Layered Adaptive Modulation and Coding For 4G Wireless Networks

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Emerging 4G standards, such as WiMAX and LTE have adopted the proven technique of Adaptive Modulation and Coding (AMC) to dynamically react to channel fluctuations while maintaining bit-error rate targets of the transmission. This scheme makes use of the estimated channel state indication (CSI) to efficiently utilize channel capacity for next transmission, but it brings with it the stale CSI problem due to the frequently channel fluctuations. As its objective, this thesis focuses on mitigating the vicious effect of stale CSI by proposing a novel framework that incorporate AMC with layered transmission through Superposition Coding (SPC) is introduced. A layered multi-step finite-state Markov chain model (FSMC) is developed under this framework, to effectively assist the system in selecting the optimal modulation and coding scheme as well as the power allocated for each layer in every multi-resolution unicast transmission. Extensive simulations are conducted to verify the proposed framework and compare its performance with other counterparts. The effects of changing key parameters, such as the complexity factor and step size, are also investigated to get close to real world performance. Results demonstrate that the proposed framework can achieve better spectrum efficiency than similar counterparts, due to its improved robustness to the stale CSI problem for each multi-resolution modulated transmission, also these show that the performance of two-layer scheme is good enough for layer allocation, without need of more layers.

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Chapter 1

Introduction

Wireless radio communication is frequently perturbed by multipath or shadow fading effects. One way of dealing with the varying channel quality is by employing Adaptive Modulation and Coding (AMC) [1] [2] [3] [4] [5], which is a key technology to dynamically react to the channel fluctuation of fading channels. The essence of the scheme is that, with available channel state information (CSI) estimation at the transmitter, link adaptation is enabled by AMC for effective utilization of the available channel capacity for subsequent transmissions while provisioning targeted bit-error rate (BER) at the receiver in combating wireless channel fluctuations. In this way, more appropriate modulation and coding scheme can be used to improve network performance. By adjusting the transmission parameters to the momentary link quality, adaptive mechanisms can improve both spectral efficiency and link reliability. Both the concept of AMC and its implementation have been widely recognized and employed in the latest 3G cellular networks [2] [6] as well as emerging 4G wireless standards, such as WiMAX [7] and Long-Term Evolution (LTE) [8].

However, the implementation of AMC brings a challenge. In order to select the appropriate modulation and coding scheme, the scheduler must be aware of the channel quality. In the practical implementation of the AMC scheme, the CSI will have to be estimated at the receiver and then fed back to the transmitter. Uncertainty about obtain accurate CSI is one of key constrains in AMC systems. Errors in the channel estimate lead to the selection of an inaccurate coding rate. Transmitting at quite low coding rate wastes system capacity, but transmitting at a high coding rate raises the block error rate. Many AMC systems assume that transmitters have perfect knowledge of the channel or that the CSI is accurate but outdated. This thesis makes the same assumption.

1.1 Addressing stale CSI channel problem

CSI estimation is often achieved based on a set of training sequences, where a commonly known signal is transmitted to the receiver for channel matrix estimation based on the received signal within a short time frame [9]. In [10], it was shown that long training sequences enable much-improved CSI estimation at the expense lowered channel capacity, resulting from higher resource occupation that could otherwise be used to transmit actual data [11]. Such effects were detailed in [12], where an algebraic relationship between the number of training images and the corresponding information decay was derived for image transmission. However, the CSI obtained from longer training sequences are still outdated, as it is based on the average of several previous samples in time. As a result, such feedback information to the transmitter is still inaccurate.

In the conventional implementation of AMC, the transmitter employs the CSI mentioned above for optimizing the transmissions in the current data frame. The basis of the implementation using AMC is that the channels of consecutive frames are rather stable such that a precise estimation of the channel condition can be obtained to make a right selection of modulation and coding scheme for each transmission. However, if the channel is in fast fluctuation and/or the channel estimation is subject to constant imprecision, the obtained CSI could be frequently overestimated or underestimated in the transmission of the current frame, which is called stale CSI problem. In this situation, the transmitter will not choose the proper modulation and coding scheme. If the channel's status is underestimated, it may result in underestimated modulation and coding scheme transmission whereas higher rate scheme should be selected, which leads to the waste of channel capacity and a decrease in spectrum efficiency. Conversely, if the channels status is overestimated, it may result in the unqualified BER at the receiver and even in the dropping or retransmission of current packet. Thus, the performance will decrease significantly, and higher spectrum efficiency cannot be achieved.

1.2 Related Research

Precisely estimating the channel status such that the accuracy can be matched with the following real channel status, is one of the key ways to solve the stale CSI problem and improve network throughput. In this way, the transmitter/receiver can make full use of the network capacity and choose the optimal modulation and coding scheme to maximize the coding rate under the requirement of quality of service (QoS). A lot of work has been done on improving prediction accuracy to deal with the fading channel fluctuations characteristic.

1.2.1 Finite State Markov Chain Model

Previously, communication performance has been evaluated for the nonstationary fading channel with perfect interleaving, and characterized in terms of long-term parameters such as the average bit-error rate (BER). However, interleaving introduces complexity and delay; perfect interleaving is not possible in any practical system. The Finite State Markov chain model (FSMC) [13] [14] [15] [16] [17] [18] [19] [20]is effective and has been proved to be more accurately predict transitions in the receiver's time-varying channels. The model focuses on overall system design and is very useful in wireless communication. Based on the previous channel fading characteristic, through properly selection of FSMC channel parameters, such as state definition, model step size or update frequency of FSMC model, it is believed that better network throughout can be obtained with the FSMC model prediction.

The task of mitigating the impact of stale and imprecise CSI has been widely studied. However, these studies focus on the utilization of the FSMC model in non-layer data transmission. None of them has considered using multi-layer prediction in each state of the FSMC model. In [13] [14], with each state representing the current selected modulation and coding scheme, the first-order FSMC models were used to predict channel status, even in [15], the available transitions were restricted to the change of adjacent channel states, they had been reported as a good approach in the receiver's time-varying channel. In [15] [16] from a mutual information theoretic criterion, it was demonstrated that using first-order FSMC to model the envelope of a Rayleigh channel had good performance both for slow fading (successive samples were very correlated) and for fast fading (successive samples were almost independent). When FSMC model was used for ARQ Application, it was sufficient in representing fading channel characteristic shown in [19]; When the FSMC model was developed to incorporate AMC under opportunistic scheduling in [17], it was concluded that the channel estimation generally underutilizes the channel due to stale CSI.

1.2.2 Superposition coding

The physical layer technique of Superposition Coded (SPC) modulation/demodulation has been proven in the information theory community. However, unlike previous studies that focus mainly on physical layer issues, this study applies SPC to MAC layer to take advantage of the coding scheme. It shows superposition coding as an effective strategy to utilize the channel in a layered broadcast manner for sending multiple messages to different receivers within a single broadcast radio signal. When designing the broadcast scheme in mobile wireless video communication, the multi-resolution nature of SPC signals has been exploited for the use of transmitting scalable video streams, which themselves are multi-resolution encoded, and the scalable video streams are encoded into multiple quality

