DESIGN FUNDAMENTALS AND INTERFERENCE MITIGATION FOR CELLULAR NETWORKS [*]

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Abstract. Cellular networks are nowadays widely exploited to address the increasing demand of wideband data access. Cutting-edge technologies are introduced recently to fulfill such requirements. This chapter provides a comprehensive view on the design fundamentals and advanced interference mitigation technologies for wireless cellular networks. Specifically, basic design issues, as well as different multiple access approaches are introduced at first, followed by brief introductions of current and emerging commercial wireless networks. Then emphasis is put on the interference mitigation issues, covering both receiver multiuser detection and transmitter precoding. Finally, a new concept, base station cooperative processing, is introduced to address the inter-cell interference problems.

Key words. Cellular, Multiple Access, CDMA, OFDM, Interference Mitigation, Base Station Cooperation

1. Introduction. In the past few years, the demand for broadband wireless data access in mobile communication networks has grown exponentially. For example, existing standards for third generation (3G) provide up to 2 Mbps indoors and 144 Kbps in vehicular environments; while the minimum speed currently targeted for 4G systems is 10-20 Mbps indoors and 2 Mbps in moving vehicles. Cellular network is nowadays the most widely deployed wireless system. In this chapter, the term "cellular network" is used to represent all infrastructure based wireless networks, which, compared with ad hoc networks, utilize base stations (BS) or access points (AP) to provide access for mobile stations (MS) to a backbone network. Therefore here a "cell" is defined as a specific area serviced by a BS, which a subscriber in the area can *directly* access via a single hop. Base stations are usually connected by reliable wirelines to centralized processing units (PU) to facilitate advanced functionalities such as handoff and resource allocations. Therefore infrastructure based wireless networks usually significantly outperform their ad hoc counterparts, which explains why they will continuously be relied on to meet the ever-increasing wideband demands.

Some of the well-known examples of cellular networks include: cellular phone networks (GSM, IS-95, etc.), wireless local area networks (WLAN), and wireless metropolitan area networks (WMAN). The design of these wireless networks usually involves the specifications of PHY, MAC and higher layers, and this chapter will mainly focus on the first two. On the one hand, sophisticated communications and signal processing techniques are required for achieving enhanced performance (higher throughput, fewer errors, less power, etc.) in each BS-MS link; on the other hand, the existence of multiple users advocates more efficient resource allocation and interference mitigation/avoidance strategies to improve the overall network performance. Therefore the design philosophy for any cellular network involves three important aspects: link level design, multiple access, and interference mitigation. In particular, due to frequency reuse and the existence of multiple users, any well-designed cellular network is by nature interference limited. With this in mind, after giving a contemporary overview of the first two aspects in the next section, in Section 3 we put emphasis on the interference mitigation strategies for cellular networks. Some of the interference management methods are still mainly of academic interests, while others are already deployed in current or emerging wireless standards. Note that realistic deployment

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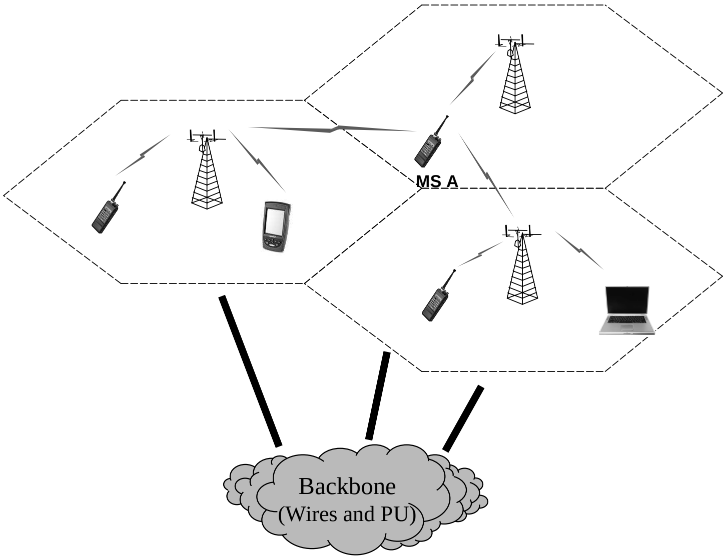

FIG. 2.1. *An Example of Cellular Networks*

of cellular networks should also take into consideration various factors in link budget evaluation such as implementation loss, hardware requirements, channel modelling, and quality of service; related fields are vast and rapid-changing, and beyond the scope of this chapter. At the end of this chapter we briefly expose the reader to the existing relevant literature.

2. Cellular Networks System Modeling.

2.1. Cellular Fundamentals. Cellular systems can use either licensed or unlicensed frequency bands. Those employing licensed bands, such as most cellular phone networks, exhibit immunity from inter-system interference, but are costly. In contrast, the unlicensed spectra (e.g. the 2.4 GHz or 5 GHz industrial, scientific, and medical radio bands) are free for use, but more vulnerable to interference. In a cellular system design, both conventional voice services and packet-oriented data services should be considered, for various application scenarios. For example, video services demand high data rate and low latency, both of which appear to be less stringent for ordinary web browsing. Similarly, downlink (BS to MS) design typically targets high spectral efficiency, while power efficiency receives more attention in the uplink (MS to BS) design. The quality of data services is also not symmetric in two directions. In this subsection some general aspects in cellular system design are introduced. The reader may refer to existing literature, including those cited in this chapter, for more details.

To accommodate a large number of subscribers with acceptable performance for each, the dedicated area is divided into cells which usually do not overlap with each other (Figure 2.1). Each cell is served by one fixed BS connected to the backbone network and controlled by PU. Conventionally, available frequency channels are allocated to different cells in such a way that adjacent cells do not share the same bands, and co-channel cells are separated as far as possible. Each group of cells covering all the available channels is called a cluster. This scheme is named **frequency reuse**, a key element in the conventional cellular system design. The *frequency reuse factor* is defined as the number of cells in each cluster. Different types of wireless networks use different frequency reuse strategies. For networks with pure orthogonal channelization, a large frequency reuse factor is required to maintain a low level of co-channel interference (CCI); while for code-division multiple access (CDMA) networks and/or those equipped with advanced interference management mechanisms (as will be shown in the subsequent sections), an universal frequency reuse (reuse factor 1) may be possible. Determining an appropriate channel allocation strategy relies on many factors such as system configurations, performance requirement, and the type of service for each user.

Two natural strategies are used to separate the communications between the uplink and downlink: **frequency-division duplex (FDD)**uses different frequency bands (usually widely separated) while **time-division duplex (TDD)** deploys different time-slots. FDD is widely used in conventional systems, where voice services are provided so that the uplink and downlink traffics are symmetric. However, the spectrum efficiency is reduced due to the large guard band between two directions. The effort for designing analog filters for traffic separation will also increase the hardware burden, especially for hand-held devices. TDD is suitable for data services because of its flexibility. Spectrum efficiency can be enhanced, given that both directions share the same channels, and the guard time can be made relatively small. Compared with FDD, it usually requires more stringent synchronization (except WLANs, which adopt the contention-based multiple-access scheme, as will be introduced later on). TDD modes are broadly recommended for 3GPP and WMAN developments.

Another important designing issue for cellular systems is **handoff**, which defines the process of maintaining an ongoing connection when an MS is approaching cell boundaries. *Hard handoff* (switching between frequency bands) is necessary when frequency reuse is applied, while *soft handoff* is usually employed otherwise. During soft handoff, the system establishes multiple links between the MS and the involved adjacent base stations (e.g., MS A in Figure 2.1). In the uplink, each BS receiving the signal will decode the data and send it to the processing unit, where the optimal one among them is selected, so a selection diversity is achieved. In the downlink, signals from different base stations with different timing offsets are coherently combined at the MS by a RAKE receiver [1], achieving both diversity and power gain. The diversity obtained in both directions are sometimes called *macro-diversity*, as in contrast to *micro-diversity* which recovers small-scale fading dips, essentially it compensates the impairments induced by the slowly varying shadowing effect. In CDMA multiple base stations should use the same spreading code for the MS under soft handoff, thus consuming more system resources than in normal modes. Due to the difficulty of synchronization among multiple base stations with respect to one mobile device, explicit inter-BS synchronization is usually required to facilitate soft handoff. Actually soft handoff is one of the simplest BS cooperation schemes, and it will be shown that (section 6.3) more sophisticated BS cooperation schemes can lead to much more significant performance improvement.

Power control is a vital technique for systems like CDMA, where the *near-far effect* (intra-cell interfering signal is much stronger than the desired signal) can significantly degrade the system performance. Both open-loop and closed-loop power control schemes are implemented in practical wireless networks (e.g. IS-95). Open-loop power control methods adjust the transmit power based on channel strength measurement, which could vary slowly; while in the closed-loop power control a receiver adaptively informs a transmitter to update its power level based on instant channel estimation. In the latter case, the control loop has to be chosen so that it can compensate for small-scale fading, i.e., the feedback rate should be on the order of Doppler frequency. For the CDMA uplink both open-loop and closed-loop schemes are deployed to mitigate the near-far effect; while in the CDMA downlink, or orthogonally channelized cellular networks, the requirement for accurate power control is less stringent, and open-loop control is sufficient to reduce the transmit power as well as the interference appearing at other cells. Open-loop control is particularly charming for downlink designs where a large number of narrow-band users are accommodated; extra bandwidth required for feedback channels seems too expensive for them. Note that power control is mainly implemented on a per-cell basis, so the inter-cell interference is usually not constant. Some detailed interference analysis will be given in section 3.

Sectorization is widely used in current cellular phone networks, especially in urban areas with high subscriber density. Sectors at each cell are typically formed by directional antennas, and either different frequency channels or universal frequency reuse may be employed among sectors. For a cellular system with sectorization, the interference level can be effectively reduced, as ideally interference only arrives at a much narrower range. Truncating theory [2] indicates that the *system capacity* (i.e., the maximum number of users supported) in each cell is significantly improved by sectorization. Note that the non-idealness of directional antennas may introduce *inter-sector interference* especially at sector boundaries.

Channel coding and **interleaving** are also widely deployed in cellular networks for point-to-point link-level designs. Briefly speaking, channel coding brings about receive power improvement, and both of them introduce diversity in fading channels, resulting in higher robustness. Examples of other link-level techniques include: adaptive modulation/coding selection, smart antennas, space-time coding, multi-carrier systems, and multiple-input-multiple-output (MIMO) systems.

2.2. Multiple Access. Multiple access methods in cellular networks concern the way multiple users can effectively share the system resource so that each of them can obtain certain quality of service. Therefore multiple access and interference management are coupled with each other. In this subsection we briefly review the multiple access strategies in current cellular networks, and leave the second problem to Section 3.

2.2.1. Orthogonal Multiple Access. **Frequency-division multiple access (FDMA)** is the first multiple access method used in commercial cellular phone systems. The Advanced Mobile Phone Service (AMPS), an analog FDMA system, was released in 1983 as a fully automated mobile telephone service, occupying the 800 MHz to 900 MHz frequency band with 30 kHz for each channel. The underlying idea of FDMA is quite intuitive: users are separated by different frequency channels inside one cell, while a large frequency reuse factor is deployed to mitigate the interference from co-channel users in other cells.

Time-division multiple access (TDMA) is another popular orthogonal multiple access method, where a single channel is divided into a number of time slots and each user is assigned a distinct one. Within a cell, TDMA and FDMA are usually combined in a way such that different users are assigned transmission opportunities that are non-overlapping in both time and frequency. Therefore a large frequency reuse factor is also important to limit the inter-cell interference. To achieve perfect intra-cell orthogonal channelization, time and frequency synchronization are crucial elements in the system design. For example, in GSM specific channels are dedicated for frequency synchronization and timing acquisition, while a control loop is employed to assist the mobile users to adjust their timing advances so that their time orthogonality can be maintained, even in high mobility conditions. TDMA is used in the digital AMPS IS-54 cellular networks (often known as D-AMPS), which provides 3 TDMA voice channels in one 30 kHz frequency band. IS-136, the next generation of IS-54, extends the use of TDMA to the control channels, and is now recognized by ANSI. Another well known TDMA system is GSM, as will be introduced in Section 2.3. Generally speaking, TDMA is appropriate for voice services where static resource allocation is sufficient for each user, but it is not a good choice for the packet-based data services, where data rate is often time dependent.

Carrier Sense Multiple Access (CSMA) is typically defined in the computer network context, which is similar to TDMA in the sense that different users are separated by different time slots, while their difference is: in CSMA transmission opportunities are allocated dynamically, i.e. no fixed time slot for a specific user. Different from voice services, most data services have arrivals in bursts, and there is variance among users and asymmetry between two directions. Therefore CSMA appears to be an appropriate alternative. The well-know example is WLAN, in which the protocol *Carrier Sense Multiple Access/Collision Avoidance*(CSMA/CA) is implemented, which can be interpreted as "listen before talk, back off whenever busy" [3].

2.2.2. Spread Spectrum (SS) Systems. A spread spectrum system spreads the information over a large bandwidth, which includes frequency-hopped multiple access (FHMA) and CDMA.

FHMA is different from FDMA in that it varies the carrier frequency of the narrowband signal so that the transmission is conducted in one channel only for a short period, an effective way to mitigate narrowband interferers. Moreover, by applying appropriate channel coding and interleaving, frequency hopping can be used to average out fading dips in certain frequency channels, i.e. frequency diversity is achieved. When used with multiple access, FHMA is usually combined with TDMA (e.g. in GSM networks). In the synchronized case, e.g. in the downlink of cellular systems, different users are allocated distinct hopping patterns in such a way that at any time slot there is no collision between any two users on their frequency bands, achieving the FDMA capacity as well as performance improvement due to frequency diversity. On the other hand, if the users are not synchronized, e.g. in the uplink with imperfect timing advance control or inter-cell interference, careful hopping sequence design and allocation methods are required to avoid severe collision.

