PREFACE

Wireless communications is one of the most active areas of research over the past and the current decades. In fact, the demand for wireless services has been changing from the regular voice telephony services to mixed voice, data, and multimedia services over the wireless media. Since the mid-1990s, the wireless industry has been advancing at an incredible speed. For example, the 2G cellular systems (such as GSM, D-AMPS, and IS-95) have significantly improved the spectral efficiency and network capacity to support wireless telephony services. Fueled by the explosion of demands for applications over the fixed-line and broadband Internet access, there is a parallel development in the wireless domains to support high-quality and high-speed data and multimedia services. For example, we have the development of 3G systems (CDMA2000, UMTS), 3.5G systems (HSDPA, EV-DO, EV-DV), B3G systems (Beyond 3G), wireless LAN (IEEE 802.11a/b/g), ultrawideband (UWB) systems, and Wi-MAX (IEEE 802.16) as well as Wi-MAN (IEEE 802.20) systems. These technologies have spurred a lot of research in the signal processing and cross-layer design for wireless communications.

Realizing reliable and efficient communications over the wireless channel has been a very challenging topic for over 50 years. This is attributed to the hostile nature of the wireless channel in the form of rapid time variation, extreme fading, and multipath. For instance, the transmission of signals over the wireless channels is affected by time-varying channel attenuation, called *fading*. The received signal strength can fluctuate over a wide range of 80 dB in the order of milliseconds. On one occasion, the transmission may experience good fading and the transmission error probability will be low. On the other hand, the transmission may experience bad fading on other occasions and the error probability will be high. Hence, in general, the fading effects of wireless channels impose additional challenges for signal transmissions besides the regular channel noise. Two very promising more recent approaches address the challenging problems of wireless transmissions: the *multiple-antenna technologies* and the *cross-layer transmitter adaptation designs*. In addition, these two techniques can be combined to achieve significant performance advantages. In the subsequent chapters, we shall follow a bottom–up

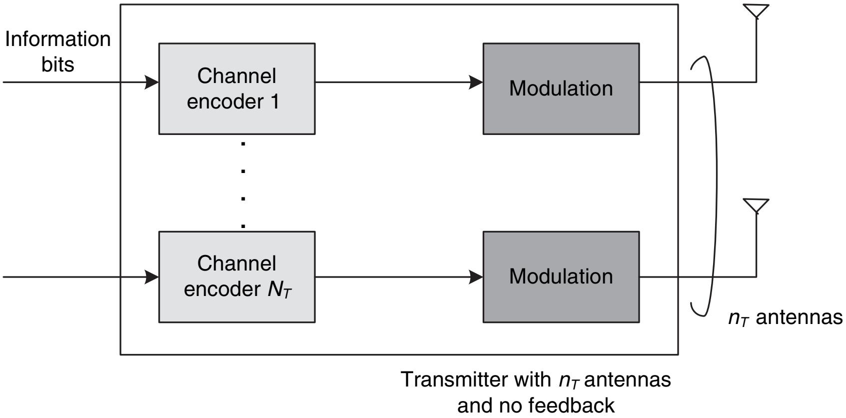

Figure P.1. Architecture of multiantenna transmitter without feedback.

approach to elaborate on the adaptive physical layer design and adaptive MAC layer design as well as adaptive routing layer design combined with multiple antenna technologies.

Multiple-Antenna Technologies

In point-to-point wireless links, the primary design objective is to increase the data rate, and a promising way to do so (without increasing the bandwidth and power budget) is through multiple-antenna technologies. Specifically, the transmitter is equipped with n_T transmit antennas and the receiver is equipped with n_R receive antennas as illustrated in Figure P.1. The antennas are assumed to be sufficiently separated so that they are spatially uncorrelated.

The advantage of having multiple antennas at the transmitter and the receiver is to transform the original wireless fading channels into *multiple-input multiple-output* (MIMO) wireless fading channels. It has been shown [126] that the link capacity can be increased by $m = \min(n_T, n_R)$ times relative to single-antenna wireless links. This is because there are $m$spatial channels created as a result of the multiple antennas and the scattering environment surrounding the transmitter and the receiver. Hence, independent information streams can be delivered on the$m$parallel spatial channels to realize the increased transmission bit rate; this is called *spatial multiplexing*. On the other hand, one can deliver the same information bits over multiple spatial channels to exploit the *spatial diversity* so as to enhance the reliability of the transmission. These important concepts of spatial diversity and spatial multiplexing have been employed in the framework of *spacetime coding* design. We will discuss the advantage of multiple antennas and spacetime coding design in Chapters 2–5.