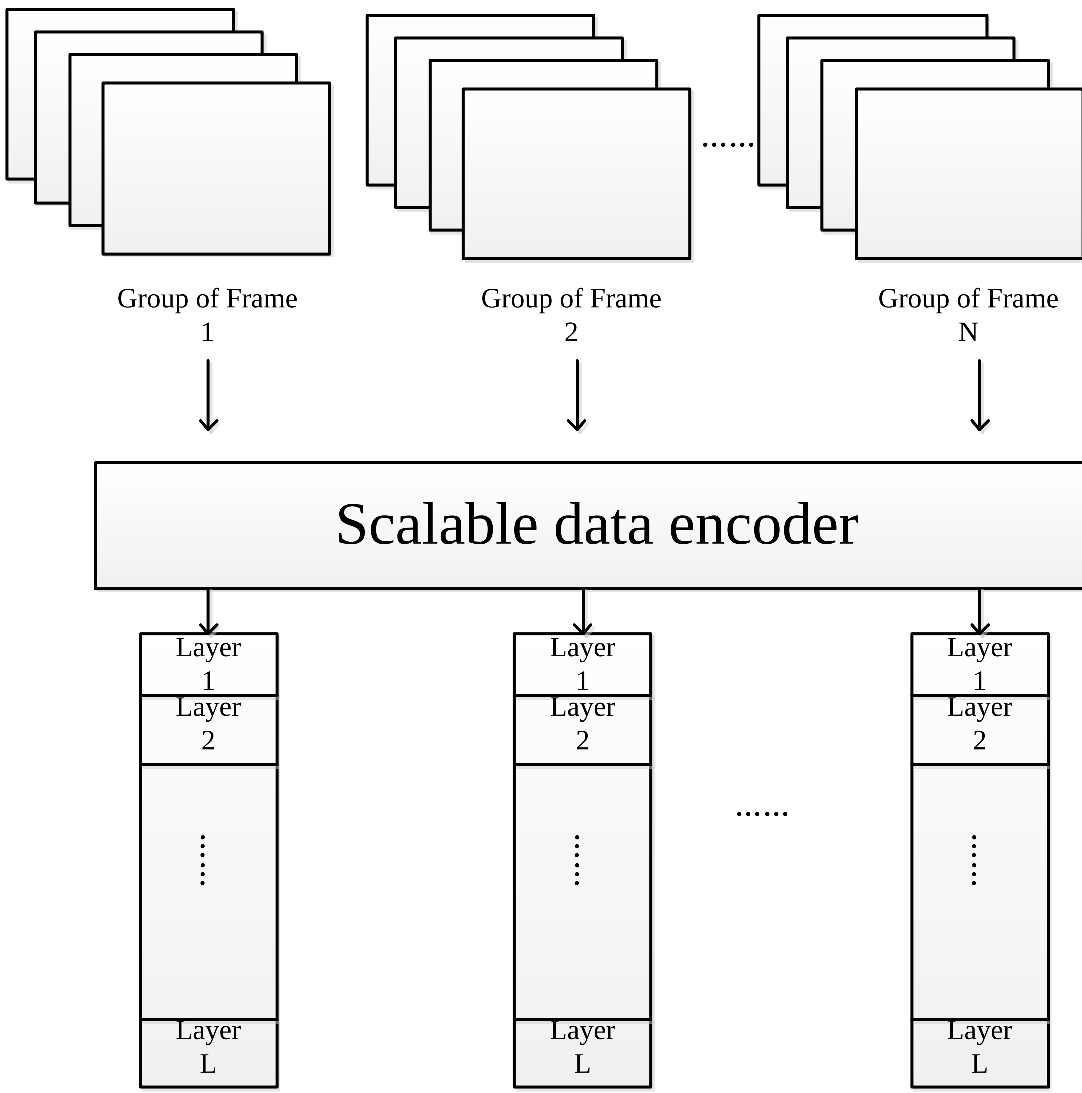

Figure 1.1: Scalable bit streams with L quality layers.

layers. The SPC scheme has great capacity in reducing the vicious effect of multi-user diversity. An overall performance increase can be obtained because the lower rate data can be received successfully even in the bad channel condition.

Multi-layered communication is discussed in [21] [22] [23] for the simultaneous transmission of multiple layers of data to the same user. The studies in [21] [22] superimpose multiple video quality layers of a common group of frames in a single transmission, aiming to achieve better robustness to the short-term channel fluctuation. However, these two papers do not consider utilization of the dynamically obtained CSI available in state-of-the-art communication systems to improve the channel spectrum efficiency. In [23], multi-layered modulation is adopted such that the lower layer of a signal is dedicated to data traffic while the higher layer is used to transfer voice traffic. The amount of voice traffic that can be supported in each transmission is opportunistically based on the receiver estimated CSI. While the scheme in [23] can achieve higher efficiency in utilizing the available channel capacity, its advantage is limited to a receiver requiring different applications simultaneously, which lacks generality for practical wireless networks.

Figure 1.1 shows the general structure of scalable bit streams. A group of frames is encoded into scalable bit streams with L quality layers as shown. The bit stream is strategically split into bit stream segments according to the boundaries of each quality layer. Usually in this scheme, the encoded bit streams for low performing channels are embedded as subsets of bit streams for high ones, which enable the same content supporting heterogeneous conditions of user-side channel communication. The proposed framework in this thesis generically exploits the multi-layer property of any advanced coding, which generates scalable bit streams with multiple quality layers.

1.2.3 Thesis Motivation and Contribution

Although using a channel prediction model may improve the precision of CSI estimation, it is not able to completely solve the CSI imprecision problem. The capability of using multi-layered signals has been witnessed in mitigating the vicious effect of multi-user diversity [6] [10] [20]. Furthermore, it could be an effective solution to further mitigate the vicious effect of stale and imprecise CSI by launching multi-layered signals via SPC modulation.

Combining these two schemes allows superimposed layered data to be transmitted on the channel which is under the predication of the FSMC channel model. If the channel is underestimated, both the lower-rate and higher-rate data of an SPC transmission can be decoded and obtained. However if the channel CSI is overestimated, the lower-rate portion of an SPC transmission may still be secured instead of being completely lost. In this sense, the whole system throughput can be enlarged. Figure 1.2 shows the software process required for interactions between architectural layers at the transmitter and receiver. The