CDMA allocates a distinct code to each user for spectral spreading and user separations. The direct sequence spread spectrum (DS-CDMA) technique is widely used, for which a well-designed sequence of chips (or *signature code*) is directly multiplied on the transmitted signal. Each user spreads its signal over the entire bandwidth and symbol duration by its chip sequence, such that signals for other users are transparent or at most appear (approximately) as white noise at the receiver. The ratio between the overall bandwidth and the signal bandwidth is called *spreading factor*. Different from orthogonal channelization systems where the number of frequency channels or time slots impose a *hard* system capacity limit, in CDMA the number of users that can be supported only depends on the aggregate interference level, which results in a *soft* system capacity limit. Therefore one of the key goals in CDMA system designs is to choose appropriate spreading codes, for which zero or low cross-correlation is required for user separation or inter-cell interference control, and good auto-correlation (impulse-like functions) is desired to suppress the interference caused by multipath delay dispersions. Note that the functionalities of spreading and user/BS separation may be accomplished by different codes, named *spreading codes* and *scrambling codes*, respectively. Since universal frequency reuse is typically adopted for CDMA systems, adjacent cells cannot be allocated the same code sets. Therefore code planning (instead of frequency planning) is required for interference management. Some widely used spreading sequences include: pseudo noise (PN) sequences, Gold sequences and Kasami sequences, and orthogonal Walsh-Hadamard sequences [4]. In the uplink, since delay offsets are usually presented for signals of different users, sequences with low auto-correlation is preferred (e.g. PN sequence); while in the downlink, Walsh-Hadamard codes are employed to make signals of different users completely orthogonal to each other, cascaded with other codes for suppressing the inter-path and inter-cell interferences. A RAKE receiver is typically utilized in CDMA to recover multipath, which can be modelled with a tapped delay line structure [1]. If different paths are independent and the noise is white, delay diversity (frequency diversity) can be achieved, and the RAKE receiver is equivalent to a matched filter for the equivalent channel, which essentially maximizes the output SNR. The practical RAKE combining schemes include selection combining (SC), maximal-ratio combining (MRC), and the hybrid combination of them. By using RAKE receivers, inter-path interference may be present due to non-ideal auto-correlation of the spreading codes, which requires careful sequence selection as discussed above; while the inter-symbol interference (ISI) is unavoidable if the maximum excess delay is comparable with symbol interval, e.g. in highly frequency selective channels, which requires equalization at the receiver. Chip level equalizers can achieve better interference mitigation than symbol level equalizers, but are more costly. Generalized RAKE (GRAKE) receivers [65] pre-whiten the noise plus interference before RAKE combining, hence requiring the estimation of the second-order statistics of the interference.

CDMA can also be combined with other multiple access methods: for example, in IS-95, 1.25MHz bands are divided among different groups of users (FDMA), in each of which CDMA is applied; and in TDMA systems different cells can be separated by distinct spreading sequences instead of frequencies

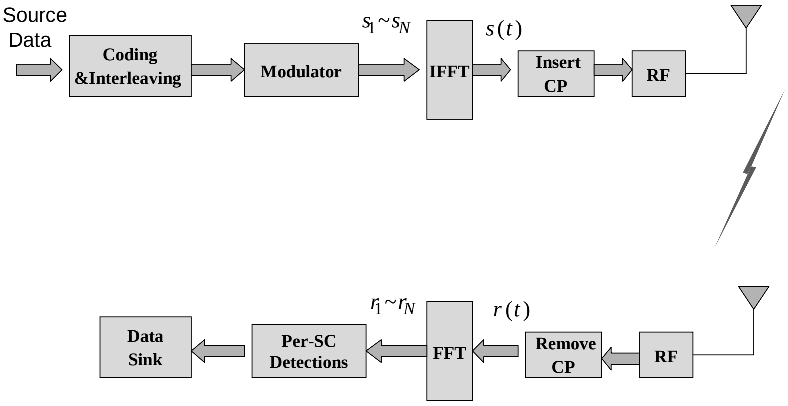

FIG. 2.2. *OFDM Transmitter and Receiver Block Diagram*

(e.g. the TDD mode of 3GPP).

Despite various gains discussed above, CDMA also bears some disadvantages such as bandwidth inefficiency caused by inaccurate power control, ISI related problems, the difficulty of timing acquisition for chip-level synchronization, and inter-cell interference particularly in the downlink. We leave the discussions of CDMA interference mitigation to Section 3, which involves power control, spreading sequence allocation, interference averaging, and other advanced signal processing methods.

2.2.3. Multi-Carrier (MC) Systems. Orthogonal Frequency Division Multiplexing (OFDM) is a wideband modulation scheme designed for high data rate networks, whose original link level design is based on a single user scenario. However, when combined with multiple access schemes, it bears some unique properties compared with conventional systems. As introduced above, when operated at high data rate, the performances of TDMA, FDMA or CDMA could be significantly degraded under severe multipath environments, advocating the implementation of prohibitively complicated equalizers, which are usually not acceptable in most practical systems especially at the MS. In OFDM, a wideband signal is simultaneously transmitted on multiple orthogonal (non-interfering) narrowband subcarriers, each of which experiences a near-flat fading channel. Therefore no equalizer is required. Compared with conventional FDMA, in which a large frequency separation between carriers is required for avoiding the cross-talks, OFDM achieves the same goal with consecutive frequency spectrum usage, thus is more efficient. Specifically, Figure 2.2 gives a block diagram of the OFDM transmitter and receiver. The channel coding and interleaver spread the information bits over the time-frequency plane for diversity gain, and the same benefit can also be achieved by adaptive modulation and power allocation across subcarriers. If there are totally N available subcarriers, every N modulated symbols $s_1 \sim s_N$ are grouped together on which inverse fast Fourier Transform (IFFT) is applied. Then the transmitted baseband discrete signal is given by

$$s(t) = \sum_{n=1}^{N} s_n f_n(t), \tag{2.1}$$

where $f_n(t) = \frac{1}{\sqrt{T_S}} exp\left(j2\pi n \frac{t}{T_S}\right)$ is the waveform function corresponding to subcarrier n, in which T_S is the symbol interval. The orthogonality between any two subcarriers is easily seen: $\int_0^{T_S} f_n(x) f_k(x)\, dx =$

δ_{nk}. Thus theoretically there is no cross-talk among subcarriers. Due to delay dispersion, the ISI in time domain leads to a loss of orthogonality (or *intercarrier interference (ICI)*)in frequency domain, therefore a *cyclic prefix (CP)* is required to eliminate this negative effect. The length T_{CP} of the CP depends on the channel delay dispersion, so that by stripping off CP and applying FFT at the receiver, the ISI is completely eliminated. CP is also a key factor for maintaining the orthogonality between different subcarriers, since it converts the linear convolution of the time-domain signal with the delay dispersive channel, into cyclic convolution, which makes the equivalent time-domain propagation matrix circular and diagonalizable by FFT and inverse IFFT matrices. The baseband received signal in subcarrier n is then given by

$$r_n = h_n s_n + z_n, \tag{2.2}$$

where h_n and z_n are the channel gain and noise in subcarrier n respectively. Basically, OFDM extends the symbol duration in each subcarrier to $T_S + T_{CP}$, thus is less vulnerable to ISI. The price paid for achieving this benefit is the reduced efficiency by adding such "redundant" information, and the hardware requirement for conducting IFFT/FFT. When implemented in realistic systems, usually not all the N subcarriers are dedicated for data transmissions. Pilots are inserted to selected subcarriers for tasks as channel variation tracking, frequency and time offset adjustment. Zero subcarriers are usually placed on the two ends of the occupied spectrum as guard bands. Moreover, in packet radio networks, a preamble containing several OFDM symbols is required for synchronization, automatic gain control (AGC) and channel estimation.

One of the major problems faced by OFDM is its high *peak-to-average-power ratio (PAPR)*, since the transmitted time domain signal is the superposition of N sinusoidal functions (c.f.(2.1)). As a consequence, the peak amplitude of the emitted signal can be considerably higher than the average amplitude, undesirable for transmitter power amplifier (PA) or receiver AGC and A/D conversion designs. Since a high PAPR causes power inefficiency, extra attention should be paid to the uplink applications of OFDM. In contrast, PAPR in single carrier systems is relatively moderate, even in the CDMA and FDMA downlink (where the transmitted signal is the superposition of multiple signals) or when higher modulation schemes(e.g. 64+ QAM) are implemented. Several PAPR reduction techniques are proposed in literature, the interested readers may refer to [4] and the references therein for more details. Another impairment in OFDM is ICI. Except the delay dispersion impairment caused by insufficient CP as introduced above, ICI could also be a consequence of time selectivity (i.e. the *Doppler effect*) in the channel. Therefore, the length of each OFDM symbol should be shorter than the channel coherence time if possible. The other factors causing ICI include synchronization error, frequency offset and phase noise at the receiver. A comprehensive summary of ICI mitigation strategies is provided in [4].

To accommodate multiple OFDM users, the most common way is TDMA or similar time sharing schemes, where a large frequency reuse is still required for inter-cell interference mitigation. An alternative multiple access method is *orthogonal frequency division multiple access (OFDMA)*, in which each user in a cell is allocated a distinct part of the available subcarriers (usually not adjacent). In the downlink, due to the flat fading approximation in each subcarrier and the fact that all signals are transmitted from the BS (no delay offsets), intra-cell interference can be eliminated; while in the uplink, the same orthogonality effect is achievable if OFDM symbols from different users arrive at the BS with delay offsets less than the duration of CP minus the channel delay dispersion. As for inter-cell interference, to achieve interference averaging as in CDMA such that universal frequency reuse can be realized, per-user coding/interleaving and subcarrier hopping are required. Some well-known examples of practical OFDM networks include digital video broadcasting (DVB), IEEE 802.11 WLAN and IEEE 802.16 WMAN.

An alternative modulation method to fully exploit frequency diversity is **Multi-carrier CDMA (MC-CDMA)**, in which each data symbol is spread over all the N subcarriers by a spreading sequence of length N. Meanwhile, N such data symbols, spread by N orthogonal sequences (e.g. Walsh-hadamard sequences), are added together within one OFDM symbol. It is then equivalent to an interleaving-only OFDM system. Compared with normal single-carrier CDMA, in this scheme the signal is spread in frequency subcarriers instead of in time domain, therefore greatly mitigate the multipath delay dispersion effect, thanks to the CP provided by OFDM.

2.2.4. Multiple Antenna Systems. When multiple antennas are deployed at the transmitter and/or receiver, if different mobile users are located far apart, their corresponding channel vectors/matrices provide a distinct spatial signature for each of them. Whenever their spatial signatures are "orthogonal" enough (i.e. with low correlation), their signals can be effectively separated by well-designed detection algorithms, an idea equivalent to a randomly coded CDMA. However, compared with CDMA, since the spatial signatures cannot be artificially optimized and there are usually insufficient spatial dimensions due to the hardware limitations, more effort on the transmitter/receiver design is required for interference mitigation. This scheme is termed **Spatial Division Multiple Access (SDMA)**.

Meanwhile, the remarkable spectral efficiency gain of MIMO systems in a point-to-point scenario was unveiled in recent years [16]-[19], in which different spatial data streams (for one user) can be separated by their independent spatial signatures, a concept similar to SDMA. However, in an interference limited environment, it was shown ([44][45][63]) that the enormous data rate advantages of MIMO systems could be significantly degraded. Some of the reasons include: the increased interference to other users due to multiple data streams, and the lack of degree of freedom at the receiver for inter-user interference mitigation. Therefore, when delpoying MIMO-SDMA, judicious transmitter/receiver design becomes crucial. In the subsequent section, we will focus on the interference mitigation problems in both CDMA and SDMA schemes.

2.2.5. Advanced Schedulers. Schedulers are designed to intentionally allocate transmission opportunities to specific user(s) at each time slot, so that the overall system performance (e.g. throughput) can be improved. *Multiuser diversity* is therefore achieved by taking advantage of user independencies. In another word, when per-user channels have large variance, a well-designed scheduler can always "ride on the peak" by selecting user(s) with good channels. One of such examples is the high-data-rate (HDR) mechanism used in CDMA2000 1x EV DO proposed by Qualcomm [6][26]. On the other hand, when user fairness or latency is taken into considerations, modifications are required to make an appropriate tradeoff between system level performance and fairness. In this sense, conventional TDMA is a "round-robin" scheduler, and CSMA acts like a first-come-first-serve (FCFS) scheduler, both of which fail to explore any multiuser diversity. Moreover, when combined with CDMA or SDMA, multiple users may be scheduled in one time slot, so more sophisticated scheduling designs and analysis are required.

2.3. Current and Emerging Cellular Networks. In this subsection we briefly go through some current and emerging commercial cellular networks. Part of the features of these systems have been introduced above. An interested reader may get more technical details of the introduced standards from the references provided in Section 4.

GSM is a set of European standards originally proposed for digital voice services in mobile cellular networks, which is employed worldwide in current days. As introduced in Section 2.2, TDMA and FDMA are combined in such a way that each narrowband frequency channel (200 KHz) is shared by 8 users in a time-division manner. Slow FHMA is further adopted to obtain frequency diversity. Frequency reuse is a necessity to keep the interference below an acceptable level. The data service extensions of GSM include the well-recognized technologies **General Pack Radio Service (GPRS)** and **Enhanced Data Rate for GSM Evolution (EDGE)**, enabling transmission rates up to 144 kb/s and 384 kb/s respectively.

IS-95 is the first CDMA cellular network for narrow bandwidth applications, operated at both 800-900MHz and 2 GHz PCS bands. As introduced previously, CDMA is combined with FDMA so that the 25 MHz band is split into CDMA channels of width 1.25 MHz, each of which is shared by multiple users employing distinct spreading/scrambling sequences. Convolutional encoders and bit interleavers are applied for time diversity and coding gain, and RAKE receivers are used for frequency diversity.

Accurate power control is employed to mitigate the near-far effect in uplink, and soft handoff provides the macro-diversity. PN sequences and Hadamard sequences are adopted on the uplink and downlink for different purposes [2][5]. Accurate synchronization is a basic requirement, as well as the synchronization among base stations (through wireline backbones) to facilitate soft handoff.

