Emerging Technologies for High-Speed Mobile Communication

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ABSTRACT

Throughput requirements in mobile communication are increasing permanently as they are increasing for wireline links. Besides new approaches for mobile network architecture and protocols there are also significant opportunities in the Physical and MAC layer to increase the throughput. Various strategies are studied using both pre-processing in the transmitter as well as more advanced processing in the receiver. Multi-antenna systems and a multi-user view even on the physical and MAC layer are key approaches to achieve the goals. This paper gives an overview of promising approaches which will be discussed in more detail in the lecture.

1.0 INTRODUCTION

Key requirements for future mobile radio systems are mobility, high quality of service and transfer of high amounts of data with many devices communicating within a small area. To meet these requirements systems have to be smart and broadband but they also must be cost-efficient. Important research areas that are expected to provide technologies for such systems are high-density and multi-hop radio environments, physical layer technologies boosting the performance of the cell rather than of the individual link (and, thus, have strong cross layer aspects), and, as an overarching concept, cognitive radios. This lecture will focus on the physical layer related topics.

To get the required high data rates the links have to be operated near the capacity limit. Since in mobile communication we are facing a time-varying frequency selective fading environment, channel estimation and equalization are significant challenges. An advantage of OFDM is that the individual subcarriers only exhibit flat fading which allows a straightforward equalization in the frequency domain. The capability to flexibly assign different users or data-streams to different subcarriers (OFDMA), adaptive modulation, coding, and power assignment per subcarrier are further advantages of OFDM, in particular, since the subcarrier selective (and, thus, frequency selective) assignment can be matched to the (frequency selective) channel. Therefore, we will use **OFDM/OFDMA** to discuss the various other techniques to optimize the physical layer performance. It should be mentioned, though, that OFDM also has disadvantages, most notably, the high peak-to-average-power-ratio (PAPR).

A key to highest data rates for many users even within a small area is an optimum use of the **space** enabled by multi-antenna systems. In this case we get a transmission path between each transmit and each receive antenna. Such Multiple-Input-Multiple-Output (**MIMO**) systems can be used for spatial multiplexing and for spatial diversity, but multiple antennas can also be used to apply **Beamforming**.

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When talking about channel capacity, a very frequent assumption is that the channel is known to the transmitter and the receiver. In reality, however, the channel is unknown and has to be estimated. Furthermore, in frequency division duplex (FDD) systems the channel estimate is only available in the opposite receiver and has to be fed back via the return link to become known to the transmitter. Thus, two further important areas of research are **channel estimation** and optimized **information feedback**.

2.0 PHYSICAL LAYER TECHNOLOGIES

2.1 OFDM(A) Signal Model:

Consider an OFDM system with N_T transmit and N_R receive antennas. The channel is assumed to have a total impulse response length of N_C taps, so that the channel impulse response at time t is represented by

$$\boldsymbol{C}(k,t)=\sum_{i=0}^{N_C-1}\boldsymbol{C}_i(t)\cdot\delta(k-i), \tag{1}$$

where the $N_R \times N_T$ matrix $\boldsymbol{C}_i$ represents the i-th channel tap.

Assume that the cyclic prefix (CP) is long enough, i.e. at least of length N_C, and that the channel can be assumed to be constant during the transmission of one OFDM symbol. Then, the channel $\boldsymbol{C}(k,t)$ can be described in the frequency domain with the channel transfer function

$$\boldsymbol{H}(n,t)=\frac{1}{\sqrt{N}}\sum_{i=1}^{N_C}\boldsymbol{C}(i,t)\cdot\exp(-j2\pi\frac{n}{N}i), \tag{2}$$

and the vector of received signals can be represented in the frequency domain as

$$\boldsymbol{r}(n,t)=\boldsymbol{H}(n,t)\boldsymbol{s}(n,t)+\boldsymbol{w}(n,t). \tag{3}$$

Here, $\boldsymbol{s}$ denotes the transmitted signal on subcarrier n at time t and $\boldsymbol{w}$ represents the received noise.

If linear precoding is used, the vector of transmitted signals $\boldsymbol{s}$ can be written as

$$\boldsymbol{s}(n,k)=\boldsymbol{P}_{SM}(n,k)\boldsymbol{d}(n,k), \tag{4}$$

where $\boldsymbol{P_{SM}}$ describes the $N_T \times N_S$ precoding matrix that is multiplied with the $N_S \times 1$ vector of transmitted data symbols $\boldsymbol{d}$. This case of a simultaneous transmission of $N_S>1$ data symbols on the same subcarrier is called spatial multiplexing. The case that the vector of transmitted symbols is actually a scalar ($N_S=1$) and therefore, the precoding matrix is a precoding vector $\boldsymbol{p_{BF}}$, is called beamforming:

$$\boldsymbol{s}(n,k)=\boldsymbol{p}_{BF}(n,k)d(n,k) \tag{5}$$

2.2 Transmitter Pre-processing

Techniques that allow transmission on a single link (SISO-Single Input Single Output) with acceptable error rates and a data rate near the link capacity under the assumption that the channel is known are well understood and will therefore not be discussed in detail.

