solely by the MeNB and the others being served with the help of the SeNB/RN. As shown in Fig. 2.7, communications take place in five transmission steps. In the first step, MeNB decides, for each M-UE, whether to serve cooperatively with the SeNB/RN or not. Based on that, MeNB sends scheduling and data information to the UEs and the SeNB/RN, respectively. The same information is sent to the C-UE and the SeNB/RN at a data rate that ensures successful decoding at the SeNB/RN. Upon receiving the data information, the UEs and the SeNB/RN decode their respective received information. In the second step, the UEs send back ACK/NACK message to the MeNB. The SeNB/RN monitors the ACK/NACK message from the C-UE. In the third step, the MeNB sends scheduling information to the SeNB/RN to arrange for retransmission from the SeNB/RN to the C-UEs that fail to decode. In the fourth step, the MeNB sends scheduling and data information to the other M-UEs. The SeNB/RN re-transmits its received data information to the C-UEs as scheduled in the third frame. Upon receiving from the SeNB/RN, the C-UE decodes its information using the received signal from the MeNB and the SeNB/RN in the first and the third steps. The rate of the re-transmitted information from the SeNB/RN is pre-determined and is set to ensure successful decoding at the C-UE. In the fifth step, the ACK/NACK message is then sent back from each C-UE to the associated MeNB. In this intra-cell CoMP scheme, the SeNB/RN is transparent to the UEs, i.e., all the scheduling instruction is sent from the MeNB, and the UEs is not aware of the existence of the SeNB/RN. The SeNB/RN does not have a cell ID and thus does not create any new cells.

In [13–15], a downlink intra-cell cooperative transmission and optimal intra-cell CoMP resource allocation schemes are explored in heterogeneous networks with cooperative relays. The schemes are optimized by selecting the best SINR threshold to form intra-cell cooperation. In Chap. 5, radio resource allocation schemes with the two-tier heterogeneous networks in LTE are presented. Radio resource allocation schemes with intra-cell CoMP and in-band wireless backhaul are studied, and an optimal framework with resource allocation strategy is presented that is asymptotically optimal on the proportional fairness metric.

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