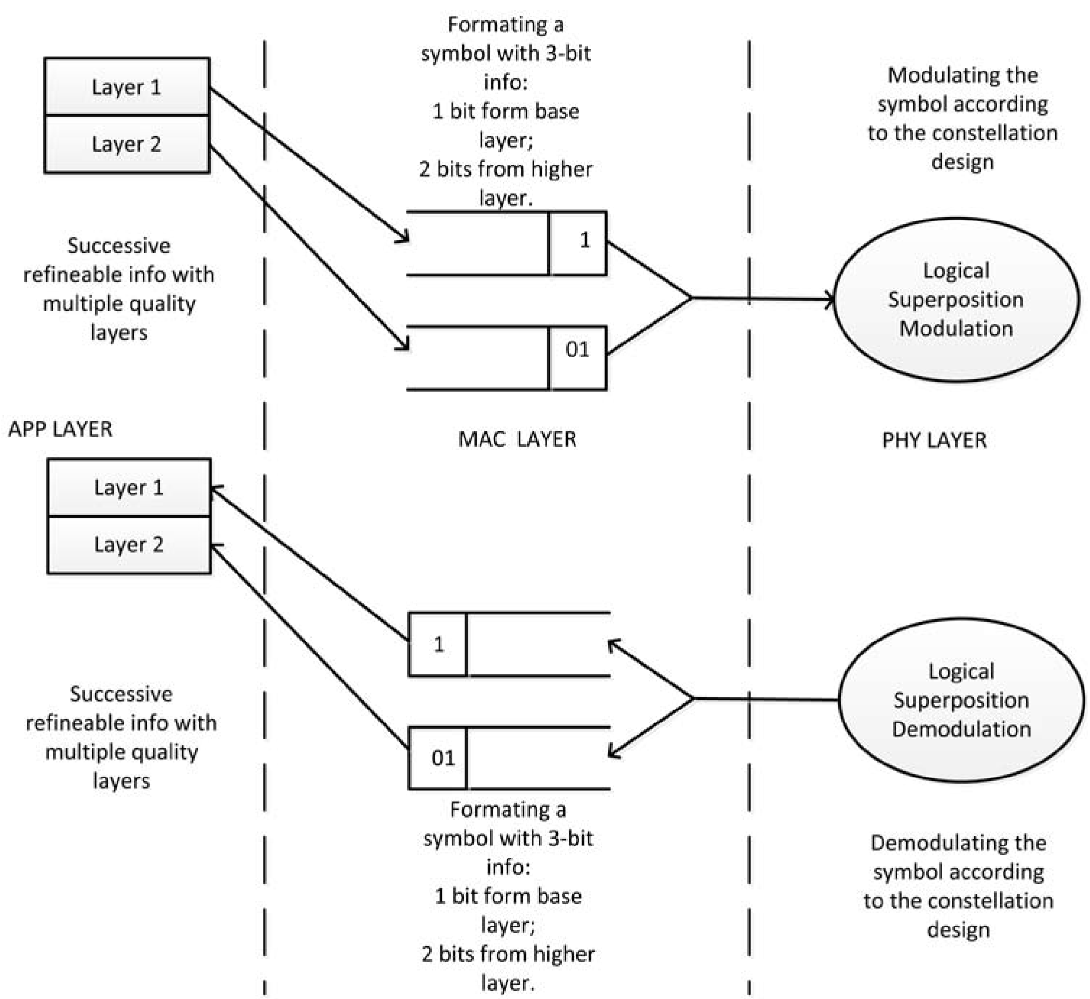

Figure 1.2: Software process required for interactions between architectural layers at the transmitter.

implementation of SPC at the transmitter and receiver requires a new software module in the existing MAC layer. The new module obtains the knowledge of information bits dependency between the multi quality layers from the scalable data. At the transmitter, data from different layers are buffered in the corresponding queues. The modified MAC software interacts with the modulation chipset in the PHY layer through a set of primitives to execute modulation and generate logical SPC signals. At the receiver, the reverse process is performed to demodulate the SPC signal. Data is buffered into corresponding queues at each layer after demodulation at the MAC layer.

Motivated by the above observations, we address the following issues in this thesis: 1) For unicast transmissions independent of traffic type constraints, a new framework is proposed that incorporates AMC and layered transmissions through SPC, to tackle poor performance caused by stale CSI problem; 2) An efficient, layered, multi-step FSMC model using CSI that fits into the mentioned framework is proposed, and allocates better modulation and coding schemes across layers in such proposed framework, as far as we know, this is the first attempt where a such model is used to achieve proper adaptive selection of modulation and coding schemes for layered unicast transmissions; 3) Initial model parameters such as model step size and model complexity factor are examined to get close to real world performance. Meanwhile optimal search strategy for power and coding schemes is also proposed in the thesis to efficiently maximize the overall network throughput.

The thesis is organized as follows:

In chapter 2, the required background on the fading channel models and SPC schemes are provided. For fading channel models, the classification and the procedure to set up the FSMC channel model is shown. The encoder/decoder scheme design scheme for superposition coding is also shown.

In chapter 3, the details of proposed framework are provided. It shows the procedure to incorporate AMC and layered transmission through SPC together. The layered multi-step FSMC model is discussed as one of the new key technology in the proposed framework.

In chapter 4, an analytical formulation for performance evaluation of the proposed framework is presented. The network spectrum efficiency is chosen as the measure of performance for the proposed scheme. The key parameters, such as step size and complexity factor are defined. The values of the parameters will be discussed in chapter 5.

In chapter 5, simulation results are given. Performance evaluation based on the simulation results is conducted for the proposed scheme. The spectrum efficiency is compared with another other two schemes: non-layer AMC with and without FSMC model estimation. Performance measurement are obtained in terms of BER target, fading parameter, step size and system complexity factor. A search strategy is also proposed to achieve the optimal power and coding scheme efficiently.

In chapter 6, conclusive remarks and a summary of the contributions of research efforts are provided. Certain directions for future work required to realize the scheme is also given.

Chapter 2

Background

Having estimates of future fading coefficients enhances the performance of many tasks, which includes AMC channel process at the transmitter and receiver. In this thesis for simplicity, zero delay and no error in the feedback path transmission is assumed. To tackle the stale CSI problem, precise channel prediction models and modulation/coding scheme selection needs to be studied.

The chapter provides the background required for the proposed scheme. Channel models and their fading characteristics, FSMC models and the procedure to set up are first presented. Next a multi-layer Scheme focusing on the allocation of layers and describing the SPC scheme operation as well as layer symbols representation is shown.

2.1 Fading channel and AMC

2.1.1 Fading channel model

Due to the constructive and destructive combination of randomly delayed, reflected, scattered, and diffracted signal components, radio-wave propagation through wireless channels is affected by various effects which makes the fading characteristic complex. Multipath effect is an example of a kind of relatively fast fading that is responsible for the short-term signal variations. To describe the statistical behavior of the multipath fading envelope, considerable efforts have been devoted and mathematical models are developed, depending on the nature of the radio propagation environment.

A great number of distributions models exist that well describe the statistics of the mobile radio signal. One of the fading models is Rayleigh distribution fading model. In this case the channel fading amplitude is distributed according to

$$P_{\gamma}(\gamma) = \frac{2\gamma}{\Omega}\mathrm{e}^{(-\frac{\gamma^2}{\Omega})}, \Omega = E(\gamma^2), \tag{2.1}$$

This model typically agrees very well with experimental data for mobile systems, where no line of insight (LOS) path exists between the transmitter and receiver antennas. It also applies to the propagation of reflected and refracted paths through the troposphere and ionosphere and to ship-to-ship radio links. Another model the Rician fading model occurs when one of the paths, typically the LOS, is much stronger than the others. In Rician fading, the amplitude gain is characterized by a Rician distribution [24] [25] [26] [27].

Among all these models, the Nakagami distribution has been given a special attention for its ease of manipulation and wide range of applicability. Moreover, The Nakagami fading model has been found to be in good fitting because it closely matches empirical results for short wave propagation. It has been shown that the Nakagami distribution often gives the best fit to large land mobile [24] - [26] and indoor-mobile [25] [27] multipath propagation, as well as scintillating ionospheric radio links [28] [29] [30] [31]. The generic Nakagami distribution is chosen to model the fading characteristic of the channel in this thesis. The probability distribution function (PDF) of Nakagami-m distribution is given in Eq. (2.2).

$$P_{\gamma}(\gamma) = (\frac{m}{\overline{\gamma}})^m \frac{\gamma^{m-1}}{\Gamma(m)}\mathrm{e}^{-\frac{m}{\overline{\gamma}}\gamma}, \tag{2.2}$$

where $m \in [0.5, \infty)$ is the Nakagami fading parameter, $\overline{\gamma}$ is the average SNR per symbol, and $\Gamma(m)$ is the gamma function defined by Eq. (2.3).

$$\Gamma(m) = \int_0^{\infty} x^{m-1}\mathrm{e}^{-x}dx, \tag{2.3}$$

As a special case, when $m = 1$ the model becomes the Rayleigh distribution with an exponentially distributed instantaneous power. Motions between receiver and transmitter cause Doppler shift in the received signal components. Thus, channel fading effect depends on the speed of the antennas.

2.1.2 FSMC Representation

Fading channel characteristics can be well approximated by FSMC model to represent the time-varying behavior of the channel. FSMC model parameters are determined according to the fading distribution mentioned in section 2.1.1. The simplest FSMC model is known as the Gilbert-Elliott two-state channel, where each state in the model corresponds to a specific channel quality which is either noiseless or totally noisy. The transition probability of each channel is 0.5. It is easy to find that the two-state models does not reasonable accurately represent the variable channel quality, the extension of the two state models that is the FSMC model is proposed in [13] - [20].