With the ability to transmit with a rate near capacity for SISO links, an optimum use of space is required to achieve higher data rates and/or reliability of transmission. For spatial multiplexing or spatial diversity we need paths between the different transmit and receive antennas which are only weakly correlated (ideally uncorrelated). This requires a rich scattering scenario excluding, in particular, line-of-sight connections. So, it depends on the scenario (the geometry and the position of the scatterers) how much gain via spatial diversity/multiplexing can be achieved.

Actually, the choice of the optimal precoding strategy depends on many parameters: spatial multiplexing performs only well if the SNR is high and the antennas on both the transmitter and receiver side are only weakly correlated [1], [2]. On the other hand, beamforming yields large increases in capacity if the SNR is low. With beamforming, high spatial correlation is beneficial if long-term beamforming is employed [3].

An important trade-off exists in the choice of the number of parallel data streams N_S: The larger the number of data streams N_S (up to the maximum number $N_S = \min(N_T,N_R)$), the higher the data rate but the lower the order of spatial diversity. More diversity improves the received signal strength and, thus, reduces the error rate. A similar trade-off exists in the case of beamforming: On the one hand, if antenna elements are only weakly correlated, beamforming can be used to provide diversity. This can be achieved for example by the use of cyclic delay diversity. However, this technique does not alter the mean SNR of the users. On the other hand, long-term beamforming, which requires correlated antenna elements, increases the mean SNR of the users but does not provide diversity.

Because of the time-varying, frequency-selective fading channel, the received signal strength varies over time and frequency. Depending on the scatterer and user distribution, these variations are more or less independent. In a multi-user scenario this can be utilized by appropriate scheduling and carrier assignment. If users are scheduled for transmission only when their SNR is high, we can trade latency against quality and throughput [4]. The trade-off strongly depends on the channel dynamics (Doppler frequency). Furthermore, we can partition dynamically frequency bands such that we assign each user the band where his receive signal is strongest. This is particularly easy with OFDMA [5].

2.3 Receiver Processing

For optimum detection the channel must be known. In a real receiver the known channel is replaced by an estimate. For channel estimation predefined symbols, also called “pilot symbols”, (which are, thus, known to the receiver) are inserted into the data stream. With OFDM several subcarriers in each OFDM symbol are modulated with such pilot symbols. The temporal density of the pilots depends on the Doppler frequency and the spectral density on the delay spread [6]. Since each pilot symbol only yields a noisy estimate, optimal filtering making use of the spectral and temporal correlation of the channel samples is required to obtain estimates with acceptable estimation error variance. For MIMO systems each channel estimate actually is a $N_R x N_T$ matrix. So, for large delay spread, high Doppler frequency or large number of antennas the required density of pilot symbols significantly reduces the achievable information bit rate.

The required pilot density can be reduced if the data symbols can also be used for channel estimation. However, detection of the data symbols requires channel estimates. A solution is an iterative approach using tentative channel estimates for tentative detection followed by an improvement of the channel estimates using the tentative detection. The estimation step can be implemented by the expectation-maximization method [7] combined with any soft-output detection method. Since the data symbols are now also used for channel estimation, the pilot density can be reduced. An issue is however the convergence, which requires a sufficiently good initial estimate [8]. The required initial estimate quality now determines the required pilot density. Since the iterative estimation requires significant additional receiver processing, reduction of this effort with negligible performance loss is a key research issue.

2.4 Information Feedback

Most transmitter pre-processing schemes assume some or even perfect channel knowledge. In time division duplex (TDD) systems this knowledge may be obtained on the transmitter side (i.e. in the device where the transmitter is located) from the reverse link receiver. In FDD systems this information must be provided by the distant receiver over the reverse link. This leads to a capacity gain in the forward link at the expense of increased transmission requirements on the reverse link, which is a trade-off. A further issue is the delay between actual channel state and availability of knowledge about the channel state at the transmitter. The estimation of the channel requires processing (and averaging) time which represents a delay. The reverse transmission introduces a further delay (and potential quality loss). Thus, the achievable gain depends on the dynamics of the channel. The faster the time variation the more the channel estimates are outdated when they are available at the transmitter. This can only partly be compensated by prediction strategies [9].

3.0 SUMMARY

Pre-processing and scheduling at the transmitter which is matched to the channel state is essential to achieve higher data rates in mobile communication. Multi-antenna systems allow for a better use of the space and, thus, enable higher data rates to multiple users even in a smaller area. However, better receiver processing also contributes to higher data rates both by increasing the transmission efficiency directly and by providing the channel state information required for transmitter pre-processing. Future physical layers have to be “network aware”, i.e. optimization does not only consider the individual link but the intra-cell and, subsequently, the inter-cell traffic.

4.0 REFERENCES

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