WCDMA is the 3G solution evolved from the GSM based systems such as GPRS and EDGE, which essentially combines FDMA with DS-CDMA so that universal frequency reuse can be realized. Variable options on sub-channel bandwidth (therefore different data rate) are available for different service requirements. Either convolutional codes or turbo codes can be used. Note that the spreading factor is also adjustable based on different sub-channel bandwidth. Different from IS-95, a tight inter-BS synchronization may not be required in WCDMA, therefore the different scrambling codes in adjacent cell sites play a more important role during handoff. WCDMA defines a more stringent fast closed-loop power control scheme than other contemporary standards, which runs by a frequency of about 1600 Hz. Finally, besides the above features, one of the key technique used by WCDMA for spectral efficiency improvement is multiple antennas, by which transmitter and/or receiver spatial diversity can be readily obtained. An updated version of WCDMA for the "Beyond 3G" development, called **High-Speed Downlink Packet Access (HSDPA)**, is attracting more and more attention recently [7].

Similar as WCDMA, the Chinese 3G standard **TD-SCDMA** is evolved from GSM networks, and combines DS-CDMA with TDMA and FDMA. The adopted TDD mode eliminates the need for uplink/downlink spectrum pair as in FDD systems, and the reciprocity principle between the uplink and downlink channels facilitates the use of smart antenna techniques at BS, where spatial receiver diversity and joint detection (multiuser and multipath) are implemented in the uplink, and the receiving beamforming vector of the uplink can be directly used for the downlink. To simplify the *multiuser detection (MUD)* algorithm design, one unique feature of TD-SCDMA is its uplink synchronization among different users (by timing advance), known as synchronized CDMA (SCDMA). Moreover, since TDMA is deployed with CDMA, the number of scrambling sequences in each frequency-time slot is reduced, therefore the MUD algorithm can be further simplified. Base stations are synchronized with each other, so efficient handoff algorithms can be readily applied. Since the system has the capability of locating the mobile terminals based on the information provided by synchronous CDMA and smart antennas, the efficiency of handoff and resource allocation can be further improved.

CDMA2000 is the American version of 3G solution, evolved directly from IS-95. The evolution of CDMA2000 1x is labeled as CDMA2000 1x EV. Corresponding to different applications, 1x EV is implemented in steps as 1x EV DO and 1xEV DV, standing for "1x Evolution Data Only" and "1x Evolution Data and Voice" respectively. Compared with WCDMA, some of the distinct features of CDMA2000 include: a lower working frequency of the closed-loop power control (800 Hz), and inter-BS synchronization (by GPS) for soft handoff. In particular, the new version CDMA2000 3x applies MC-CDMA to achieve higher data rates.

Other than commercial cellular phone networks, the WLAN (or known as *Wi Fi* technology) industry has emerged as another fastest-growing segments of the wireless communications industry, mainly based on the **IEEE 802.11** series standards. The most famous IEEE 802.11b was issued in 1999, defining the PHY and MAC specifications to achieve data rate up to 11Mbps at the 2.4 GHz ISM band. CSMA/CA is used for multiple access, and link level designs only consider the point-to-point scenario, while DS-CDMA is used at the PHY layer. The subsequent standards: 802.11a and 802.11g, increase the achievable data rate to 54 Mbps by replacing DS-CDMA with OFDM, and operate at 5.2 GHz and 2.4 GHz bands respectively. The overall bandwidth (20 MHz) is split into 64 subcarriers, therefore each OFDM symbol is of length $4\mu s$ including a $0.8\mu s$ CP. A preamble in each packet is designed for synchronization, AGC control, frequency offset/phase noise compensation, PHY feature signaling, and channel estimation. Four pilots are required for frequency shift and phase noise fine tunes. Since the indoor channel bears a small Doppler frequency (typically around 5Hz), channel variation tracking is not needed. Convolutional encoders and interleavers are used to spread the information data over time and subcarriers for frequency/time diversity and coding gain. The adaptable modulation level and coding rate (based on a slow adaptation algorithm defined in the MAC layer)is up to 64 QAM and 3/4 respectively, due to the high SINR and near-flat fading seen in typical WLAN applications. The emerging standard 802.11n, expected to be released in 2007, targets a data rate of at least 100 Mbps observed at MAC service access point (SAP), necessarily demanding more advanced technologies. The candidate multi-antenna (up to 4 RF chains on each device) transmission modes include basic open-loop spatial spreading (SS), space-time block coding (STBC), and the optional closed-loop MIMO schemes such as transmitter beamforming (TxBF) and antenna/beam selections. Optional LDPC coding is also in the standard. Moreover, MAC improvements such as fast link adaptation, aggregated packets and block acknowledgement are under broad discussions.

The **IEEE 802.16** family of WMAN standards and the corresponding industry consortium *WiMax* endeavor to make portable internet a reality by enabling a wireless alternative for cable, DSL and T1 level services for the "last mile" broadband access, as well as extending public WLAN hotspots to metropolitan area coverage. WiMax provides large coverage distance up to 30 miles under the line-of-sight (LOS) condition, and the data rate could reach hundreds of Mbps per BS in the working frequency band (10-66 GHz and sub-11 GHz). Therefore it is particularly suitable for providing broadband services in rural and under-developed areas. The early versions 802.16 and 802.16a define single carrier air interface for fixed wireless accesses, and the subsequent version 802.16d (or 802.16-2004) introduces some performance enhancement features such as the OFDM mode. While the above standards mainly work for fixed wireless access, IEEE 802.16e (late 2005) added support for mobile users. TDMA is applied in both single carrier and basic OFDM modes, while the new 802.16e is based on OFDMA, where STBC, beamforming and closed-loop spatial multiplexing MIMO with pre-coding are all supported. A group of subcarriers, separated with adjustable resolution over frequency domain, are provided for feedback. Also as in 802.11n, the fast adaptive modulation and coding feature is included. In the OFDMA mode, multiple user may co-exit in the same subcarrier, separated by their spatial signatures (i.e. SDMA) together with advanced interference cancellation techniques. Different from OFDM based WLANs, when dealing with mobile subscribers, both packet preambles and pilot subcarriers may be dedicated for channel estimation and tracking. Other important features include Hybrid ARQ (HARQ), optional LDPC codes, fast handoff, and adjustable IFFT/FFT length in OFDM (Scalable OFDM-SOFDM). Note that the upcoming mobility supporting features provided in 802.16e will definitely make it a competitive scheme for 3G or even "Beyond 3G" cellular phone networks.

3. Interference Mitigation in Cellular Networks.

In this section, we discuss one of the most important issues for designing cellular networks: how to effectively mitigate the interference generated from intra-cell or inter-cell co-channel users.

3.1. Conventional Interference Mitigation Methods.

In conventional systems employing orthogonal channelization schemes such as GSM, the intra-cell interference is nearly cancelled. Even though multipath may introduce some cross-talk among different users, its impact is limited as the per-user rate is low, and the symbol duration is long enough to immunize channel delay dispersions. Therefore by ignoring the intra-cell inference, the received SINR for one user k (in the uplink or downlink) is:

$$SINR_k = \frac{P_k |h_k|^2}{\sigma^2 + \sum_j I_j}, \tag{3.1}$$

where P_k is the transmit power for user k, h_k is the fading channel gain, σ^2 represents the additive noise power, and I_j denotes the power of the interfering signal from co-channel user j located out of the cell, a random variable whose distribution is related to small-scale fading, shadowing, and path loss (with respect to the random position of interferers). Due to the deployment of orthogonal channelization, the limited number of interferers leads to high interference power variations and therefore undesirable communication quality fluctuations. Although diversity techniques are applied to compensate the small-scale channel variation, they have nothing to do with the large-scale fading (path loss and shadowing).

This explains why FDMA and TDMA usually requires a large frequency reuse factor to mitigate the inter-cell interference. Moreover, open-loop power control and sectorization are usually deployed to further reduce the interference level.

The interference modelling of CDMA networks bears some different properties. In CDMA, the overall system capacity is interference limited, i.e., multiple users co-exit in the same frequency-time slot in the network. In particular, the uplink and downlink use slightly different strategies to suppress interference.

In the uplink, signals transmitted by different mobile users, either inside or out of the cell, are received asynchronously at the BS (the intra-cell synchronous case as in TD-SCDMA will be discussed in the next subsection). By using different spreading/scrambling sequences on different users, and by applying the corresponding matched filters at the BS, the received SINR for user k is expressed as:

$$SINR_k = \frac{P_k |g_k|^2}{\sigma^2 + \sum_{j \neq k} \rho_{kj} P_j |g_j|^2}, \tag{3.2}$$

where $|g_k|^2$ is the equivalent channel gain from user k to the considered BS after RAKE combining, ρ_{kj} represents the (timely shifted) correlation between the scrambling sequences of user k and j, with $\rho_{kk} = 1$. The following three factors are important to reduce the impact from interference:

- By choosing the scrambling sequences with good cross- and auto-correlation quality (e.g. the long PN sequence used in IS-95), ρ_{kj} in (3.2) can be made small and almost uniform among interferers. Note that the scrambling sequences cannot be reused in adjacent cells.
- By closed-loop power control among intra-cell users, the near-far effect can be mitigated, and at the BS received signals from all intra-cell users are roughly of the same power; by open-loop power control, the transmit power can be reduced while maintaining acceptable performance for each user, leading to reduced inter-cell interference.
- Since mobile users co-exit in the same frequency-time slot, the number of interferers in (3.2) could be very large, but none of them contributes a significant part of the interference.

By *central limit theorem*, the term $\sum_{j \neq k} \rho_{kj} P_j |g_j|^2$ in (3.2) can be roughly approximated by a Gaussian random variable. In another word, the overall interference appearing at the receiver is nearly white, so the per-user link acts like a fading channel with only additive Gaussian noise. This phenomenon is called *interference averaging*. Therefore universal frequency reuse can be readily applied in CDMA.

In the downlink, the intra-cell interference can be cancelled by orthogonal sequences (e.g. Walsh-Hardamard sequence). The signals for different intra-cell users are transmitted simultaneously from the BS, therefore present almost no delay offset at MS (cross-talk from multipath can be handled by accurate RAKE designs). However, the inter-cell interference is worse behaved, as it comes from a limited number of adjacent base stations, each transmitting with high power. Therefore, there is much less interference averaging, and these major interferer(s) appear to be more "annoying" than the whitened ones as in the uplink. To avoid catastrophic interference impact and accommodate universal frequency reuse, besides open-loop power control, different scrambling sequences are allocated to different base stations to mitigate the interfering power at the MS. Nevertheless, the lack of interference averaging usually makes the CDMA downlink a capacity limiting bottleneck.

SDMA acts similarly as CDMA in the sense that different users with single spatial data stream are separated by their spatial signatures. However, if we simply apply matched filtering (also named single-user beamforming) on each user as in CDMA, the residue interference could be very large, due to the uncontrollability of spatial signatures. Therefore, advanced signal processing methods are usually needed at the receiver and/or the transmitter, as will be discussed in the next subsection.

GRAKE receivers present a certain interference mitigation capability, by whitening the multiuser interference and ISI before matched filtering. However, whenever the interference comes from a few number of major blockers, this whitening process may significantly raise the equivalent noise floor.

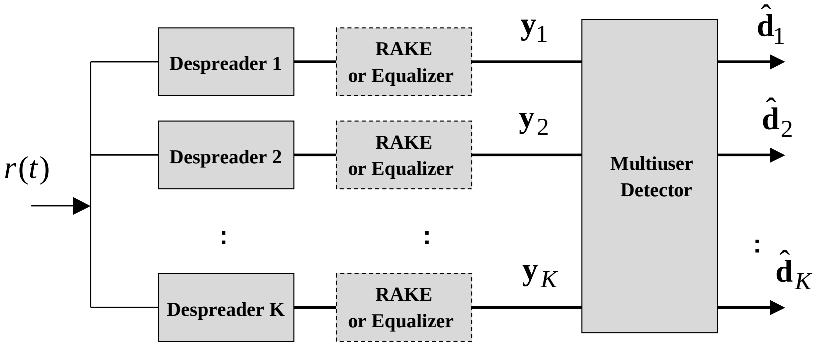

FIG. 3.1. *Block Diagram of Multiuser Detector in CDMA*

3.2. Advanced Intra-Cell Interference Mitigation Methods. Generally speaking, the conventional techniques optimize the statistics of the interference. Therefore in the best case, the aggregate interference acts like additive white Gaussian noise. On the other hand, advanced signal processors can be applied to jointly detect and/or pre-compensate both the desired and interfering signals such that the interference for any user is actively suppressed. Otherwise, we have to allocate the system resource less efficiently (e.g. larger frequency reuse factor) for interference immunization. This is reminiscent of ISI suppression [1]: rather than decrease data rate to avoid ISI, equalizers conducting active interference mitigation is usually more preferable in high data-rate systems.