To represent the FSMC mode, received SNR values are partitioned into a finite number of states according to a criterion based on the average duration of each state. Let $S = S_0, S_1, S_2, \ldots, S_n$ denote a finite set of channel states. The channel allocation is modeled by a Markov process defined as $S_n, n = 0, 1, 2, \ldots$. The states represent discrete, non-overlapping intervals of the received signal envelope, the finite Markov process has the property of stationary state transitions, and the transition probability is independent of the time index. At time t, if current channel SNR is in between γ_k and γ_{k+1}, the FSMC model is said to be in state S_k for this transmission slot. After one or several packet transmission periods time T_p, if the channel SNR value changes into the range $[\gamma_j, \gamma_{j+1})$, the FSMC model is said to change to channel state S_j. Figure 2.1 illustrates the FSMC channel state partitioning.

The FSMC model has been applied to design adaptive error control schemes and improve network performance for wireless video transmission systems. The time-varying fading channel can be estimated from observations of the impulse response of the channel. On the feedback path observations on channel impulse response are received from CSI. Based on this AMC scheme dynamically chooses optimal Modulation and Coding Scheme to make full use of network capacity in the subsequent frames. In the scheme, the channel state information is fed back to transmitter through feedback path. By incorporating AMC scheme and FSMC model prediction, systems' performance enhance compared to systems that do not utilize AMC schemes and FSMC predication.

2.2 Layered scheme and SPC

2.2.1 Definition

As physical layer technique, SPC scheme has been proven in the information theory community. Now it has been used in wireless broadcast communication, where the channel is commonly utilized to different receivers within a single broadcast radio signal. The SPC symbol contains multi-layer resolution modulated symbol, enabling a receiver to decode its own, as well as its peers' information if its channel condition is sufficient for the higher resolution. This multi-resolution nature of SPC signals has been exploited for the use in transmitting scalable video which is multi-resolution encoded through hardware based or logical based SPC operation.

To implement the proposed SPC modulation for video multicast, strategic mapping of the $log_2 m_1$ bits from the base layer and $log_2 m_2$ bits from the enhancement layer are

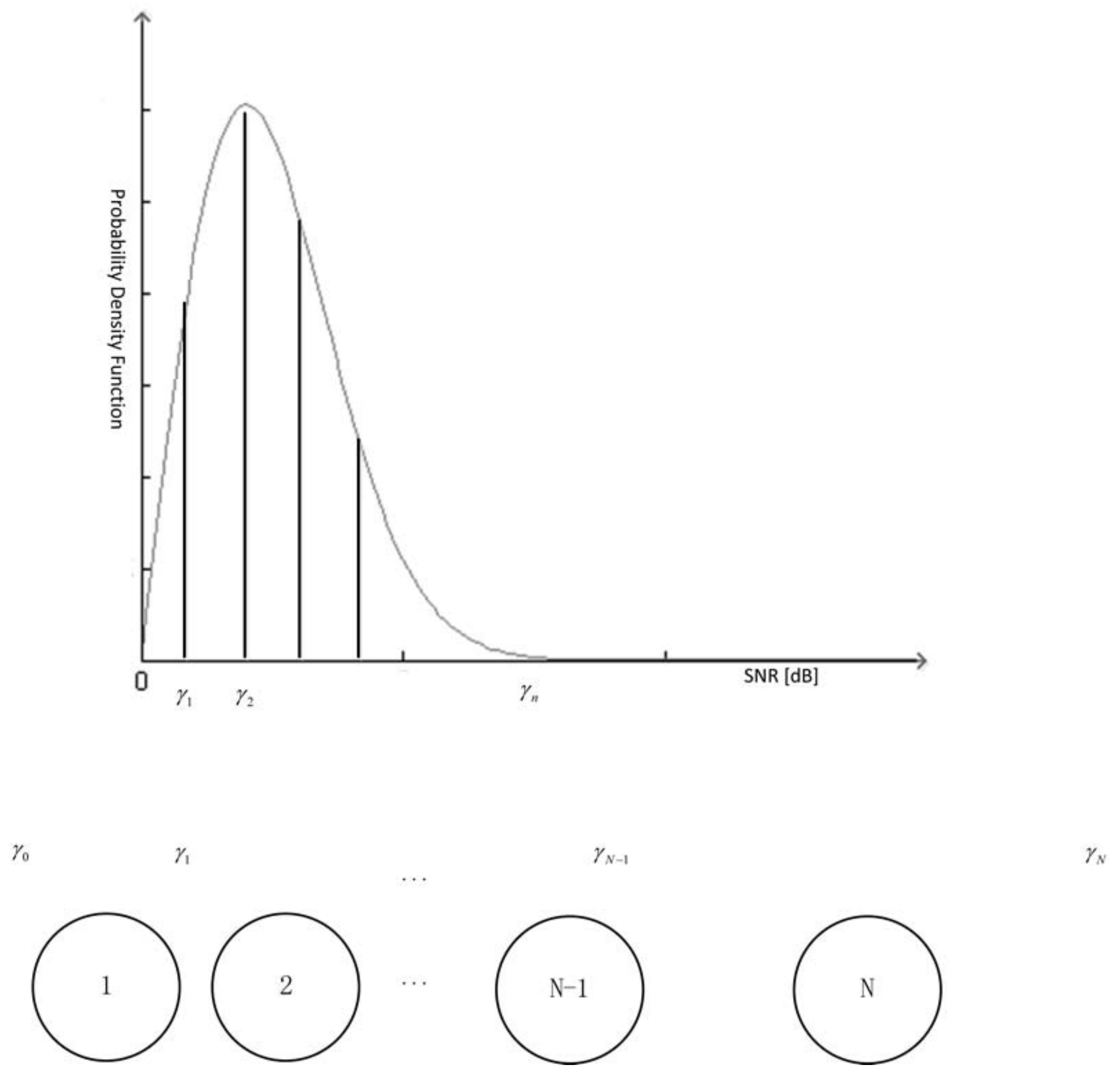

Figure 2.1: illustration of finite state Markov model partitioning.