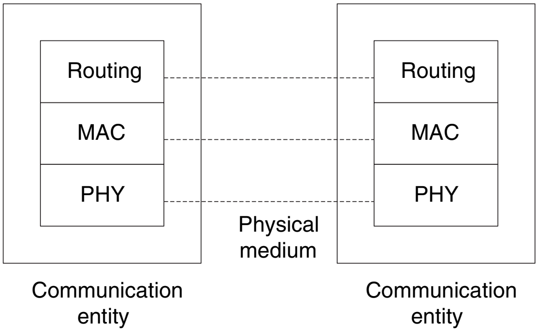

Figure P.2. Layered architecture of communication systems.

Cross-Layer Adaptive Transmission

Atypical communication system can be conveniently modeled by a layered approach (physical layer, MAC layer, routing layer) where each layer has a specific role and performance measure (as illustrated in Figure P.2). For example, the *physical layer* is responsible for the reliable and efficient delivery of information bits. The *MAC layer* is responsible for the resource management among multiple users in the system. The *routing layer* is responsible for the delivery of packets to the destination.

The traditional approach of communication system design is based on an isolated procedure while optimization is isolated within layers. In other words, there is no cross-optimization between layers. This isolated approach is reasonable for fixed-line network because the fixed-line channel is essentially time invariant. However, such an isolated approach usually results in a suboptimal design for wireless systems because the wireless channel is a time-varying channel. Hence, adaptation techniques are needed at various layers to enhance the wireless communication system design to exploit the time-varying nature of the channel. In other words, a jointly adaptive design or a *cross-layer design* is needed. The roles and challenges of the physical layer, MAC layer, and the routing layer are elaborated below.

Physical Layer. The role of the physical layer is to deliver information bits across a wireless channel in an efficient and reliable manner given a limited resource. *Resource* in this context refers to the bandwidth and transmit power; *performance* refers to the bit rate (bits per second) and the frame error rate. Information bits (source) are first protected by adding redundancy in the "channel encoder" so that error recovery is possible at the receiver. Following channel encoding is the modulation process where coded bits are mapped into physical channel symbols. Two research directions are followed to tackle the physical layer design: the information-theoretic approach and the practical coding design approach. For information-theoretic design, Shannon's coding theory has shown that error-free transmission is possible when the bit rate is less than the channel capacity. In other words, the Shannon's capacity represents the best data rate achievable given a particular channel model. Unfortunately, the information-theoretic approach does not reveal how to achieve the channel capacity.

On the other hand, the coding design approach focuses on finding practical encoding and decoding algorithms that could approach the Shannon capacity. The design objective is to increase the bit rate at a given target frame error rate with fixed bandwidth and power budget.

Various approaches have been investigated to improve the performance of the physical layer. One promising approach is to utilize channel feedback information at the transmitter. We call it the "channel—adaptive approach." Another promising approach is to utilize multiple antennas at the transmitter and the receiver. We call this the "MIMO approach" (multiple-input multiple-output). Depending on the level of feedback information available at the transmitter, we have different transmission strategies for the MIMO systems. For FDD systems with perfect feedback of channel state information (CSI), channel adaptation can be done at the transmitter as illustrated in Figure P.3. This will introduce significant capacity gain on top of the linear capacity gain of open-loop MIMO systems.

With the availability of perfect channel state information (channel matrix), power adaptation (in both the temporal and spatial domains) and rate adap-

