Chapter 2
System Models

2.1 MIMO Broadcast Channel System Model

In the MIMO broadcast channel, a centralized transmitter serves K decentralized users who cannot cooperate and therefore have to process and decode their received signals on their own. Each of the K users asks for data that is specific to him thus constituting a type of information theoretic broadcast channel [1]. This is in contrast to the conventional radio, TV, or satellite broadcast where common data is sent to all receivers. The considered scenario with different data for the users as depicted in Fig. 2.1 can be used to model the downlink of a cellular network in a single radio cell but also for wired communication like the digital subscriber line (e.g., [2, 3]). The number of antennas deployed at the base station shall be denoted by N and the kth terminal is equipped with M_k antennas where $k \in \{1, \ldots, K\}$. The information-bearing symbol vector $\boldsymbol{s}_k \in \mathbb{C}^{L_k}$ that is dedicated to user k is modeled as an L_k-dimensional complex-valued zero-mean random variable with identity covariance matrix $\mathrm{E}[\boldsymbol{s}_k \boldsymbol{s}_k^H] = \mathbf{I}_{L_k} \forall k \in \{1, \ldots, K\}$. Here, L_k is the number of streams assigned to user k. When needed, the distribution of the symbol vectors will be specified further in the respective sections and chapters. In addition, the symbol vectors of all K users are pairwise independent. The modulated symbol vector $\boldsymbol{s}_k$ is then filtered by the precoding matrix $\boldsymbol{P}_k \in \mathbb{C}^{N \times L_k}$ which maps the L_k data streams to the transmit signal of the N transmit antennas in the discrete-time system model. This way, the overall transmit signal

$$\boldsymbol{x} = \sum_{k=1}^{K} \boldsymbol{P}_k \boldsymbol{s}_k \in \mathbb{C}^N \tag{2.1}$$

is generated by summing up all the precoded symbol vectors and then radiated from the N antennas leading to a symbol-averaged dissipated transmit power

$$P_{\text{diss}}^{\text{BC}} = \mathrm{E}\big[\|\boldsymbol{x}\|_2^2\big] = \sum_{k=1}^{K} \|\boldsymbol{P}_k\|_{\mathrm{F}}^2. \tag{2.2}$$

R. Hunger, *Analysis and Transceiver Design for the MIMO Broadcast Channel*,
Foundations in Signal Processing, Communications and Networking 8,
DOI: 10.1007/978-3-642-31692-0_2,

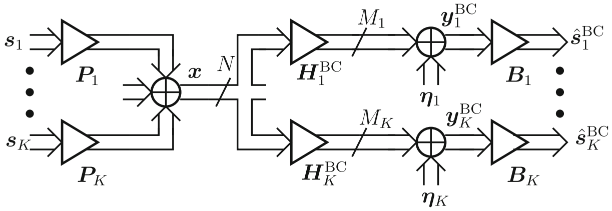

Fig. 2.1 System model for the K user MIMO broadcast channel

Apart from the feasibility analysis with given quality of service requirements in Chap. 9, we impose a sum power constraint on all antennas as upper bound on the totally radiated power:

$$P_{\text{diss}}^{\text{BC}} \leq P_{\max}. \tag{2.3}$$

We assume a frequency-flat physical channel between the transmitter and the K receivers. In the discrete-time system model, the radio propagation from the base station to the kth receiver is described by the channel matrix $\boldsymbol{H}_k^{BC} \in \mathbb{C}^{M_k \times N}$ whose entry in the ith row and the jth column defines the channel coefficient describing the propagation from the jth antenna at the transmitter to the ith antenna at receiver k. Every channel coefficient subsumes the effects of the pulse shaping filter, the physical channel involving the path loss and fading effects, the analog receiver stage, the up- and downconversion, and the sampling with analog-to-digital conversion. At the kth receiver, circularly symmetric complex Gaussian noise $\boldsymbol{\eta}_k$ is added, which we assume to be zero-mean with covariance matrix $\boldsymbol{C}_{\eta_k} := \mathrm{E}[\boldsymbol{\eta}_k \boldsymbol{\eta}_k^{\mathrm{H}}]$. This perturbation contains both the thermal noise and inter-cell interference from surrounding cells and it is assumed to be independent of all symbol vectors $\boldsymbol{s}_1, \ldots, \boldsymbol{s}_K$. Hence, the received signal at the kth user reads as