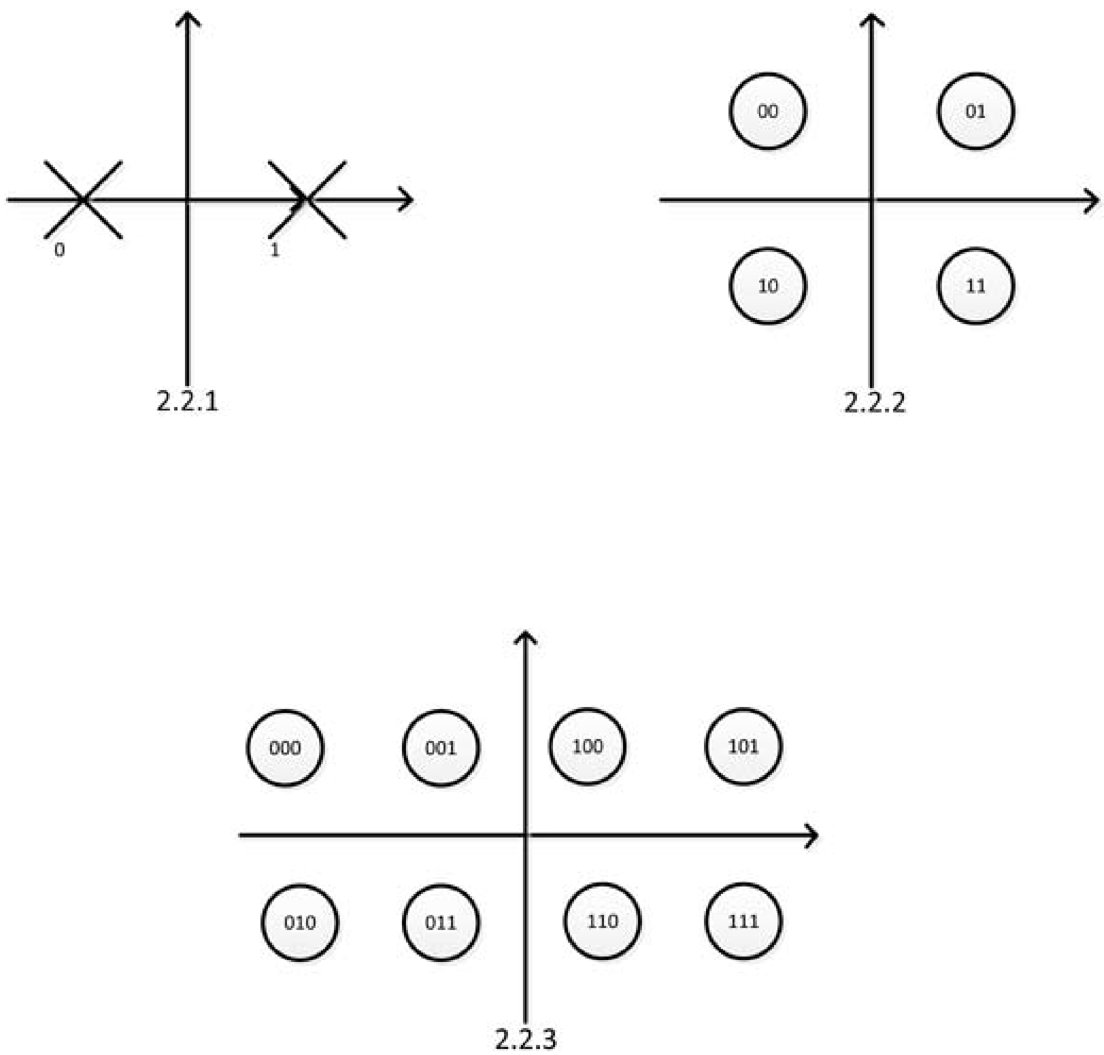

Figure 2.2: Mapping of a 3-bit symbol block to one of the eight constellation symbols.

required into a $log_2 m_1 m_2$-bit symbol block, where m_1, m_2 is the number of bits needed to be transmitted for each layer in one group of frame. Take the following example, the SPC base layer x_1 is BPSK modulated, the SPC upper layer x_2 is QPSK modulated, correspondingly in the constellation diagram there will be one bit from the base layer and two bits from the enhancement layer. Each SPC symbol block will contain 3 bits and these two conventional modulation schemes will yield the resultant constellation diagram with eight points, mapped from this SPC symbol block (Figure 2.2).

The mapping of the 3-bit symbol block to the 8-point constellation is based on the knowledge regarding the information bits of the scalable video bit streams in the application layer. For a symbol referring to '0' in the base layer and a symbol referring to '01' in the enhancement layer, a corresponding 3-bit symbol block containing '001' (i.e. '0'—'01') can be formed and mapped to the symbol '0, 01' in the constellation diagram of the existing modulation scheme for generating a logical SPC modulated signal equivalent to the conventional approach.

2.2.2 Encoder

The intrinsic goal of SPC is to facilitate the transmission of two independent receiver's information in a single wireless transmission block by the superimposition of the two signal's symbol blocks. The superposition process of multiple signals is analogous to the vector addition of the signal constellation symbols, the constellation symbol belonging to each layer will vector add together before they are transmitted [21] - [23].

The example diagram of the constellation is Figure 2.3. x_1 (Figure 2.3.1) and x_2 (Figure 2.3.2), are information for receiver 1 modulated using QPSK and information for receiver 2 modulated using BPSK, respectively. Modulation using QPSK has the capability to achieve a higher transmission rate over BPSK at the expense of robustness when subject to a noisy channel. The superimposed signal x is a vector sum of the two modulated signals governed by $x = x_1 + x_2$.

As shown in Figure 2.3.3, vector x consists of symbol '01' from Figure 2.3.1 and symbol '1' from Figure 2.3.2. Signal x is the SPC symbol, launched as a single wireless transmission block, and received by various receivers with diverse channel conditions within the same coverage.

2.2.3 Decoder

Correspondingly at the receiving side, the signal is expressed as $y = x + z$, where z is the noise perceived by receiver. Vector Subtract can be used to get the right demodulation

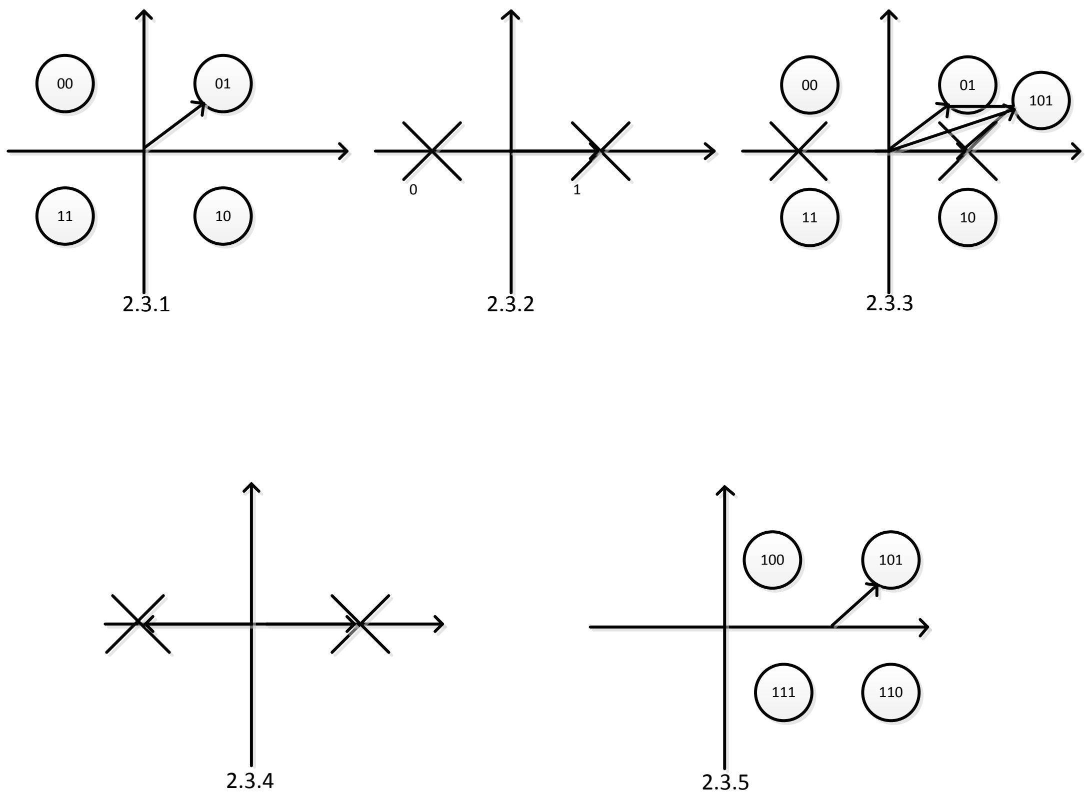

Figure 2.3: Superposition coded (SPC) modulation: (2.3.1)-(2.3.3) encoding; (2.3.4)-(2.3.5) decoding.

data. The conventional technique to decode the received SPC signals is known as Signal-Interference Cancellation (SIC), which is used to identify the signal components meant for the noise and other receivers.

Thus as shown in Figure 2.3.4 and Figure 2.3.5, the receiver can obtain its own information by subtracting the undesired signal components belonging to other receivers from its received SPC signal. For receiver 1 to decode its data from y_1, it must use the demodulator corresponding to the information used for receiver 2, x_2 and then subtract x_2 from the received signal y_1. The result of the subtraction using SIC is x_1, which is usually distorted by the noise experienced at receiver 1, z.