3.2.1. Multiuser Detection.

CDMA

Let the baseband transmitted signal for user k be: $s_k(t) = c_k(t) \cdot d_k$, where d_k is the information symbol and $c_k(t)$ represents the signature waveform (in the range $t \in [0, T]$) of user k. Denoting h_k as the channel response of user k, K as the number of users, T as the symbol interval, τ_k as the propagation delay of user k, b as the symbol index inside one frame, and B as the frame length, the received signal can be expressed as:

$$r(t) = \sum_{k=1}^{K} \sum_{b=0}^{B-1} d_k(b) f_k(t - bT - \tau_k) + z(t), \tag{3.3}$$

where $z(t)$ is the additive noise, and $f_k(t) = c_k(t) \otimes h_k(t)$ is the convolution of the signature waveform and channel response $h_k(t)$, modeled with a tapped delay line model: $h_k(t) = \sum_{l=1}^{L} a_{kl} \delta(t - \tau_{kl})$ with a_{kl} the channel gain in path l and τ_{kl} the corresponding relative multipath delay (actual delay minus τ_k), with $\tau_{k1} = 0$. Therefore, $f_k(t) = \sum_{l=1}^{L} a_{kl} c_k(t - \tau_{kl})$. By assuming perfect synchronization and negligible ISI, the receiver applies despreading and RAKE combining for each user as in Figure 3.1. If $\int_0^T c_k(t)^2 \, dt = 1$, we can then derive the discrete-time sufficient statistics for the b_kth symbol of user k as:

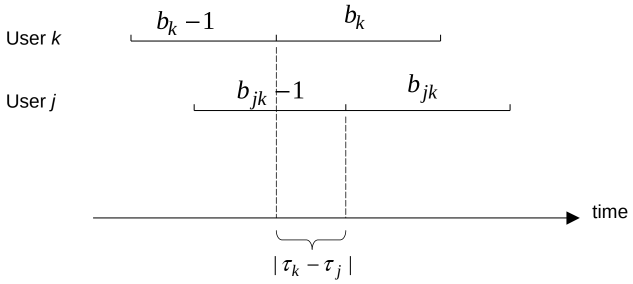

FIG. 3.2. *Illustration of Delay Offset*

$$y_k(b_k) = \sum_{l=1}^{L} a_{kl}^* \int_0^T r(t) c_k(t - b_k T - \tau_k - \tau_{kl})\, dt = g_k d_k(b_k) +$$

$$\sum_{j \neq k} \left[\sum_{l=1}^{L} \sum_{p=1}^{L} a_{kl}^* a_{jp} \left(\rho_{kj}^{(lp)}(b_k, b_{jk} - 1) d_j(b_{jk} - 1) + \rho_{kj}^{(lp)}(b_k, b_{jk}) d_j(b_{jk}) \right) \right] + z_k(b_k), \tag{3.4}$$

where $z_k(b_k)$ is the discrete noise component, $g_k = \sum_{l=1}^{L} |a_{kl}|^2$, $\rho_{kj}^{(lp)}(b_1, b_2) = \int_{-\infty}^{+\infty} c_k(t - b_1 T - \tau_k - \tau_{kl}) c_j(t - b_2 T - \tau_j - \tau_{jp})\, dt$, and b_{jk} is the index of the symbol of user j seen at the output of user k's despreader, with delay offset $|\tau_k - \tau_j|$ (Figure 3.2). The involved multipath model with asynchronous reception makes the detection of the signals in (3.4) prohibitively complex, as there are KB symbols to be detected let alone the estimation of timing information. On the other hand, in CDMA downlink or synchronous uplink (e.g. TD-SCDMA), the delay offsets among different users ($|\tau_k - \tau_j|$) can be assumed zero, then we get the synchronous model. Furthermore, if the delay spread is negligible compared with T (non-dispersive), the symbol index b_k can be dropped for the ease of illustration. In summary, we have

$$y_k = g_k d_k + \sum_{j \neq k} R_{kj} d_j + z_k, \tag{3.5}$$

where $R_{kj} = \sum_{l=1}^{L} \sum_{p=1}^{L} a_{kl}^* a_{jp} \rho_{kj}^{(lp)}$, in which $\rho_{kj}^{(lp)} = \int_{-\infty}^{+\infty} c_k(t - \tau_{kl}) c_j(t - \tau_{jp})\, dt$. By denoting $\mathbf{d} = [d_1, d_2, ..., d_K]^T$, and $\mathbf{y} = [y_1, y_2, ..., y_K]^T$, we obtain the classical channel model:

$$\mathbf{y} = \mathbf{R}\mathbf{d} + \mathbf{z}, \tag{3.6}$$

where $\mathbf{z}$ is the $K \times 1$ discrete noise vector, and the correlation matrix $\mathbf{R}$ is of size $K \times K$. Moreover, for synchronous non-dispersive channels, (3.5) can be further simplified as

$$y_k = a_k d_k + \sum_{j \neq k} \rho_{kj} a_j d_j + z_k, \tag{3.7}$$

in which RAKE combining is not required, and $\rho_{kj} = \int_0^T c_k(t) c_j(t)\, dt$. For the ease of illustration, in the following, multiuser detection methods are investigated based on the synchronous model in (3.7).

A simple way of joint detection is linear MUD, where a matrix filter $\mathbf{W}$ is applied on $\mathbf{y}$ in (3.6):

$$\hat{\mathbf{d}} = \mathbf{W}\mathbf{R}\mathbf{d} + \mathbf{W}\mathbf{z}. \tag{3.8}$$

Decorrelating or *zero forcing (ZF)* linear MUD is designed to completely eliminate the interference for each user. As long as the correlation matrix $\mathbf{R}$ is non-singular, the matrix filter is designed as: $\mathbf{W} = \mathbf{R}^{-1}$, so $\hat{\mathbf{d}} = \mathbf{d} + \mathbf{R}^{-1}\mathbf{z}$, and the K signals are decoupled. The advantage of this approach is its simplicity, but its drawback lies in undesirable noise enhancement in the term $\mathbf{R}^{-1}\mathbf{z}$. On the other hand, minimum mean square error (MMSE) linear MUD achieves a tradeoff between interference mitigation and noise enhancement by allowing the existence of residue interference. Specifically, it solves the problem $\mathbf{W} = \arg\min_{\mathbf{W}_1} E[\|\mathbf{d} - \mathbf{W}_1\mathbf{y}\|^2]$, leading to $\mathbf{W} = [\mathbf{R} + \sigma^2\mathbf{I}]^{-1}$. Note that at high SNR, where σ^2 is negligible and the system is interference limited, MMSE converges to the decorrelating MUD.

Different from linear MUD, nonlinear detectors exploits the fact that the transmitted symbols are drawn from a finite alphabet(with cardinality M). Therefore nonlinear approaches usually outperform their linear counterparts. The *maximum likelyhood (ML)* detector achieves the best performance among all detectors. From a mathematical view, it solves the basic problem of $\hat{\mathbf{d}} = \arg\max_{\mathbf{d}} Pr(\mathbf{y}|\mathbf{d})$ with a Viterbi detector. Since there are as many as M^K possible values in $\mathbf{d}$, the number of states in the trellis diagram increases exponentially with the number of users, rendering ML detection impractical in general.

Successive interference cancellation (SIC) MUD detects the users one by one, while the interference contributed by previously detected users can be subtracted in each step. Consequently at the first stage one user is detected with a full set of interferers, while the user detected at the last stage is conceptually interference free, if all previous decisions are correct. In each stage, the detected symbol from the previous stage is re-spread and subtracted from the received signal. The "cleaned-up" desired signal is sent through the despreader again, followed by the (optional) mitigation of the interference from subsequent users with a linear (ZF or MMSE) filter and the detection. This process is repeated until the last user is met. Specifically, assuming perfect decision feedback, in stage k the equivalent received discrete signal is:

$$\mathbf{y}^{(k)} = \mathbf{y} - \sum_{j=1}^{k-1} \mathbf{r}_j \hat{d}_j = \sum_{i=k}^{K} \mathbf{r}_i d_i + \mathbf{z}, \tag{3.9}$$

where $\mathbf{r}_j$ is the jth column of $\mathbf{R}$ in (3.6). Then the detection for user k can either be conducted directly without active interference suppression, or after further linear filtering, i.e. $\hat{d}_k = \mathbf{w}_k\mathbf{y}^{(k)}$, where $\mathbf{w}_k$ can be designed according to the decorrelating or MMSE criterion. However, error propagation can seriously affect the performance, so usually in each stage we need to pick up the "strongest" user to detect. An alternative way is to use *soft* decision feedback, in which a scaled-down signal from the previous stage is subtracted. Moreover, for more accurate detection in each stage, the detected (coded) symbols can be decoded before feedback. Then the decoded bits need to be re-encoded and modulated again before being subtracted in the subsequent stage. The price we need to pay for SIC detection includes larger latency and higher detection complexity.

Similar as SIC, the *parallel interference cancellation (PIC)* receiver also jointly detects the signals in an iterative manner. The difference is: instead of subtracting interference user by user, in each stage of PIC, signals for all the users are detected, such that in the next stage the current decisions can be used for the interference subtraction (after re-spreading and despreading) for all users simultaneously. In another word, the iteration at stage n for user k can be expressed by (c.f. (3.7)):

$$y_k^{(n)} = y_k^{(n-1)} - \sum_{j \neq k} \rho_{kj} a_j \hat{d}_j^{(n-1)}, \text{ for } k = 1...K, \tag{3.10}$$

where $\hat{d}_j^{(n-1)}$ is the detection result for user j at stage $n-1$. The iteration will continue until the decisions do not change, or the number of iterations surpasses a pre-defined threshold. Also, error propagation could lead to serious performance degradation. At each stage, the users with higher SINR are more likely to be correctly detected, and the wrong decisions for other users can even worsen the SINR in the next stage. This motivates an approach to alleviating error propagation that groups the users based on their SINRs, and interference subtraction is conducted only with signals from reliable groups. Another solution is *soft* interference cancellation, which subtracts the scaled-down decisions from the previous stage.

Note that the above discussions on CDMA multiuser detection assume negligible ISI. When the channel delay dispersion is comparable to symbol interval T, equalization might be required (instead of RAKE combining in Figure 3.1), which will further increase the system complexity.

Multiple Antenna Systems

As mentioned in Section 2, multiple antenna systems (SDMA) behave as CDMA with random (spatial) signatures. Assuming N_r antennas at the BS, in the uplink of a flat fading channel the received discrete signal (after matched filtering) for user k can be expressed by $\mathbf{y}_k = \mathbf{h}_k x_k + \mathbf{z}_k$, where $\mathbf{h}_k$ represents the $N_r \times 1$ spatial signature, and x_k is the transmitted signal of user k. Therefore the aggregated received signal, assuming perfectly synchronized at the receiver, can be expressed by:

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{y}_k = \mathbf{H}\mathbf{x} + \mathbf{z}, \tag{3.11}$$

where the $N_r \times K$ channel matrix $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, ..., \mathbf{h}_K]$, $\mathbf{x}$ is the $K \times 1$ transmitted signal vector and $\mathbf{z} = \sum_{k=1}^{K} \mathbf{z}_k$. It can be easily seen that (3.11) assumes the same form as (3.6), so all multiuser detection methods discussed in the CDMA context can be readily applied to SDMA. The difference is: in SDMA the spatial signatures cannot be pre-designed, so whenever the channel matrix $\mathbf{H}$ is ill-conditioned (i.e. with high correlations between channel columns or rows), the amount of interference appearing at the input of a multiuser detector might be much stronger. Therefore other multiple access methods are usually combined with SDMA to reduce the number of interferers. When CDMA works with SDMA, multiuser detection may be conducted in both spatial and temporal (spreading code) dimensions, as introduced in [22][24], so-called *space-time multiuser detection*. Note that the channel model in (3.11) also includes the MIMO systems [16], where each data stream is equivalent to a virtual user transmitting single data stream.

Moreover, when each MS is also equipped with multiple antennas (say N_t antennas) and operates at the spatial multiplexing (SM) mode (i.e., transmits multiple streams simultaneouly), the (synchronous) uplink channel can be expressed as:

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{H}_k \mathbf{x}_k + \mathbf{z}, \tag{3.12}$$

where $\mathbf{H}_k$ is the $N_r \times N_t$ channel matrix for user k. In this case, if we treat each data stream as a virtual single-antenna user, (3.12) can be rewritten as (3.11) with $\mathbf{H} = [\mathbf{H}_1, \mathbf{H}_2, ..., \mathbf{H}_K]$ and $\mathbf{x} = [\mathbf{x}_1^T, \mathbf{x}_2^T, ..., \mathbf{x}_K^T]^T$, so multiuser detection can be conducted in the same manner as above, except with the increased number of users. On the other hand, the inter-user interference and inter-stream interference may be suppressed separately, by MUD and SM-MIMO receivers respectively. It was shown in [26] that the aggregated Shannon capacity in the MIMO multiple access (uplink) channel (3.12) is:

$$C_{UL} = \log \left| \mathbf{I} + \sum_{k=1}^{K} \mathbf{H}_k^* \mathbf{Q}_k \mathbf{H}_k \right|, \tag{3.13}$$

where $\mathbf{I}$ is an $N_t \times N_t$ identity matrix, and $\mathbf{Q}_k$ is the covariance matrix of $\mathbf{x}_k$: $\mathbf{Q}_k = E\left[\mathbf{x}_k . \mathbf{x}_k^*\right]$.

Note that in the downlink (also known as *broadcast channel (BC)*), receiver MUD is not effective for intra-cell interference mitigation, because all the signals are transmitted from the BS and go through the same channel before arriving at the MS. In this case, whenever channel state information (CSI) is available at the transmitter, precoding may be deployed to actively suppress the interference, as introduced in the next subsection.

3.2.2. Transmitter Precoding for Interference Mitigation. The multiuser transmitter precoding schemes in the cellular downlink are similar to the precoding of point-to-point SM-MIMO in the sense that each spatial stream acts like a virtual single-stream user. The difference is: in a point-to-point scenario, the receiving streams can be jointly processed, while in multiuser downlink (or BC) users detect their own signals in a distributed manner. So basically only single user receivers are employed at each MS. In this section, we assume a SDMA scenario where in the downlink K co-channel users are receiving signals from the BS. Note that the downlink channel is usually synchronous, so in flat fading channels we can drop the symbol index. Without loss of generality, we assume N_t antennas are equipped at each BS, and N_r at each MS. The received signal at MS k is then expressed by:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{z}_k, \tag{3.14}$$

where $\mathbf{x} = \sum_{k=1}^{K} \mathbf{x}_k$ is the superposition of the signals for the K users transmitted from the BS, and $\mathbf{H}_k$ is the $N_r \times N_t$ channel matrix for user k. In severe delay dispersive channels, $\mathbf{H}_k$ may include the channel characteristics for different paths, and the detection should be both over multiple users and over multiple symbols in a frame, to jointly mitigate multiuser interference and ISI.