$$\boldsymbol{y}_k^{\text{BC}} = \boldsymbol{H}_k^{\text{BC}} \boldsymbol{x} + \boldsymbol{\eta}_k = \boldsymbol{H}_k^{\text{BC}} \sum_{i=1}^{K} \boldsymbol{P}_i \boldsymbol{s}_i + \boldsymbol{\eta}_k \tag{2.4}$$

and this signal is filtered by the $L_k \times M_k$ receive filter $\boldsymbol{B}_k$ to generate the symbol estimate

$$\hat{\boldsymbol{s}}_k^{\text{BC}} = \boldsymbol{B}_k \boldsymbol{y}_k^{\text{BC}} = \boldsymbol{B}_k \boldsymbol{H}_k^{\text{BC}} \boldsymbol{x} + \boldsymbol{B}_k \boldsymbol{\eta}_k \tag{2.5}$$

which is the input of the decoder. As long as the receive filters $\boldsymbol{B}_1, \ldots, \boldsymbol{B}_K$ generate a sufficient statistic and do not destroy any information, they do not have an impact on the mutual information. Note that we implicitly assume perfect coding, i.e., the symbol vectors $\boldsymbol{s}_1, \ldots, \boldsymbol{s}_K$ refer to the *encoded* symbols.

Throughout this book, perfect channel state information (CSI) is assumed to be available at both the transmitter and all receivers. While receiver-side CSI consisting of the *precoded* channel matrices can be obtained with reasonable accuracy by transmitting dedicated and common pilot symbols to the receivers either in a timemultiplexed or superimposed pilot scheme (see for example [4, 5] for the single-user scenario and [6] for the multi-user scenario), the situation is more complicated at the transmitter side. Depending on the coherence time of the channel, accurate transmitter-side CSI may be hard to obtain. In time-division duplex (TDD) systems, the reciprocity of the channel can be exploited to use the uplink channel estimates for the transmitter-side channel state given a proper calibration in signal space, i.e., a proper modeling and estimation of the radio frequency circuitry impulse responses [7]. Outdating due to a time-variant scenario can be overcome by means of a robust precoder design including channel prediction, see for example [8, 9, 10, 11]. Another possibility to obtain CSI at the transmitter which is also applicable in non-TDD systems is feedback from the receivers, e.g. [12, 13]. There, analog or quantized receiver-side CSI is fed back to the transmitter. Although perfect transmitter and receiver-side CSI will never be available, its assumption makes sense for the following two reasons. First, it is necessary to know how the idealized system without any kind of imperfections performs in order to have an upper bound on the realizable performance and in order to be able to evaluate the efficiency of robust algorithms taking into account imperfect CSI. Second, such robust transceiver designs are often based on their idealized counterparts which assume perfect CSI. A degradation of the CSI may for example become manifest in regularized inverses in robust transceivers, see [9, 10] amongst others.