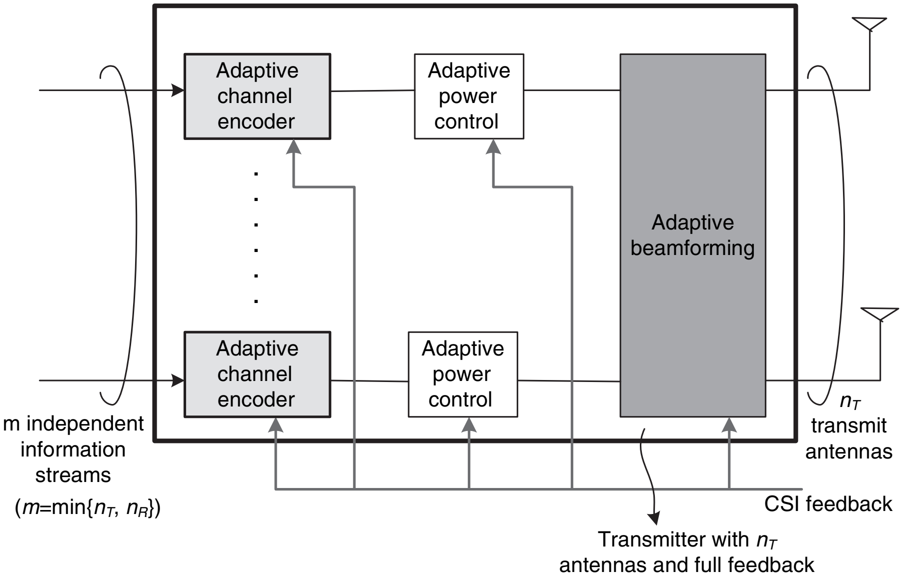

Figure P.3. Architecture of MIMO transmitter with feedback of channel state.

tation can be performed at the MIMO transmitter. In fact, the adaptation across the spatial domain contributes to significant performance gains over open-loop performance and therefore has received tremendous attention in the research community more recently.

MAC Layer. In a wireless system with a centralized access point (base station) and multiple mobile users, the physical layer design is just part of the big picture because it focuses on the point-to-point link performance only. On the other hand, the MAC layer is a very crucial component in multiuser communication systems because it is responsible for resource allocation (scheduling) among multiple competing users.

A MAC layer usually consists of a request collection sublayer and a scheduling sublayer as illustrated in Figure P.4. The request collection sublayer is responsible for the collection of payload transmission requests from the active users. On the other hand, the scheduling sublayer is responsible for the prioritization and the allocation of resource among the competing users.

Conventional MAC layer designs for wireless systems follow the isolated approach where there is no cross-optimization across the physical layer and the MAC layer. For instance, a lot of research effort has been devoted to designing efficient request collection sublayer. Examples are slotted ALOHA, dynamic TDMA, and PRMA. The scheduling sublayer is essentially very simple in the sense that the “first come–first serve” scheduling is done. The focus is to integrate realtime (voice, video) and background (email) sources nicely into the MAC layer.

More recently, because of the wide acceptance of adaptive physical layer, plenty of research effort has been devoted to considering a jointly adaptive

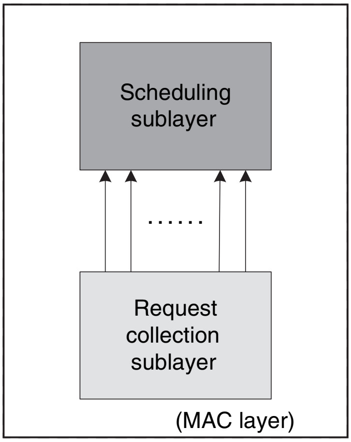

Figure P.4. Architecture of MAC layer with channel state feedback.

physical and MAC layer design, with focus on improving system performance by taking advantage of the time-varying throughput delivered by the adaptive physical layer.

We characterize "system performance" as a utility function of the throughputs achieved by all the active users. Depending on the forms of the utility function, we can have different emphasis on system performance. For example, we may focus on system capacity (where the utility function is the sum of average user throughput) for better resource utilization. We may also wish to strike a compromise between resource utilization and fairness among users, and we may set the utility function to be "proportionally fair." In any case, priority should be given to users with good channel conditions because such users could utilize the limited radio resource more effectively (enjoying a highly throughput due to the adaptive physical layer). Therefore, we could always find "good users" at any time to transmit at high-throughput modes, and as a result, the overall multiuser system capacity is greatly enhanced. This is called *multiuser selection diversity*.

Routing Layer. Ad hoc network is important for mobile devices due to its robustness with respect to hostile propagation environment. While traditional table-based or on-demand routing protocols can be used, it is much more efficient to use a routing protocol that is channel-adaptive—judiciously selecting links that can transmit at higher data rates to form a route. Devising channel-adaptive routing protocols is a very hot field. We shall provide a detailed survey of existing techniques. We also describe a reactive ad hoc routing algorithm, called *RICA* (receiver-initiated channel-adaptive) protocol, to intelligently utilize the multirate services (based on different modulation schemes). NS-2 simulation results show that the RICA protocol is highly effective.