If downlink CSI for all the in-cell users are available at the BS (either by explicit feedback in FDD, or reverse link channel estimation in TDD) transmitter beamforming (linear precoding) is one of the most effective schemes. Specifically, in (3.14) the transmitted signal for user k can be expressed as $\mathbf{x}_k = \mathbf{T}_k \mathbf{d}_k$, where $\mathbf{d}_k$ contains the L original data streams for user k, and $\mathbf{T}_k$ is the corresponding $N_t \times L$ beamforming matrix ($L \leq \min(N_t, N_r)$). Therefore $\mathbf{x}$ in (3.14) is given by

$$\mathbf{x} = \mathbf{T}\mathbf{d} = [\mathbf{T}_1, \mathbf{T}_2, ..., \mathbf{T}_K] \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \\ \vdots \\ \mathbf{d}_K \end{bmatrix}. \tag{3.15}$$

Conventionally, to maximize per-user Shannon capacity, eigen-beamforming with water-filling power allocation is usually applied: $\mathbf{T}_k = \mathbf{V}_k \mathbf{P}_k$, where $\mathbf{V}_k$ collects the right singular vectors for the L largest singular values of $\mathbf{H}_k$, and $\mathbf{P}_k$ is the diagonal matrix denoting the power allocation. Intuitively single user eigen-beamforming produces narrowed beams for the desired user, and works well if $L = 1$. However when $L > 1$, in multiuser downlink the random fluctuation of user channels may introduce tremendous residue interference, especially in those weak eigen-modes, advocating more sophisticated joint precoding schemes.

For this purpose, we stack the K received signals as:

$$\mathbf{y} = \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \vdots \\ \mathbf{y}_K \end{bmatrix} = \mathbf{H}_T \mathbf{T}\mathbf{d} + \mathbf{z}, \tag{3.16}$$

where $\mathbf{H}_T$ and $\mathbf{z}$ are the stacked channel matrix and noise vectors, respectively. The simplest joint transmitter (JT) beamforming is zero forcing (JT-ZF, see [50]), in which the pseudo-inverse of $\mathbf{H}_T$ is applied: $\mathbf{T} = c_0 \mathbf{H}_T^{\dagger} = \mathbf{H}_T^{*}(\mathbf{H}_T \mathbf{H}_T^{*})^{-1}$, where c_0 is a factor designed to fulfill the transmit power constraint of the BS. Just as decorrelating multiuser detectors eliminate the interference at the expense of noise enhancement, JT-ZF generally increases the average transmit power by the same factor. Joint transmitter MMSE (JT-MMSE) makes a good tradeoff between interference cancellation and transmitter power efficiency, whose precoding matrix is given as $\mathbf{T} = c_0\mathbf{H}_T^*(\mathbf{H}_T\mathbf{H}_T^* + \frac{\sigma^2}{P_t}\mathbf{I})^{-1}$, where P_t is the total transmit power at the BS. While JT-MMSE and JT-ZF are dedicated to interference mitigation for each data stream, the joint transmitter decomposition (JT-Decomp, see [39]) algorithm accomplishes inter-user and inter-stream interference mitigation in two steps. First we impose $\mathbf{T}_k = \mathbf{Q}_k\mathbf{V}_k$, where $\mathbf{Q}_k \in null(\mathbf{H}_j)_{(j \neq k)}$ such that $\mathbf{H}_j\mathbf{Q}_k = \mathbf{0}$ ($\mathbf{Q}_k$ may be derived by taking the right singular vectors corresponding to the zero singular values in the stacked matrix $\mathbf{H}_T$ excluding $\mathbf{H}_k$; note that JT-ZF also satisfies this constraint); therefore from (3.14) and (3.15) we get $\mathbf{y}_k = \mathbf{H}_k\mathbf{Q}_k\mathbf{V}_k\mathbf{d}_k + \mathbf{z}_k$. Then $\mathbf{V}_k$ is dedicated to the inter-stream interference suppression in the equivalent per-user MIMO channel $\mathbf{H}_k\mathbf{Q}_k$. It can be shown that by deploying a well-designed single user precoder $\mathbf{V}_k$, JT-Decomp can outperform JT-ZF and JT-Decomp. By simple dimension counting, JT-ZF, JT-MMSE and JT-Decomp all require the following constraint on the number of antennas: $N_t \geq KN_r$. On the other hand, if a linear receiver $\mathbf{W}_k$ can be jointly designed with the transmitter beamformer, (3.14) may be rewritten to:

$$\hat{\mathbf{d}}_k = \mathbf{W}_k\mathbf{y}_k = \mathbf{W}_k\mathbf{H}_k\mathbf{T}\mathbf{d} + \mathbf{W}_k\mathbf{z}_k. \tag{3.17}$$

Therefore the above nullification requirement becomes $\mathbf{W}_j\mathbf{H}_j\mathbf{Q}_k = \mathbf{0}$, leading to a less stringent constraint $N_t \geq KL$.

Another category of JT beamformers employ an optimization procedure for transmitter or joint transmitter/receiver designs. Specifically, given a channel realization $\mathbf{H}_T$, the optimization problem can be formulated as:

$$\{\mathbf{T}_k^{opt}, \mathbf{W}_k^{opt}\}_{k=1...K} = \arg \max_{\substack{\mathbf{T}_1...\mathbf{T}_K \\ \mathbf{W}_1...\mathbf{W}_K \\ C(\mathbf{T}_1...\mathbf{T}_K)}} F(\mathbf{T}_1...\mathbf{T}_K, \mathbf{W}_1...\mathbf{W}_K|\mathbf{H}_T), \tag{3.18}$$

where $C(\mathbf{T}_1...\mathbf{T}_K)$ represents a certain constraint on the transmit beamformers, e.g. power constraint $\sum_{k=1}^{K} Trace(\mathbf{T}_k\mathbf{T}_k^*) \leq P_t$, and rank constraint $rank(\mathbf{T}_k) = L$; the target function $F(\mathbf{T}_1...\mathbf{T}_K, \mathbf{W}_1...\mathbf{W}_K|\mathbf{H}_T)$ in (3.18) could be, e.g. the minimum SINR among all the data streams, the product of all SINRs, the sum Shannon capacity, the inverse of mean square error (MSE) or transmit power (usually with minimal SINR requirements), and many other criteria. Note that the optimization of transmit and receive beamformers are coupled with each other, so iterative algorithms are usually required (e.g. [34][36]). Furthermore, the non-convex and highly non-linear nature of F demands careful examination on the convergence property and the global optimality of the obtained results. To avoid iteration and derive closed form solutions, suboptimal target functions (usually lower bounds of F) are sometimes used (e.g. [32][40]).

Similar to nonlinear MUD, nonlinear transmitter precoding usually achieves better performance at the expense of increased complexity. When the users are encoded sequentially and the channel state for all users are known at the BS, the transmitter is aware of the (noncausal) interference generated from previously encoded users seen by each MS. Then by "smart" encoding, the corresponding portion of interference can be "cleaned out" before actual transmission, so the receiver of any user only "sees" the interference from subsequently encoded users. This scheme is known as *dirty paper coding*(DPC), a transmitter counterpart of SIC multiuser detection. It is shown in [28] and [30] that DPC achieves the maximum sum capacity in multi-antenna broadcast channels. Specifically, assuming the sequential encoding is ordered from user 1 to K, the (Shannon) spectral efficiency of user k can be expressed by:

$$C_k = \log \frac{\left|\sigma^2\mathbf{I} + \mathbf{H}_k\left(\sum_{j \geq k}\mathbf{T}_j\mathbf{T}_j^*\right)\mathbf{H}_k^*\right|}{\left|\sigma^2\mathbf{I} + \mathbf{H}_k\left(\sum_{j > k}\mathbf{T}_j\mathbf{T}_j^*\right)\mathbf{H}_k^*\right|}. \tag{3.19}$$

Therefore the SDMA downlink sum capacity is:

$$C_{DL} = \max_{\substack{\mathbf{T}_1 \ldots \mathbf{T}_K, \pi \\ C(\mathbf{T}_1 \ldots \mathbf{T}_K)}} \sum_{k=1}^{K} C_{\pi(k)}, \tag{3.20}$$

where π represents the user encoding order. It is shown that (3.20) is actually the saddle point (with worst-case colored noise) of the Sato's bound, the sum rate of a heuristic system where the mobile users can cooperate with each other [26]. However, similar to (3.18), the optimization in (3.20) on $\mathbf{T}_1 \ldots \mathbf{T}_K$ is coupled and non-convex. By the duality between the broadcast and multiple access channel, (3.20) can be obtained by calculating the sum capacity of a dual uplink channel with the same total power constraint P_t, i.e. we can optimize (3.13) with the aggregate power constraint $\sum_{k=1}^{K} Trace \mathbf{Q}_k \leq P_t$, which is a convex optimization problem. This principle then motivated the iterative numerical methods proposed in [27] based on the well-known *iterative water-filling* algorithm in [25]. Moreover,a suboptimal algorithm, DPC with linear preprocessing (LP-DP), can be exploited to further simplify the optimization with negligible performance penalty, especially at high SNRs (see [53][56]). Specifically, by setting the linear preprocessor as $\mathbf{T}_k \in null(\mathbf{H}_1, .., \mathbf{H}_{k-1})$ (similar to JT-Decomp except that the nullification are only applied on the channels of "previous" users), the equivalent channel in (3.16) assumes a form of block lower triangular matrix:

$$\mathbf{H}_T \mathbf{T} = \begin{bmatrix} \mathbf{H}_1 \mathbf{T}_1 & \mathbf{0} & \ldots & \mathbf{0} \\ \mathbf{H}_2 \mathbf{T}_1 & \mathbf{H}_2 \mathbf{T}_2 & \ldots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{H}_K \mathbf{T}_1 & \mathbf{H}_K \mathbf{T}_2 & \ldots & \mathbf{H}_K \mathbf{T}_K \end{bmatrix} = \mathbf{L}_T. \tag{3.21}$$

So (3.16) becomes $\mathbf{y} = \mathbf{L}_T \mathbf{d} + \mathbf{z}$, indicating that the interference only comes from the "previous" users, which can be eliminated by DPC. Then no complicated iteration as in [27] is required, and we obtain K decoupled single user channels $\mathbf{y}_k = \mathbf{H}_k \mathbf{T}_k \mathbf{d}_k + \mathbf{z}_k$ for $k = 1 \ldots K$. The performance LP-DP approaches that of optimal DPC at a high SNR, as indicated in [26][53][56].

DPC usually serves as a performance upper bound in practice, and it is desirable to exploit suboptimal precoders with performance close to DPC. One example is *Tomlinson-Harashima Precoding* (THP), whose first application is on DSL systems. When applied to MIMO, the block diagram of a typical multiuser THP can be seen in Figure 3.3, where the DPC portion in LP-DP has been replaced by the combination of a feedback filter bank $\mathbf{B}$ and a modulo operator. The backward signals from the feedback filters are added to the data vectors $\mathbf{d}_1 \ldots \mathbf{d}_K$ to pre-eliminate the interference from "previous" users. The resultant signals $\mathbf{b}_1 \ldots \mathbf{b}_K$ are fed into modulo operators, which serve to limit the transmit power. The modulo output vectors $\mathbf{s}_1 \ldots \mathbf{s}_K$ are then transformed by the feedforward filters $\mathbf{T}_1 \ldots \mathbf{T}_K$ respectively, and the transmitted signal for user k can be expressed by $\mathbf{x}_k = \mathbf{T}_k \mathbf{s}_k$. Due to the modulo operation, the precoder is nonlinear. Similar as in LP-DP, the interference from subsequent users are cancelled by the nullification designs in $\mathbf{T}$: in the full-rank scenario where $L = N_r$ and $N_t = KN_r$, suppose the LQ decomposition of the square matrix $\mathbf{H}_T$ is $\mathbf{H}_T = \mathbf{L}_T \mathbf{Q}_T$, where $\mathbf{L}_T$ is the lower triangular matrix and $\mathbf{Q}_T$ is an unitary matrix, the joint feedforward filter bank set to $\mathbf{T} = \mathbf{Q}_T^*$. So $\mathbf{H}_T \mathbf{T} = \mathbf{L}_T$. By further decomposing $\mathbf{L}_T$ as $\mathbf{L}_T = \mathbf{D} \mathbf{L}'_T$, where $\mathbf{D} = diag\left(\mathbf{L}_T\right)$ and $\mathbf{L}'_T$ is the corresponding lower triangular matrix with ones on its diagonal, to completely eliminate the interference from "previous" users and data streams, the feedback filter is designed as $\mathbf{B} = \mathbf{I} - \mathbf{L}'_T$. Therefore with the definitions $\mathbf{b} = \left[\mathbf{b}_1^T, \mathbf{b}_2^T, \ldots, \mathbf{b}_K^T\right]^T$ and $\mathbf{s} = \left[\mathbf{s}_1^T, \mathbf{s}_2^T, \ldots, \mathbf{s}_K^T\right]^T$, we have $\mathbf{b} = \mathbf{d} + (\mathbf{I} - \mathbf{L}'_T)\mathbf{s}$, and $\mathbf{L}'_T \mathbf{s} = \mathbf{d} + (\mathbf{s} - \mathbf{b})$. Note that $(\mathbf{s} - \mathbf{b})$ represents the factor imposed by the modulo operator. Then the stacked received vector is

$$\mathbf{y} = \mathbf{D} \mathbf{L}'_T \mathbf{s} + \mathbf{z} = \mathbf{D}[\mathbf{d} + (\mathbf{s} - \mathbf{b})] + \mathbf{z}, \tag{3.22}$$

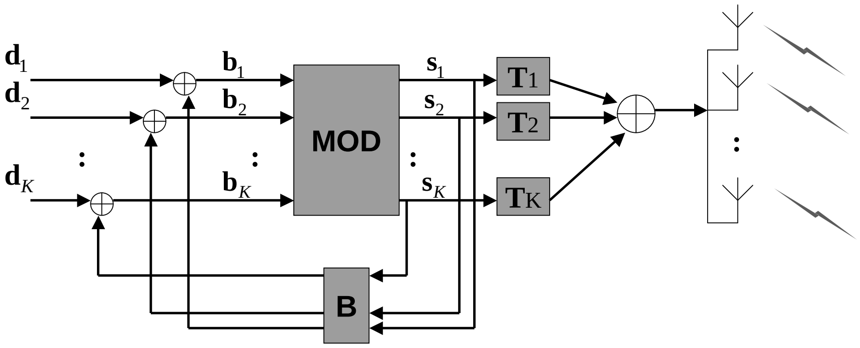

FIG. 3.3. *Block Diagram of THP*

and we obtain KL decoupled interference free substreams. Finally $\mathbf{d}$ can be restored by applying the reverse modulo operation. The extension to general settings with $L < N_r$ and/or $KN_r < N_t$ is straightforward.