The design mechanisms of logical superposition coded modulation for mimicking a conventional BPSK/QPSK SPC modulation can be extended to any combinations of two existing modulation schemes, such as QPSK, 16-QAM, and even 64-QAM, which are adopted in current and emerging wireless standards. Any combination of modulation schemes chosen with the conventional SPC implementation with m_1 and m_2 points for the base and enhancement layers, respectively, can be theoretically decoded by M points SPC demodulator, where $M = m_1 m_2$. So at the receiver, the proposed approach can only requires simple modifications in the MAC layer software, which demonstrates full decoding compatibility with the conventional multi-stage SIC approach involving additional hardware devices.

Moreover, the logic superposition process can be applied to more than two layers, where the coding representation will get from logical operation of all the layers. In the process the symbols in the constellation diagram are decided, not only by the total energy available π, but also by the energy allocation ratio between the layers. Mathematically, the overall signal layer during the transmission power is satisfied:

$$\pi = \pi_1 + \pi_2 + \ldots + \pi_L, \tag{2.4}$$

The SPC symbol x in constellation diagram can be represented as:

$$x = \sum_{l=1}^{L} \sqrt{\pi_l} x_l, \tag{2.5}$$

where $x_1, ..., x_l, ..., x_L$ are independent and identical Gaussian random variables referring to the individual channel symbol of layer $1, ..., l, ..., L$, π_l is the power allocation to layer l under a total power constraint π.

Chapter 3

Proposed Scheme

The objective of this thesis is to improve network throughput in a fading channel, which is affected by the stale channel CSI problem. Network spectrum efficiency is used to measure network performance. To achieve this objective, a new framework incorporating AMC with layered transmission through the SPC scheme is proposed. A layered multi-step FSMC model is employed under this framework to effectively assist the system in selecting the optimal modulation and coding scheme for each layer in every multi-resolution unicast transmission. Based on previous CSI, the layered multi-step FSMC model will attempt to predict current channel status for each layer, and each layer will choose an appropriate coding scheme and be superimposed together for each transmission by the SPC operation mentioned in chapter 2.

3.1 System architecture of layered AMC

The system architecture of the proposed layered AMC framework is illustrated in Figure 3.1. As shown in every multi-resolution unicast transmission, multi-layer schemes achieved through SPC are employed both at the MAC layer of transmitter and receiver. The proposed layered multi-step FSMC model is located on the transmitter side. It will receive CSI from the feedback path and predicate the optimal power and coding scheme of each layer in the SPC symbol to maximize network throughput in subsequent symbols transmission.

In the framework, the same modulation and coding scheme must be employed for corresponding layers in the transmitter and receiver to ensure data retrieval is successful. When symbols of each layer are superimposed into one unicast, the SPC scheme should completely satisfy the power constraint for that transmission.

Periodically, signaling mechanisms between the transmitter and receiver are necessary to establish knowledge of the FSMC characteristics, including optimized power allocation

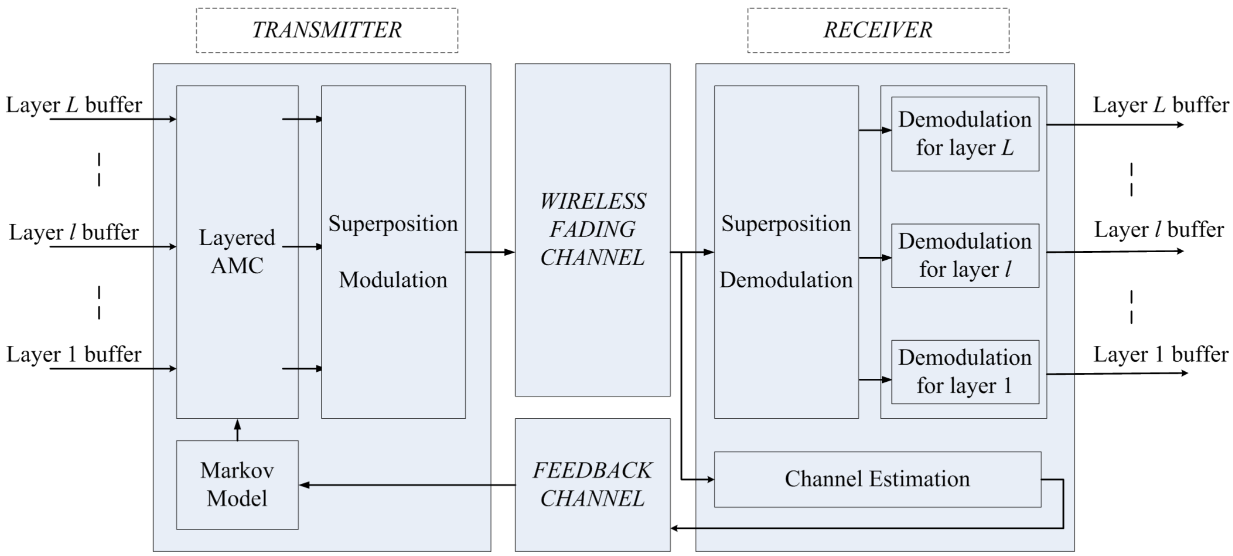

Figure 3.1: Architecture of proposed layered AMC with multi-step FSMC modulation and demodulation.

and layered coding selection for each state. This enables receivers to employ the same set of demodulation schemes to successfully recover the received SPC modulated signal. For every certain number of transmissions, the CSI feedback is sent to the transmitter with an indication of the receiver's instantaneous channel condition. Using this CSI, the layered FSMC model performs channel estimation for subsequent transmissions.

In Figure 3.1, the general unicast process is shown after employing the proposed framework. There is one transmitter and one receiver in the figure. After setting up the original CSI and layered multi step FSMC model parameters, the process of the proposed scheme works as follows.

Step 1: On the transmitter side, with previous CSI getting through the feedback path, the scheme decides whether to update the layered multi-step FSMC model. If updated, the next transition states are determined, while the corresponding transition probabilities are calculated. If not, the current layered multi-step FSMC prediction model and transition probabilities can be kept.

Step 2: Based on channel predictions resulting from layered FSMC model, the layered AMC framework selects the optimal power allocation and coding scheme for each layer to fully utilize network capacity and maximize network throughput, while satisfying QoS requirements of each layer and the total power constraints of each transmission.

Step 3: From the optimal selection for power and modulation scheme of each layer, symbols of each layer are superimposed into one single unicast SPC symbol and sent to the receiver on the fading channel. The channel fading effect and noise result in errors in the transmission.

Step 4: Signaling mechanisms enable the transmitter and the receiver to have the same knowledge, such as the modulation and coding scheme of each layer. After receiving the SPC symbol at the receiver, the receiver uses the SPC scheme to demodulate the symbol for each layer. Lower rate transmissions are easier to demodulate than higher rate transmissions even after channel fading.

Step 5: For every certain number of transmissions, the receiver sends feedback of the CSI to the transmitter. The process goes back to step 1 and fully adapts to the new channel status.

3.2 Coding scheme error

In the proposed framework, each layer of the transmitter will choose the optimal modulation and coding scheme for current channel status to maximize network throughput while satisfying the QoS of that layer. However if two coding schemes, such as two turbo scheme 16QAM (1/2) and QPSK (1/1), have the same effective information bit. What is the metric to choose coding scheme? Turbo codes have been used extensively and the following section will begin by explaining the turbo code structure.

Turbo codes seek to achieve reliable information transmission over bandwidth or latency constrained communication links in the presence of data-corrupting noise, and they have been used extensively in 3G and 4G mobile telephony standards e.g. in HSPA and LTE. The turbo code encoder is a parallel concatenation of two recursive systematic convolutional (RSC) codes whereas the turbo code decoder is an iterative serial concatenation of two soft output Viterbi algorithm decoders. These make the turbo code complex, and the presence of interleaver in both the encoder and the decoder further complicates this coding scheme.