2.2 Dual MIMO Multiple Access Channel System Model

By switching the roles of transmitter and receivers, the dual multiple access channel arises with reversed signal flow. The K decentralized users send their data to the centralized receiver and the same symbol vectors $\boldsymbol{s}_1, \ldots, \boldsymbol{s}_K$ shall be transmitted as in the original BC. But now, the precoder $\boldsymbol{T}_k \in \mathbb{C}^{M_k \times L_k}$ of user k maps the L_k-dimensional symbol vector $\boldsymbol{s}_k$ to his M_k antennas, where the precoded signal $\boldsymbol{T}_k \boldsymbol{s}_k$ propagates over the channel described by the matrix $\boldsymbol{H}_k \in \mathbb{C}^{N \times M_k}$, see Fig. 2.2. In principle, the MAC channel matrices $\boldsymbol{H}_1, \ldots, \boldsymbol{H}_K$ correspond to the Hermitian channel matrices $\boldsymbol{H}_1^{\mathrm{BC,H}}, \ldots, \boldsymbol{H}_K^{\mathrm{BC,H}}$ in the BC, but they are also influenced by the noise covariance matrices $\boldsymbol{C}_{\boldsymbol{\eta}_1}, \ldots, \boldsymbol{C}_{\boldsymbol{\eta}_K}$ as will be seen in Chaps. 3 and 4. For a shorter notation, we omit the superscript $(\cdot)^{\mathrm{MAC}}$ for the MAC channel matrices and the MAC symbol estimates. If all K noise covariance matrices in the BC are scaled identities, i.e., $\boldsymbol{C}_{\boldsymbol{\eta}_k} = \sigma_{\eta_k}^2 \boldsymbol{I}_{M_k}\ \forall k$, the dual MIMO MAC can be seen as a system with reversed signal flow having the same channel transfer function as the original broadcast channel. However, imposing the same upper bound $P_{\mathrm{diss}}^{\mathrm{MAC}} \leq P_{\max}$ as in the BC on the *sum* power

$$P_{\mathrm{diss}}^{\mathrm{MAC}} = \sum_{k=1}^{K} \mathrm{E}\left[\|\boldsymbol{T}_k \boldsymbol{s}_k\|_2^2\right] = \sum_{k=1}^{K} \|\boldsymbol{T}_k\|_{\mathrm{F}}^2 \tag{2.6}$$

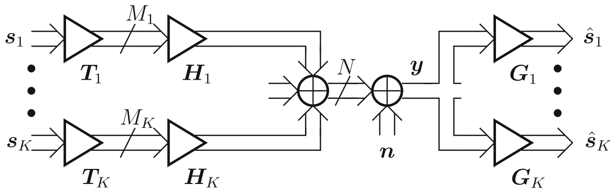

Fig. 2.2 System model for the K user MIMO multiple access channel

dissipated in the MAC distinguishes this dual MIMO MAC from a conventional MIMO MAC where individual power constraints for every user are imposed since cooperation and power sharing between the users is not possible. All precoded symbol vectors are superimposed by the wireless channel and constitute the received signal

$$\boldsymbol{y} = \sum_{k=1}^{K} \boldsymbol{H}_k \boldsymbol{T}_k \boldsymbol{s}_k + \boldsymbol{n} \in \mathbb{C}^N \tag{2.7}$$

where the additive white Gaussian noise $\boldsymbol{n} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_N)$ can be chosen to be zero-mean with identity covariance matrix. By means of the receive filter $\boldsymbol{G}_k \in \mathbb{C}^{L_k \times N}$, the symbol estimate for user k reads as

$$\hat{\boldsymbol{s}}_k = \boldsymbol{G}_k \boldsymbol{y} = \boldsymbol{G}_k \sum_{i=1}^{K} \boldsymbol{H}_i \boldsymbol{T}_i \boldsymbol{s}_i + \boldsymbol{G}_k \boldsymbol{n} \in \mathbb{C}^{L_k} \tag{2.8}$$

which can then be passed to the detector.

Most parts of the analysis and the transceiver designs presented in this book are done in the dual MIMO MAC instead of the original MIMO BC. The equivalence between these two domains is shown in Chaps. 3 and 4. Thus, problem settings in the BC can equivalently be solved in the dual MAC.

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http://www.springer.com/978-3-642-31691-3

Analysis and Transceiver Design for the MIMO Broadcast Channel
Hunger, R.
2013, X, 322 p., Hardcover
ISBN: 978-3-642-31691-3