3.3. Advanced Inter-Cell Interference Mitigation Methods. While the intra-cell interference mitigation techniques are relatively well developed in literature, the inter-cell interference problem only receives attention in recent years, which presents some unique challenges due to distinctions in the modeling of interference. Moreover, when designing systems with inter-cell interference mitigation capabilities, different levels of channel estimation and hardware requirements should be jointly considered regarding the tradeoff between performance and applicability.

3.3.1. Problem Formulations. Conventionally inter-cell interference are mitigated by interference averaging and careful resource allocations (e.g. frequency reuse, base station scrambling code assignment, and open-loop power control). As mentioned in Section 3.1, in cellular networks with universal frequency reuse, due to inadequate interference averaging, CDMA downlink usually limits the system capacity. The situation is similar in SDMA. Although single user transmitter beamforming may make each data stream more "focused" on its desired user so that the "leakage" of interference to other users can be reduced (e.g. in TD-SCDMA), the achieved gain is still marginal in strong interference limited environments. In particular, the spectral efficiency gain of SM-MIMO could be greatly degraded when applied in cellular networks, as the multiple data streams for each user may contribute more co-channel interference and more vulnerable to inter-cell interference. This effect can be illustrated by the following example:

Example 3.1: A two-cell ($N_B = 2$) scenario is shown in Figure 3.4, where one co-channel mobile user is arbitrarily located in each of the two adjacent cells ($\tau_k^{(b)}$ is the propagation delay from BS b to MS k). Rayleigh flat fading and shadowing effect are considered for a downlink communication scenario. we set $N_t = 3, N_r = 2$, and compare the averaged spectral efficiencies for one user corresponding to different number of data streams per user (i.e. L), as shown in Figure 3.5. Here we simulate interference-free (i.e. one "isolated" cell) MIMO and the scenario with inter-cell interference (i.e. the interfering scenario in Figure 3.4), both applying eigen-beamforming and water-filling power allocation based on the per-user MIMO channel [17]. It is easily seen that single-stream ($L = 1$) is more robust with inter-cell interference, while the spatial multiplexing gain of multi-stream MIMO ($L = 2$) is significantly reduced

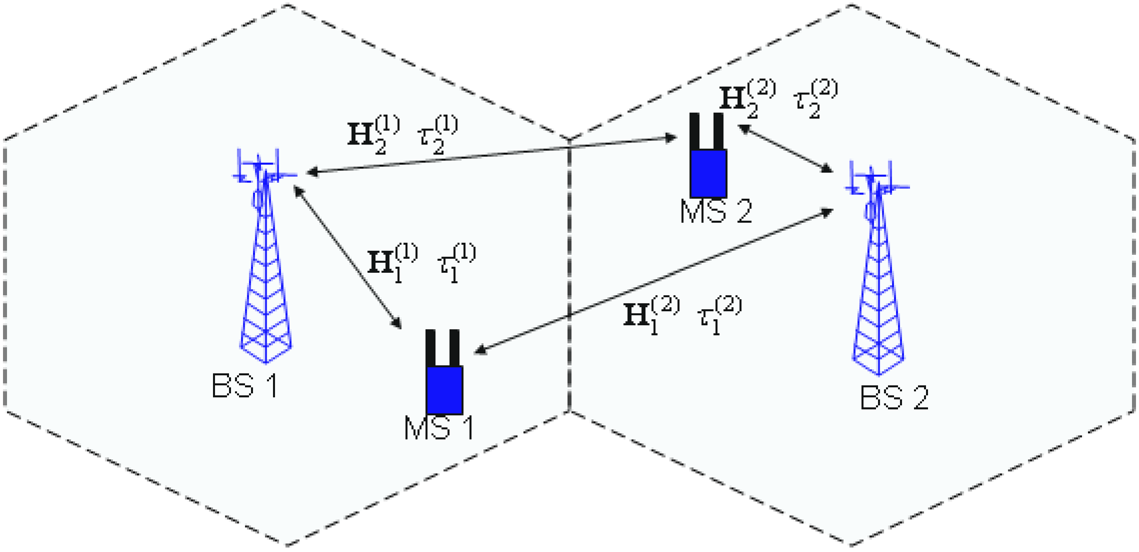

FIG. 3.4. *The Two-Cell Scenario in Example 3.1*

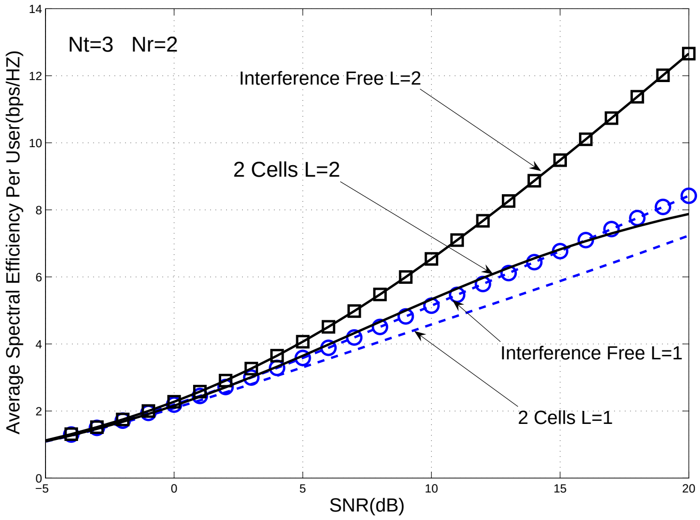

FIG. 3.5. *Spectral Efficiency Comparisons in Example 3.1*

by the inter-cell interference. Note that at high SNRs the two-stream MIMO performs even worse than single-stream interference-free case. An intuitive explanation is that: the weaker eigen-beams of MIMO channel matrices are less "focused", therefore more vulnerable to the inter-cell interference.

All the above facts advocate sophisticated signal processing methods to actively suppress inter-cell interference, rather than merely improving its statistics. For succinctness we focus on the downlink in multiple antenna systems; the application in CDMA and their combinations follow readily.

In a general multicell multiuser MIMO system, assuming there is one co-channel mobile user in each cell (see Figure 3.6), the received signal (after matched filtering) for a particular user k is:

$$\mathbf{y}_k = \mathbf{H}_k^{(b_k)}\mathbf{x}_k + \sum_{j\neq k}\mathbf{H}_k^{(b_j)}\mathbf{x}'_{jk} + \mathbf{z}_k, \tag{3.23}$$

where b_k is the index of the associated base station of user k, $\mathbf{x}'_{jk}$ denotes the equivalent signal intended for user j which is asynchronously received by user k (since the matched filter at MS k only synchronizes with $\mathbf{x}_k$), and $\mathbf{H}_k^{(b)}$ is the channel matrix from BS b to MS k. Meanwhile we assume $\mathbf{x}_k = \mathbf{T}_k\mathbf{d}_k$. Traditionally inter-cell interference is treated as background noise, so $\mathbf{T}_k$ only applies single user precodings (provided CSI is available at the transmitter), and the receiver of user k also deploys single user MIMO detection. The studies in [44][45] and [63] indicated the ineffectiveness of the MIMO system in such an interference-limited environment, and revealed that reducing the number of data streams may increase the effective system-level performance. On the contrary, advanced signal processing schemes are proposed in recent years for actively mitigating inter-cell interference at the expense of increased complexity in channel estimation and computation. These schemes can be employed either at the receiver or the transmitter, as will be introduced in the following subsections.

3.3.2. Receiver Processing. We assume the knowledge of channel information for the interfering users, which can be obtained either through an initial joint training phase with the coordination of base stations, or through adaptive tracking algorithms from the received signals directly. Therefore multiuser detectors can be deployed for inter-cell interference mitigation. The transmit beamformers are designed based on the channel information, assumed constant over a period longer than the largest delay, therefore we have $\mathbf{x}'_{jk} = \mathbf{T}_j\mathbf{d}'_{jk}$, where $\mathbf{d}'_{jk}$ represents the corresponding asynchronously received interfering data vector. Note that when treating $\{\mathbf{d}'_{jk}\}_{j\neq k}$ as virtual *synchronous* interfering signals, the system model in (3.23) is identical to a multiple access channel (c.f. (3.12)), hence the multiuser detection algorithms can be readily applied (actually it might be more appropriate to apply these algorithms in the uplink, since the BS can easily accommodate complicated signal processing and channel estimation). Linear multiuser detectors are the simplest way for inter-cell interference mitigation. Furthermore, the receiver is only interested in its desired signal, and it is not efficient to detect the asynchronous interfering signals. With this in mind, in [46][47] the inter-cell interference is mitigated by an *interference-aware* single user MMSE detector, which is dedicated to minimize the MSE in $\mathbf{d}_k$. Specifically, by assuming normalized data vectors $\{\mathbf{d}_k\}_{k=1\ldots K}$ a linear receiver $\mathbf{W}_k$ is designed as:

$$\begin{aligned}\mathbf{W}_k &= \arg\min_{\mathbf{W}} E\left[\|\mathbf{W}^*\mathbf{y}_k - \mathbf{d}_k\|^2\right] \qquad (3.24)\\ &= \left(\mathbf{H}_k\mathbf{T}_k\mathbf{T}_k^*\mathbf{H}_k^* + \sum_{j\neq k}\mathbf{H}_k^{(b_j)}\mathbf{T}_j\mathbf{T}_j^*\mathbf{H}_k^{(b_j)^*} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{H}_k\mathbf{T}_k,\end{aligned}$$

and the resultant spectral efficiency of user k is given by:

$$C_k = \log\left|\mathbf{I} + \mathbf{H}_k\mathbf{T}_k\mathbf{T}_k^*\mathbf{H}_k^*\Phi_k^{-1}\right|, \tag{3.25}$$

where $\Phi_k = \sum_{j\neq k}\mathbf{H}_k^{(b_j)}\mathbf{T}_j\mathbf{T}_j^*\mathbf{H}_k^{(b_j)^*} + \sigma^2\mathbf{I}$.

On the other hand, nonlinear detectors may achieve better performance. A well-known scheme is *group interference cancellation*, where information bits for each group (cell) are detected sequentially for successive interference subtractions (an extension of SIC MUD). However, given the fact that $\{\mathbf{d}'_{jk}\}_{j\neq k}$ are asynchronous receptions, any nonlinear multiuser detector exploiting the finite alphabet of the interfering signals should be carefully designed. When the signals from different transmitters introduce negligible delay offsets (due to near equal distances or long enough symbol intervals) at the receiver, the nonlinear detectors can be employed straightforwardly. Otherwise, either complicated encoding and modulation schemes or full knowledge of timing information should be required at the receiver, leading to a more stringent requirement on hardware complexity, especially undesirable for mobile handsets.

In the uplink, when the base stations can coordinate with each other to jointly detect their received signals, the inter-cell interference can be more effectively controlled, as illustrated in [48][49]. However, as ignored by many researchers, the timing issue again presents as a major problem for cooperative receivers.

In summary, receiver linear processing for inter-cell interference mitigation requires full set of channel information and the performance is by nature limited; to achieve better interference mitigation effects nonlinear processing or cooperative detection could be explored, which nonetheless impose more stringent requirements, particularly not appropriate for the downlink. In [47] and [53], it is shown that even from an information theoretic viewpoint (i.e. ignore the impact from asynchronism), performance of the optimal multiuser receiver is still significantly away from that of the single cell interference-free upper bound. On the other hand, if the full set of transmitter CSI is available, transmitter precoding (see the next subsection) may be a good alternative for inter-cell interference suppression.

3.3.3. Cooperative Transmission. In the downlink, if the base stations can work cooperatively to obtain the channel information for all the BS-MS pairs (e.g. by a joint training phase with feedback in FDD, or uplink channel estimation in TDD), the idea naturally arises to move the inter-cell interference mitigation to the transmitter (BS) side, where complex structure and advanced processing can be more easily accommodated. Moreover, as multiple users in multiple cells are involved, cooperative processing at relevant base stations can be exploited. This approach is feasible, as in the current infrastructure that is common to both cellular communications and indoor wireless internet access, the base stations and access points in the system are connected by a high-speed wired backbone that allows information to be reliably exchanged among them (see Figure 2.1). This approach is also reasonable, as in environments with strong interference a mobile usually experiences several comparable and weak links from surrounding radio ports, where soft handoff typically takes place in current CDMA networks. In this scenario, cooperative processing among relevant base stations transforms the obstructive interference into constructive signals, which should offer large performance improvement, and greatly reduce the receiver detector complexity.