Theoretical analysis of a turbo code is difficult due to coding structure [32] [33]. A few journal papers have analyzed turbo codes with this theoretical approach. However, their results do not closely match computer simulation results (too optimistic), and the theoretical analyses presented in these papers are not clearly described and thus are difficult to follow. In addition, the theoretical approach often requires tremendous computer run time to find the complete weight distribution of the turbo code words.

In this thesis, instead of directly calculating the error rate of turbo code, another approach (i.e. the effective information bit error rate) is given as the performance measurement of the coding scheme (Eq. 3.1). This is based on the following: as an effective forward error correction (FEC) codes, turbo code can improve the transmission performance. Given the turbo scheme shown in the second column of table 4.2, performance of the corresponding scheme without the turbo code correction should be lower than the scheme with the turbo code correction.

For example, two turbo schemes, 16QAM (1/2) and QPSK (1/1) are examined. In the constellation diagram representing the 16QAM Modulation scheme, every symbol has 4 bits while for QPSK each symbol has 2 bits. Considering the rates of both schemes for each symbol, the effective information bits are the same 4/2=2*1= 2 bits in these two scheme. However, the extra turbo bits in 16QAM (1/2) can correct the transmission errors, so the error occurring in the transmission of 16QAM (1/2) should be less than QPSK (1/1). This leads to the strategy of first choosing higher modulation turbo methods if the same information rate is required.

Furthermore, while the same modulation and coding scheme is chosen only with different coding rate parameters, such as 64QAM (3/4) and 64QAM (1/2), the higher rate turbo code will have more information errors. The reason for this is that fewer turbo check bits are in the higher rate code, and through interleaver, the map distance between two codes is less than the lower rate one, which usually results in higher SNR to satisfy the BER of higher rate turbo code.

In the SPC scheme, The Key parameter- average information symbol error rate denoted as $e_M(c_l, \gamma_l, l)$ can be calculated through:

$$e_M(c_l, \gamma_l, l) = 1 - \left[1 - 2\left(1 - \frac{1}{\sqrt{M(c_l)}}\right) Q\left(\sqrt{\frac{3}{M(c_l) - 1}\gamma_l}\right)\right]^2, \tag{3.1}$$

where for layer l, γ_l is the signal-to-noise ratio (SNR), and c_l represents the ID corresponding to the $M(c_l)$-ary modulation and coding scheme adopted, for example, in Table I for LTE standards. The number of constellation symbols is, as a function of the number of bits per symbol $r(c_l)$, given by:

$$M(c_l) = 2^{r(c_l)},$$

with γ_l evaluated as:

$$\gamma_l = 10 \log \left(\frac{h_l \pi_l}{1 + h_l \sum_{g=l+1}^{L} \pi_g}\right), \tag{3.2}$$

where h_l and π_l are the fading channel gain and the power allocation, respectively, for layer l, and L is the total number of layers in the layered radio signal. Based on the achievable rate and symbol error probability of each layer, the transmitter adaptively selects modulation and coding schemes for the SPC modulated signals from a collection of predefined candidates.

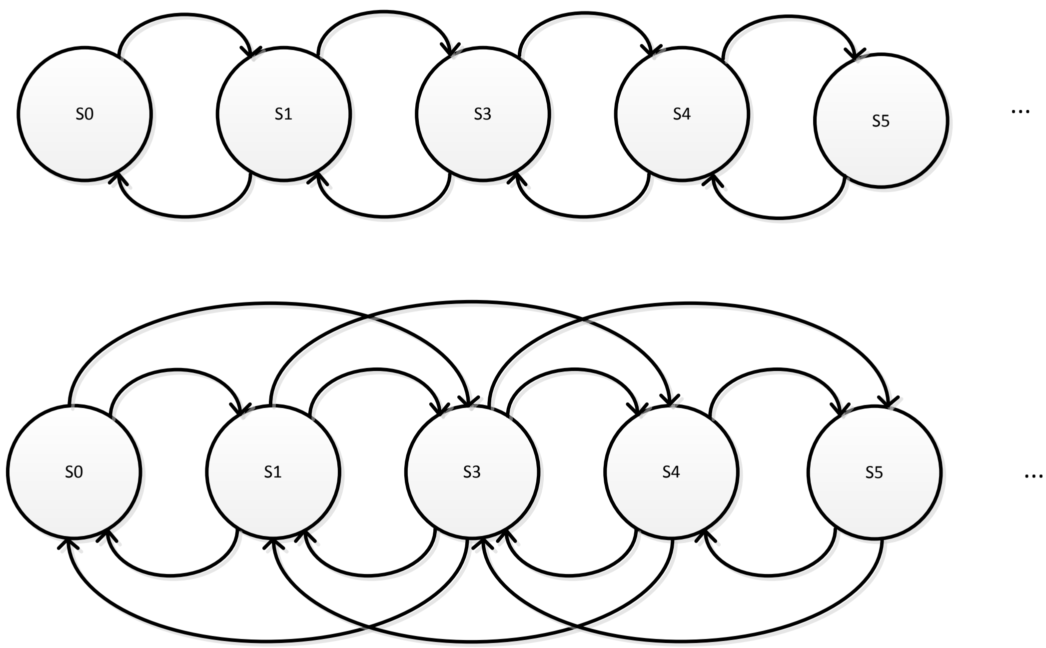

Figure 3.2: The transitions Compare between one-step markov-chain model and multi-step markov-chain model.

3.3 Layered Multi-step FSMC model

In this section unlike of the previous one-step FSMC model, a layered multi-step FSMC model is developed to model the time-varying characteristics of the receiver's layered fading channel. A Markov chain of order m, where m is finite integer, is a process satisfying:

$$
\begin{aligned}
&Pr(X_n = x_n | X_{n-1} = x_{n-1}, X_{n-2} = x_{n-2}, \ldots, X_1 = x_1) \\
&= Pr(X_n = x_n | X_{n-1} = x_{n-1}, X_{n-2} = x_{n-2}, \ldots, X_{n-m} = x_{n-m}) \ for \ n > m,
\end{aligned}
$$

In other words, the future state depends on the past m states, and it is possible to construct a chain Y_n from X_n, let $Y_n = (X_n, X_{n-1}, \ldots, X_{n-m+1})$, the ordered m-tuple of X values, then Y_n is a Markov chain. So order 0 Markov models have no memory in a sequence and they are equivalent to a multinomial probability distribution in some sense. Order 1 Markov models, also known as first-order Markov models, have a memory size of one state. Mathematically they can defined by a table of probabilities $Pr(X_t = S_i | X_{t-1} = S_j), \ for \ i, j \in [1, \ldots, k]$, this model is the number of k order 0 Markov models, one model for each state S_j.

As discussed in chapter 2, the first-order FSMC model has been proven to be very effective in capturing the time-varying nature of wireless fading channels. As first-order

FMSC models, the layered multi-step FSMC models utilize previous CSI from the feedback path to precisely predict the following layered channel status. The Receiver channel SNR is divided into small non-overlapping states according to the increased order of the channel SNR.

In the one step Markov model the transition can occur only in adjacent states. Mathematically, this means for current frame state S_j, the received SNR of the next frame can be located only in the adjacent states S_{j-1}, S_j or S_{j+1}. It is easy to notice that, due to the simplicity of one step first-order FSMC models, it considers only the adjacent state transition. In real fading channel status, the transition between non-adjacent states is possible. The fluctuations of the fading characteristic, especially in the fast fading channel suggest one possibility: in the previous MAC frame, AMC chooses a lower rate modulation and coding scheme, such as BPSK, while in the current frame, AMC choose a high rate modulation and coding scheme, such as 16QAM. Allowing multi-step transition is more likely the real channel situation. The modulation and coding schemes of the layered multi-step FSMC models are updated at the transmitter based on the fading characteristic received from CSI to improve the channel accuracy.