In conclusion, channel adaptation technologies can benefit all the three layers described above. However, one fundamental requirement for channel adaptation is the knowledge of channel state information (CSI) at the transmitter. In frequency-division duplexing (FDD) systems, the CSI is estimated at the receiver and fed back to the transmitter. In time-division duplexing (TDD) systems, the CSI of the downlink can be estimated on the basis of the uplink pilots. In either case, obtaining perfect knowledge of CSI at the transmitter is not feasible, and in practice, there is always some imperfection associated with the CSI knowledge at the transmitter. For example, in FDD systems, the feedback link usually has a limited capacity and this results in *limited feedback*. In TDD systems, the uplink pilot power transmitted by the mobiles is usually limited and therefore the CSI estimation noise at the base station side is not negligible. This situation is aggregated by the presence of multiple antennas because the CSI becomes a matrix of $n_R \times n_T$ dimensions. Hence, a significant portion of the book is devoted to addressing this practical concern—channel adaptation and cross layer design in the presence of imperfect CSI.

Audience

This is a graduate-level book intended for readers who are graduate-level research students and would like to know more about the theory and practice of channel-adaptive wireless communication technologies. This book assumes that the reader has a solid background in basic communication theory and information theory as well as queueing theory.

Organization of the Book

This book is organized into three parts. In Part 1, we shall focus on the theoretical aspects of channel adaptation in wireless communications for point-to-point and multiuser systems with multiple antennas. In Part 2, we shall focus on the applications of the channel-adaptive technologies in practical systems such asUMTS. In Part 3, we shall focus on some advanced topics such as multiuser scheduling for wideband systems, combined queueing theory, and information theory as well as ad hoc routing.

Part 1. Chapter 1 discusses the basic and fundamental theories behind SISO/MIMO communications. It addresses the channel capacity as well as spacetime code design for SISO/MIMO physical layer. Readers with a strong background in communication theory and information theory can skip Chapter 1. Chapter 2 discusses the optimal transmission adaptation strategy and feedback strategy for a point-to-point multiantenna communication link with perfect CSI knowledge based on the information-theoretic approach. The notion of ergodic capacity and outage capacity will be elaborated and the design insights from the results will be discussed. Chapter 3 extends the discussion in Chapter 2 to consider the optimal transmission and feedback strategies in the presence of imperfect CSI.

Chapter 4 gives the practical design considerations of adaptive physical layers based on the theories developed in Chapter 2. Specifically, we shall elaborate on spacetime coding and decoding techniques that could achieve spatial diversity and spatial multiplexing, respectively. The optimal MIMO transmitter and receiver architectures in fast fading and slow fading channels will be discussed. The fundamental tradeoff between *spatial diversity* and *spatial multiplexing* is elaborated. Finally, the design of adaptation thresholds, modulation levels, and encoding rates in a MIMO link is discussed.

Chapter 5 extends the discussions in Chapter 4 to consider the case with imperfect CSI. Specifically, we shall focus on the constellation and coding design for MIMO link with imperfect CSIR.

Chapter 6 addresses the optimal adaptive MIMO multiuser scheduling design. This is an extension of Chapters 2 and 3 (which address the adaptive MIMO link) to a multiuser scenario. Specifically, we shall focus on the capacity and coverage performance gains as a result of cross-layer adaptation. Cross-layer scheduling is formulated as an optimization problem, and the optimal and heuristic scheduling algorithms will be introduced. One commonly employed heuristic algorithm—the "greedy"-based algorithm—was shown to be optimal for single-antenna systems but suboptimal for multiple antenna systems. This motivates the genetic-based scheduling algorithm, which achieves near-optimal performance at significant computational savings. Finally, we consider the cross-layer design and system performance in the presence of imperfect CSI.

Part 2. Chapter 7 provides a high level review of MAC layer design for contemporary wireless systems with design examples for TDMA-based and CDMA-based systems. Chapter 8 contains overviews of various practical fairness notions and scheduling algorithms. Chapter 9 gives a detailed description of how cross-layer scheduling is applied in UMTS (W-CDMA) systems for packet-switched data users.

Part 3. Chapter 10 discusses an advanced topic of cross-layer adaptive scheduling design for wideband systems. Both DS-CDMA and OFDM are promising physical layer technologies for dealing with wideband multipath channels. We shall compare and contrast the multiuser performance of the cross-layer designs based on DS-CDMA and OFDMA systems. Chapter 11 gives the advanced application of information theory and queueing theory for the cross layer design. The concepts of stability region, throughput optimal scheduler as well as delay optimal scheduler will be discussed. Finally, Chapter 12 provides a detailed account of the design of a channel-adaptive ad hoc routing algorithm.

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