With cooperative transmission, the L data streams of each mobile user are mapped (linearly or nonlinearly) to the transmit antennas on all the N_B cooperative base stations, i.e. $\mathbf{T}_k$ becomes an $N_t N_B \times L$ matrix. Defining $\mathbf{H}_k = \left[\mathbf{H}_k^{(1)}, \mathbf{H}_k^{(2)}, ..., \mathbf{H}_k^{(N_B)}\right]$, the received signal for user k in (3.23) becomes:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{T}_k \mathbf{d}_k + \sum_{j \neq k} \mathbf{H}_k \mathbf{T}_j \mathbf{d}'_{jk} + \mathbf{z}_k, \tag{3.26}$$

where $\mathbf{d}'_{jk}$ is modeled as the asynchronously received interfering signal intended for user j, or an equivalent synchronous interfering user, as discussed above. Note that similar to the CDMA soft handoff context, (3.26) is based on the assumption that all the considered mobile users have comparable distances to adjacent base stations (see Figure 3.6), so that the delay offsets from cooperative base stations to each MS are negligible compared with the symbol interval (possibly with timing pre-compensation). As we are considering the strong inter-cell interference scenario, this assumption is reasonable; for mobile users located close to a BS, conventional single cell signaling is generally adequate and there is no need for such cooperative schemes. In the handoff procedure for IS-95 and CDMA 2000, synchronized transmission among cooperative base stations has been implemented. Therefore, defining $\mathbf{T} = [\mathbf{T}_1, \mathbf{T}_2, ..., \mathbf{T}_K]$ and $\mathbf{d}_{(k)}$ as the stacked vector of $\mathbf{d}_k$ and $\{\mathbf{d}'_{jk}\}_{j \neq k}$, (3.26) can be rewritten to

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{T} \mathbf{d}_{(k)} + \mathbf{z}_k, \tag{3.27}$$

forming a standard broadcast channel as in (3.14). We can then easily extend the precoding schemes discussed in Section 3.2.2 to the problem here. Except the great potential of interference mitigation, co-

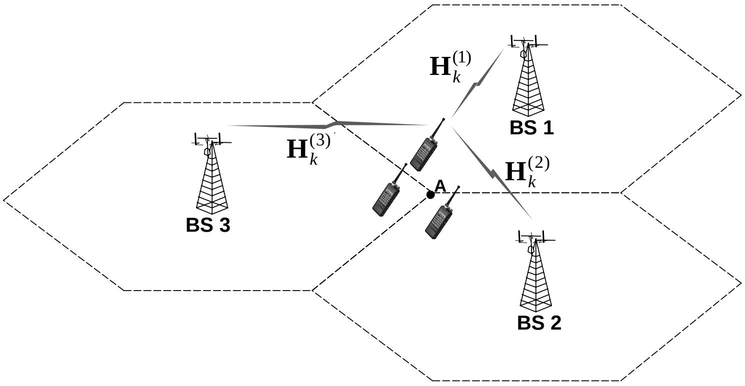

FIG. 3.6. *A Symmetric Three-Cell Scenario for Example 3.2*

operative precoding introduces other benefits such as macro-diversity and immunization to ill-conditioned channels caused by antenna correlations. One of the unique problems faced by cooperative transmission is the power constraints on each BS: a straightforward extension of single cell precoding schemes may result in a large power at one particular BS. Unfortunately, joint optimization of precoding with per-BS power constraints is a non-convex problem. To achieve near optimal performance with DPC, [58] proposes a multistage solution, which invests a small amount of power to a certain selected BS in each stage, until one BS reaches its power constraint. A simplified approach in [53] uses a linear transformation that guarantees one of the BSs transmits with full power while all the others with a proportionally reduced power.

The gain achieved by cooperative precoding can be illustrated by the following numerical example.

Example 3.2: A symmetric three-cell ($N_B = 3$) scenario with strong inter-cell interference is shown in Figure 3.6, in which one co-channel mobile user is located in each of the three adjacent cells (around the central point A). Rayleigh flat fading is assumed. The average transmit power for each user is P_t, and the JT-Decomp cooperative precoding (see [53]) applies identical per-BS power constraints of P_t. In the simulation, $N_t = N_r = L = 2$. The averaged spectral efficiencies of each user are shown in Figure 3.7, where those of the conventional single user receiver and the optimal multiuser receiver in Section 3.3.2 are also presented for reference. It is seen that the performance of the optimal MUD receiver is still far away from the single cell (i.e. point-to-point MIMO) interference free bound, while cooperative JT-Decomp performs much better.

A potential problem of cooperative precoding is the asynchronism of interference signals: when the delay offsets at the MS receiver from different base stations are not negligible (e.g. in high data rate case, or when the MS is located relatively far from cell boundaries), the correctness of the channel model (3.27) becomes questionable, and deploying the cooperative precoding schemes verbatim may lead to much worse performance than expected. Although in 3G cellular networks it is possible for the base stations to track accurate user locations so that timing advance could be applied for the desired signal $\mathbf{d}_k$ transmitted from different base stations to reach MS k simultaneously, it is hard to synchronize the interfering signals and the precoding design will be much more complicated, requiring not only the full set of channel knowledge at the transmitter, but also all the timing parameters [55]. When the channel

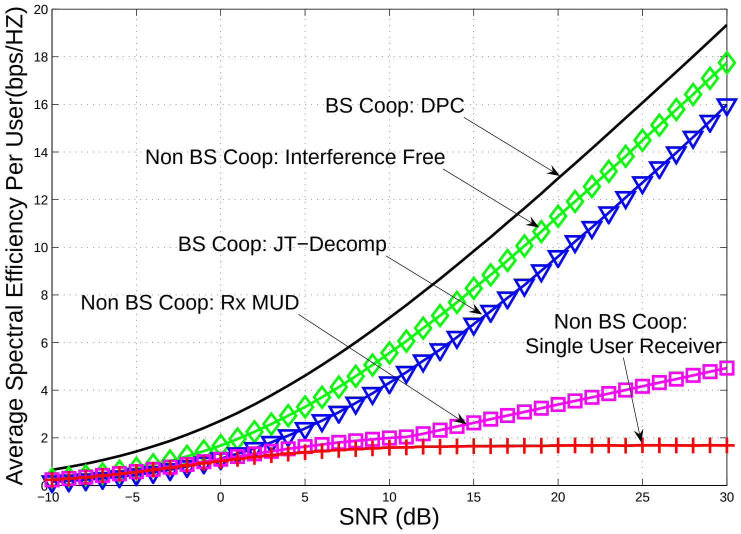

Fig. 3.7. *Spectral Efficiency Comparisons in Example 3.2*

model (3.27) does not hold, BS cooperative precoding designs based on this assumption may lead to unacceptable interference leakage. In this case the precoding designs should be conducted BS by BS, instead of on an extended MIMO matrix. The following numerical example illustrate this issue:

Example 3.3: Considering the two-cell scenario in Example 3.1 (Figure 3.4) with the setting $N_t = 3, N_r = 2$ and $L = 2$, since the two MSs are arbitrarily located in the two cells respectively, the channel model in (3.27) does not hold. From the simulation result of Figure 3.8, the JT-Decomp cooperative precoding [53] leads to significant interference leakage, while the iterative and closed-form precoding schemes [55] considering the asynchronous model may partially recover the cooperative gains.

When combined with OFDM, on the other hand, this problem can be levigated slightly: as long as the length of the cyclic prefix sufficiently exceeds both the channel delay dispersion and the delay offsets from different BSs, and the transmission from different base stations can be perfectly synchronized, the delay offsets in time domain are converted to phase shifts in frequency domain (in each sub-carrier), such that (3.27) still hold in each subcarrier except for additional phase shifts that can be included into the channel matrices. This point is further illustrated through the following example:

Example 3.4: Again the two-cell scenario in Example 3.1 (Figure 3.4) is considered with a 2 × 2 MIMO-OFDM setting defined in IEEE 802.11n WLANs [66]. Here we extend the cyclic prefix from $0.8\mu s$ (defined in [66]), to $0.8 + d_{BS}/300\ \mu s$, where d_{BS} (in meters) is the distance between the two BSs (APs). As indicated above, the delay offsets are converted into phase shifts in the equivalent channel of each sub-carrier without causing ICI. The non-line-of-sight (NLOS) version of channel model B [67] is adopted, and a received $SNR = 20dB$ is assumed thoughout the simulation. For the BS cooperative schemes, we simply extend the JT-Decomp precoding into each sub-carrier. For comparison, we also simulate the single BS-MS pair case (interference free), and the conventional 2-BS and 2-MS WLANs applying CSMA/CA protocol (essentially the same as TDMA, as introduced in Section 2.2). From the simulation result of Figure 3.9, we can see that BS cooperation achieves significant gain over

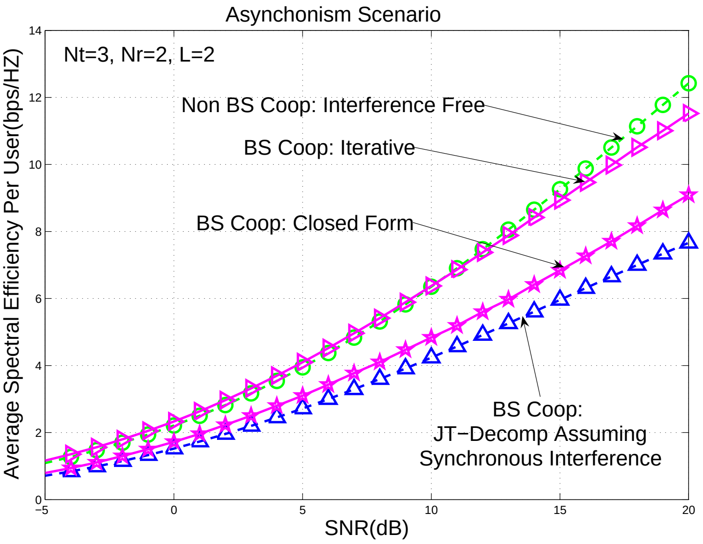

FIG. 3.8. *Spectral Efficiency Comparisons in Example 3.3*

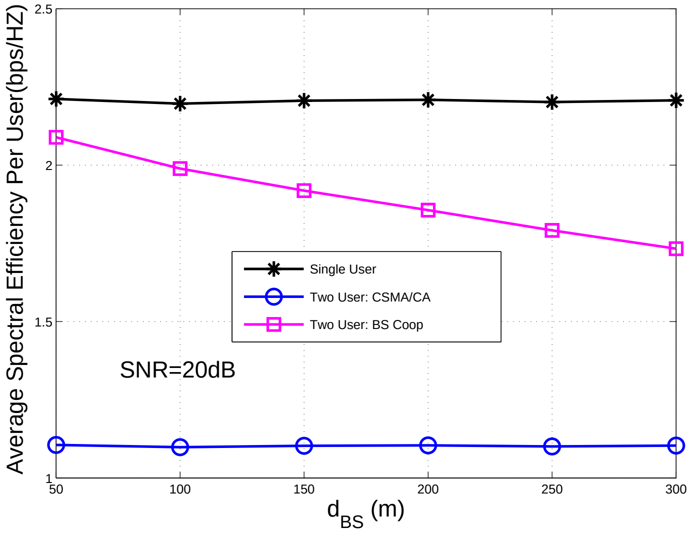

FIG. 3.9. *Spectral Efficiencies with Different d_{BS} in Example 3.4*

a large range of d_{BS}. It is then particularly suitable for the WLAN applications in highly populated areas.

To avoid the timing problem in cooperative precoding, another category of solutions apply single cell precoding (so $\mathbf{T}_k$ remains the dimension of $N_t \times L$) in an interference-aware manner: one example ([59]) is to apply JT-Decomp with the constraint $\mathbf{H}_j^{(b_k)}\mathbf{T}_k = \mathbf{0}$, i.e. the signal for user k (transmitted from BS b_k) is nulled out at user $j \neq k$. On the downside, the array dimension is constrained by $N_t \geq KN_r$, where K is the number of co-channel users in the *whole* area served by the cooperative base stations, obviously undesirable for systems intended to serve a large number of co-channel users. Another example is to serve all the co-channel users in the multicell system by one BS with linear or nonlinear precoding. This BS can be selected based on current channel information (i.e., *BS selection* [54]) or predetermined (i.e., *BS TDMA* [63]). Both schemes still achieve macro-diversity so that the outage probability for each user can be reduced. However their performances are shown good only in some specific environments, and again problems are raised concerning dimension and complexity constraints. In general, base station cooperative processing is a new topic which attracts interests only in recent years. Nowadays people are looking into associated practical issues, and the prospect of its real world applications is foreseeable in the near future.

3.3.4. Other Strategies. Except the advanced signal processing at the receiver or transmitter, simplified strategic approaches are also proposed to suppress inter-cell interference. Following is a brief overview of these schemes.

General code division multiplexing (CDM): To more effectively whiten the inter-cell interference, especially in the downlink, cell-specific channel coding schemes or interleavers may be applied ([62]). Note that DS-CDMA is a special case of general CDM.

Distributed antenna system (DAS): When installing the BS antennas within a cell at geographically separated locations, advantages such as extended coverage and reduced dead spots can be achieved. More importantly, since statistically the transmission distance from BS antennas to each user is reduced, the overall transmit power can be decreased, leading to (on average) less inter-cell interference to users in other cells ([52][64]).

BS cooperation with limited channel information: It is already shown that BS cooperation can potentially lead to significant performance gains in cellular systems. However, in practice full interfering channel information may be difficult to obtain. Alternatively, such cooperation may be conducted with limited information exchange among participating base stations. study on this topic is still at its infant stage, though.

4. Bibliographical Notes. This chapter is devoted to interference mitigation issues in cellular networks. State-of-the-art techniques are reviewed, and in particular, base station cooperative processing is advocated as a new approach of great potential to address the increasingly-severe while inadequately-treated inter-cell interference. Due to space limitations, some details are necessarily omitted, which can be further explored from the following references.

Detailed descriptions on the basic techniques applied in cellular networks, including link level designs, multiple access and conventional interference mitigation strategies can be found in [1]-[6]. Except the official standardization materials published by IEEE, [7]-[15] and references therein provide a comprehensive overview of these standards ranging from mobile cellular networks, to WLAN, WMAN, and future systems. The benefits MIMO systems are first unveiled by [16]-[19]. The fundamental ideas of multiuser detection in CDMA and multiple antenna schemes can be found in [20]-[25], while different transmitter precoding schemes are discussed in [26]-[43]. The impact of inter-cell interference on SM-MIMO systems are revealed in [44][45][63]. The limited number of works regarding inter-cell interference mitigation via cooperative or non-cooperative multiuser receivers can be found in [46]-[49], and some most recent works on downlink BS cooperative precoding for inter-cell interference suppression include [49]-[62]. Finally the strategic inter-cell interference mitigation methods are described in [62]-[64] and references therein.

REFERENCES

[1] J. G. Proakis, Digital Communications, 3rd Edition, McGraw-Hill, New York, 1995.

[2] T. S. Rappaport, Wireless Communications: Principles and Practice, Prentice-Hall PTR, NJ, 1996.

[3] C. N. Thurwachter Jr., Wireless Networking, Prentice Hall, Upper Saddle River, NJ, 2002.

[4] A. F. Molisch, Wireless Communications, Wiley, 2005.

[5] D. N. Tse, and P. Viswanath, Fundamentals Of Wireless Communication, Cambridge University Press, 2005.

[6] A. Goldsmith, Wireless Communications, Cambridge University Press, 2005.

[7] UMTS Forum, "Mobile evolution shaping the future," Whitepaper, Aug. 2003.

[8] B. Li, D. Xie, S. Cheng, J. Chen, P. Zhang, W. Zhu, and B. Li, "Recent advances on TD-SCDMA in China," *IEEE Communications Magazine*, Jan. 2005.

[9] A. Ghosh, D. R. Wolter, J. G. Andrews, and R. Chen, "Broadband wireless access with Wimax/802.16: current performance benchmarks and future potential," *IEEE Communications Magazine*, Feb. 2005.

[10] H. Honkasalo, K. Pehkonen, M. T. Niemi, and A. T. Leino, "WCDMA and WLAN for 3G and beyond," *IEEE Wireless Communications*, vol. 9, no. 2, Apr. 2002.

[11] J. Chuang, and N. Sollenberger, "Beyond 3G: wideband wireless data access based on OFDM and dynamic packet assignment," *IEEE Communications Magazine*, July 2000.

[12] B. P. Crow, I. Widjaja, L. G. Kim, and P. T. Sakai, "IEEE 802.11 wireless local area networks," *IEEE Communications Magazine*, Sept. 1997.

[13] M. S. Gast, 802.11 Wireless Networks, 2nd Edition, O'Reilly, 2005.

[14] H. Yang, "A road to future broadband wireless access: MIMO-OFDM-based air interface," *IEEE Communications Magazine*, Jan. 2005.

[15] D. N. Knisely, S. Kumar, S. Laha, and S. Nanda, "Evolution of wireless data services: IS-95 to cdma2000 ," *IEEE Communications Magazine*, Oct. 1998.

[16] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Labs Tech. J.*, vol. 2, no. 2, pp. 41-59, Autumn 1996.

[17] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311-335, Mar. 1998.

[18] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Trans. Telecomm.*, vol. 10, no. 6, pp. 585-595, Nov.-Dec. 1999.

[19] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith, and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE J. Select. Areas Commun.*, vol. 21, no. 3, pp. 281-302, Apr. 2003.

[20] S. Verd, Multiuser Detection, Cambridge, UK: Cambridge University Press, 1998.

[21] X. Wang and H. V. Poor, "Iterative (Turbo) soft interference cancellation and decoding for coded CDMA", *IEEE Trans. Commun.*, vol. 47, no. 7, pp. 1046-1061, July 1999.

[22] X. Wang and H. V. Poor, "Space-time multiuser detection in multipath CDMA channels," *IEEE Trans. Signal Processing*, vol. 47, no. 9, pp. 2356-2374, Sept. 1999.

[23] H. Dai and H. V. Poor: "Turbo Multiuser Detection for Coded DMT VDSL Systems," *IEEE J. Select. Areas Commun.*, vol. 20, no.2, pp. 351-362, Feb. 2002.

[24] H. Dai and H. V. Poor: "Iterative Space-Time Processing for Multiuser Detection in Multipath CDMA Channels," *IEEE Trans. Signal Processing*, vol. 50, no. 9, pp. 2116-2127, Sept. 2002.

[25] W. Yu, W. Rhee, S. Boyd, and J. M. Ciofli, "Iterative water-filling for Gaussian vector multiple access channels", Proc. 2001 IEEE International Symposium on Information Theory, pp. 322, Washington, DC, 24-29 June. 2001.

[26] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, "Capacity Limits of MIMO Channels," *IEEE J. Select. Areas Commun.*, vol. 21, no. 5, pp. 684-702, June 2003.

[27] N. Jindal, S. A. Jafar, S. Vishwanath, and A. Goldsmith, "Sum power iterative water-filling for multi-antenna gaussian broadcast channels," *Proc. the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers*, 2002, vol. 2, pp. 1518 -1522, Nov. 3-6, 2002.

[28] S. Vishwanath, N. Jindal and A. Goldsmith, "On the capacity of multiple input multiple output broadcast channels," *Proc. 2002 IEEE International Conference on Communications(ICC 2002)*, pp. 1444 -1450, vol.3, New York City, USA, 28 April-2 May 2002.

[29] H. Viswanathan, S. Venkatesan, and H. Huang, "Downlink capacity evaluation of cellular networks with known-interference cancellation", *IEEE J. Select. Areas Commun.*, vol. 21, no. 5, pp. 802-811, June 2003.

[30] G. Caire, S. Shamai, "On the achievable throughput of a multiantenna Gaussian broadcast channel," *IEEE Trans. Info. Theory*, vol. 49, no. 7, pp. 1691-1706, July 2003.

[31] C. Windpassinger, R. F. H. Fischer, T. Vencel, and J. B. Huber, "precoding in multiantenna and multiuser communications," *IEEE Trans. Wireless Commun.*, vol. 3, no. 4, pp. 1305-1316. July 2004.

[32] K.-K. Wong, R. D. Murch, and K. B. Letaief, "Performance enhancement of multiuser MIMO wireless communication systems," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1960-1970, Dec. 2002.

[33] K.-K. Wong, R. D. Murch, and K. B. Letaief, "A joint channel diagonalization for multiuser MIMO antenna systems," *IEEE Trans. Wireless Commun.*, vol. 2, no. 4, pp. 773-786, July 2003.

[34] K.-K. Wong, R. S.-K. Cheng, K. B. Letaief, and R. D. Murch "Adaptive antennas at the mobile and base stations in an OFDM/TDMA system," *IEEE Trans. Commun.*, vol. 49, no. 1, pp. 195-206, Jan. 2001.

[35] K.-K. Wong, R. D. Murch, and K. B. Letaief "Optimizing time and space MIMO antenna system for frequency selection fading channels," *IEEE J. on Select. Areas in Commun.*, vol. 19, no. 7, pp. 1395-1407, July. 2001.

[36] M. Schubert, and H. Boche, "Solution of the multiuser downlink beamforming problem with individual SINR constraints," *IEEE Trans. Vehicular Technology*, vol. 53, no. 1, pp. 18-28, Jan. 2004.

[37] Z. Pan, K.-K. Wong, and T.-S. Ng, "Generalized multiuser orthogonal space-division multiplexing," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1969-1973, Nov. 2004.

[38] R. L. Choi, and R. D. Murch, "A downlink decomposition transmit preprocessing technique for multi-user MIMO systems," *Proc. IST Mobile and Wireless Telecommunications Summit*, June 2002.

[39] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Processing*, vol. 52, no. 2, pp. 461-471, Feb. 2004.

[40] A Tarighat, M. Sadek, and A. H. Sayed, "A multi user beamforming scheme for downlink MIMO channels based on maximizing signal-to-leakage ratios," *Proc. IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP),* vol. 3, pp. 1129-1132, Philadelaphia, PA, March 2005.

[41] M. Joham, K. Kusume, M. H. Gzara, W. Utschick, and J. A. Nossek, "Transmit Wiener filter for the downlink of TDD DS-CDMA systems," *Proc. IEEE 7th Int. Symp. on Spread-Spectrum tech. and Appl.*, Prague, Czech Republic, vol. 1, pp. 9-13, Sept. 2002.

[42] A. Wiesel, Y. C. Eldar, and S. Shamai, "Linear precoding via conic optimization for fixed MIMO receivers," to appear in *IEEE Trans. Signal Processing.*

[43] F. Kowalewski, and P. Mangold, "Joint predistortion and transmit diversity," *Proc. IEEE Globe Telecom. Conf. (GLOBECOM)*, vol. 1, pp. 245-249, Nov. 2000.

[44] S. Catreux, P. F. Driessen, and L. J. Greenstein, "Attainable throughput of an interference-limited multiple-input multiple-output (MIMO) cellular system," *IEEE Trans. Communications*, vol. 49, no. 8, pp. 479-493, Aug 2001.

[45] R. S. Blum, J. H. Winters, and N. Sollenberger, "On the capacity of cellular systems with MIMO," *Proc. 2001 Fall IEEE Vehicular Technology Conf.*, vol. 2, pp. 1220 -1224, Atlantic City, NJ, Oct. 2001.

[46] H. Dai, and H. V. Poor, "Asymptotic spectral efficiency of multicell MIMO systems with frequency-flat fading," *IEEE Trans. Signal Processing*, vol. 51, no. 11, pp.2976-2989, Nov. 2003.

[47] H. Dai, A. F. Molisch, and H. V. Poor, "Downlink capacity of interference-limited MIMO systems with joint detection," *IEEE Trans. Wireless Communications*, vol. 3, no.2, pp. 442-453, Mar. 2004.

[48] B. L. Ng, J. S. Evans, and S. V. Hanly, "Distributed linear multiuser detection in cellular networks based on Kalman smoothing," *Proc. IEEE Globe Telecom. Conf. (GLOBECOM)*, vol. 1, pp. 134-138, Dallas TX, Dec. 2004.

[49] A. Sklavos, Service Area Based OFDM Air Interface for Beyond 3G Mobile Radio Systems, *PHD Dissertation*, University of Kaiserslautern.

[50] P. W. Baier, M. Meurer, T. Weber and H. Troeger, "Joint transmission (JT), an alternative rationale for the downlink of time division CDMA using multi-element transmit antennas," *Proc. 2000 IEEE 6th Int. Symp. Spread Spectrum Techniques*, vol. 1, pp. 1-5, Parsippany, NJ, Sept. 2000.

[51] G. J. Foschini, H. Huang, K. Karakayali, R. A. Valenzuela, and S. Venkatesan, "The value of coherent base station coordination," *Proc. 2005 Conference on Information Sciences and Systems (CISS 05)*, The Johns Hopkins University, Mar. 16-18, 2005.

[52] H. Zhang and H. Dai, "On the Capacity of Distributed MIMO Systems," *Proc. 2004 Conference on Information Sciences and Systems (CISS)*, Princeton University, Princeton, NJ, March 2004.

[53] H. Zhang, and H. Dai, "Cochannel interference mitigation and cooperative processing in downlink multicell multiuser MIMO networks," *European Journal on Wireless Communications and Networking*, 2004, no. 2, pp. 222-235, 4th Quarter, 2004.

[54] H. Zhang, H. Dai and Q. Zhou, "Base station cooperation for multiuser MIMO: joint transmission and BS selection," *Proc. 2005 Conference on Information Sciences and Systems (CISS 05)*, The Johns Hopkins University, Mar. 16-18, 2005.

[55] H. Zhang, N. B. Mehta, A. F. Molisch, J. Zhang, and H. Dai, "Joint transmission by cooperative base stations in multiuser cellular downlink with asynchronous interference, " *IEEE Trans. Wireless Communications*, submitted.

[56] S. Shamai and B. M. Zaidel, "Enhancing the cellular downlink capacity via co-processing at the transmission end," *Proc. 2001 Spring IEEE Vehicular Technology Conf.*, pp. 1745-1749, Rhodes, Greece, May 2001.

[57] S. A. Jafar, G. J. Foschini, and A. J. Goldsmith, "PhatomNet: exploreing optimal multicellular multiple antenna systems," *Proc. Fall IEEE Vehicular Technology Conference (VTC 02)*, vol. 1, pp. 261-265, Vancouver, BC, Canada, Sept. 2002.

[58] S. A. Jafar, and A. Goldsmith, "Transmitter optimization for multiple antenna cellular systems," *Proc. 2002 IEEE International Symposium on Information Theory(ISIT 02)*, pp. 50, 30 June-5 July 2002.

[59] L. Shao, and S. Roy, "Downlink Multicell MIMO-OFDM: An Architecture for Next Generation Wireless Networks," *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans LA, March, 2005.

[60] B. L. Ng, J. S. Evans, S. V. Hanly, and D. Aktas, "Transmit beamforming with cooperative base stations," *Proc. 2005 IEEE International Symposium on Information Theory(ISIT 05)*, Sept. 2005.

[61] A. Ekbal, and J. M. Cioffi, "Distributed transmit beamforming in cellular networks - a convex optimization perspective," *Proc. IEEE Int. Conf. on Commun. (ICC)*, May 2005.

[62] S. Zhou, Y. Li, M. Zhao, X. Xu, J. Wang, and Y. Yao, "Novel techniques to improve downlink multiple access capacity for beyond 3G," *IEEE Communications Magazine*, Jan. 2004.

[63] W. Choi, and J. G. Andrews, "On spatial multipexing in cellular MIMO-CDMA systems with linear receivers," *Proc.*

IEEE Int. Conf. on Commun. (ICC), May 2005.

[64] W. Choi, J. G. Andrews, and C. Yi, "The Capacity of Multicellular Distributed Antenna Networks," *Proc. IEEE Wireless Commun. and Inf. Theory Symposium*, June 2005.

[65] G. E. Bottomley, T. Ottosson, and Y.-P. E. Wang, "A generalized RAKE receiver for interference suppression," *IEEE J. Select. Areas Commun.*, vol. 18, no. 8, pp. 1536-1545, Aug 2000.

[66] IEEE P802.11n/D1.0: Draft Amendment to Wireless LAN Media Access Control (MAC) and Physical Layer (PHY) Specifications: Enhancements for Higher Throughput, Mar. 2006.

[67] IEEE P802.11 Wireless LANs TGn Channel Models, IEEE 802.11-03/940r4, May 2004.