In the proposed layered multi-step FSMC model, each state represents a specific channel SNR range. Unlike previous studies where the Markov model focuses on the non-layer data transmission, the symbol in this proposed study is the superimposed layered symbol achieved through SPC. This means that, for each state in the model, the power is allocated to different layers and each layer will have its own layer SNR in addition to the model channel SNR, and the network throughput will be the combination of all the layers in transmission. For example, if two layers exist and the current model channel SNR γ_{spc} is located at the SNR boundary of State S_j, also known as $\gamma_j \leq \gamma_{spc} \leq \ gamma_{j+1}$, based on the power each layer receives (represented by a power ratio) , the layer SNR can be calculated by Eq. (3.2). When channel SNR changes from one state to another, the layer SNR of each layer needs to be calculated again. Moreover, every state in the model should maintain an optimal power allocation ratio for layers, and based on the power ratio and QoS requirement, optimal modulation and coding scheme can be found to maximize network performance.

For each state of the proposed FSMC model, transition probabilities are calculated according to the estimated fading channel parameters from CSI. Given the model complexity parameter α, the FSMC model will choose $1th$ to αth maximum transitions in the model. From this, the layered multi-step Markov chain model is generated. The mathematical presentation of the model is described in chapter 4.

Using this derived model, the evaluation of spectrum efficiency can be conducted based on the estimation of the current channel state. By incorporating SPC-realized layered transmission with Markov-modeled channel estimation, the proposed framework will be demonstrated to achieve superior performance in mitigating the vicious impacts caused of the stale CSI feedback.

Chapter 4

Model Analysis

After the proposed new framework that incorporated layered multi-step FSMC model and multi-layer SPC scheme, mathematical analysis can be done to measure scheme performance for the proposed framework. This chapter makes use of the fading channel characteristics from CSI, sets up layer multi-step FSMC, chooses modulation and coding schemes for each layered SPC, and calculates spectrum efficiency after employing the proposed framework.

4.1 Layered Multi-step FSMC Model Representation

One practical consideration in the layered multi-step FSMC model is how quickly the transmitter changes its state. Due to the fact that the model is based on the estimate of the channel fading level, several symbol times may be required to obtain a good estimate. This is mathematically shown in [25] for flat fading channel that $\overline{\tau_j} \geq T_S \geq T_M$, where T_S is the symbol time, $\overline{\tau_j}$ is the average time that the FSMC model does not change the current state or the modulation scheme, and T_M is the root-mean-square (RMS) delay spread of the channel, for Nyquist pulses $B = 1/T_S$. In general, wireless channels have RMS delay spreads of less than 30 μs in outdoor urban areas and less than 1 μs in indoor environments [14]. In [25], the minimum $\overline{\tau_j} = 0.7/ms$, which indicates that in outdoor channels the rates can be tens of Ksymbols/s and hundreds of Ksymbols/s in indoor channels.

With the previous CSI at the transmitter side, the layered AMC framework adaptively selects the modulation and coding set which consists of the optimal modulation and coding scheme for each layer, while satisfying the total power constraint and QoS requirement for each transmission. At the receiver, the same SPC modulation and coding schemes set as the transmitters are employed, which retrieve the data of each layer from the received SPC modulated signal. Periodically, signalling mechanisms between the transmitter and receiver

Table 4.1: modulation and coding schemes in lte standards

ID (c_l)	level	$r(c_l)$ [bits/symbol]	SNR boundary [dB][1]
0	Silent	0	0
1	QPSK(1/2)	1	6
2	QPSK(3/4)	1.5	8.5
3	16QAM(1/2)	2	11.5
4	16QAM(3/4)	3	15
5	64QAM(2/3)	4	18.5
6	64QAM(3/4)	4.5	21

are necessary to establish knowledge of the FSMC characteristics, including optimized power allocation and layered coding selection for each state. This enables the receiver to use the corresponding set of demodulation schemes employed to recover the received SPC modulated signal.

Table 4.1 shows the modulation and coding schemes in LTE standards. To simplify the modulation and coding schemes selection process, assume only the modulation and coding schemes shown in the table are available for selection.

As a first-order FSMC model, layered multi-step FSMC model has stationary state probability for each state and transition probabilities for every transition. Beginning with the state definitions illustrated in Eq. (4.1), the states of the layered multi-step FSMC model are denoted by $S = \{S_0, ..., S_n\}$, corresponding to the boundary vector $B = [\gamma_0, \gamma_1, ..., \gamma_n, \gamma_{n+1}]$, where n is the number of finite SNR channel states and there is no overlapping in the SNR allocation. For the most conservative performance evaluation, receiver SNR values in the range of $[\gamma_j, \gamma_{j+1})$, with state $S_j, 0 \leq j \leq n$ assigned to a SNR of $(\gamma_j + \gamma_{j+1})/2$ for the most conservative performance evaluation. With a given step size Δ to segment the range of SNR values, the boundary vector B is defined as:

$$B = \begin{cases} \gamma_0 = -\infty \ dB \\ \gamma_1 = 0 \ dB \\ \gamma_j = \gamma_{j-1} + \Delta, \forall j = 2, ..., n \\ \gamma_{n+1} = +\infty \ dB, \end{cases} \tag{4.1}$$

In this thesis assume that ideal and zero delay in the feedback path. Average SNR of the fading channel and general Nakagami fading parameter can be estimated from CSI. Given the boundary of receiver SNR state, the stationary probability for that state can be calculated as:

$$\int_{\gamma_j}^{\gamma_{j+1}} P_A(\gamma) d\gamma, \tag{4.2}$$

where $P_A(\gamma)$ is the PDF of the fading channel model, $[\gamma_j, \gamma_{j+1}))$ is the SNR boundary of state S_j. The PDF of the Nakagami fading channel is in Eq. (2.1), the stationary probabilities of S_j, denoted as $P(j)$, can be derived as:

$$P(j) = \frac{\Gamma(m, m\gamma_j/\bar{\gamma}) - \Gamma(m, m\gamma_{j+1}/\bar{\gamma})}{\Gamma(m)}, \tag{4.3}$$

where $\bar{\gamma}$ is the average SNR, $\Gamma(x)$ is the Gamma function defined by $\Gamma(x) = \int_0^\infty e^{-t}t^{x-1}dt$, and $\Gamma(x, \alpha)$ is the incomplete upper Gamma function defined by $\Gamma(x, \alpha) = \int_0^\alpha e^{-t}t^{x-1}dt$. Note that a Rayleigh fading channel can be modeled when $m = 1$.

The next probability needed to be calculated in layered multi-step FSMC model is transition probability. Because the previous CSI current channel state status and state probabilities of each state are known, having these transition probabilities can be calculated using Eq. (4.4) and Eq. (4.5).

In [24], it is shown that the level crossing rate L_j at the threshold γ_j of the Nakagami fading channel is expressed as:

$$L_j = \sqrt{2\pi\frac{m\gamma_j}{\bar{\gamma}}}\frac{f_d}{\Gamma(m)}\left(\frac{m\gamma_j}{\bar{\gamma}}\right)^{m-1}\exp\left(-\frac{m\gamma_j}{\bar{\gamma}}\right), \tag{4.4}$$

where f_d denotes the Doppler frequency.

the transitions probability $p_{S_j,S_k}$from state S_j to state S_k, where the boundary of S_j is $[\gamma_j, \gamma_{j+1})$ and the boundary of S_k is $[\gamma_k, \gamma_{k+1})$, can be approximated by absolute value of the ratio of expected level crossing at $[\gamma_k, \gamma_{k+1})$ divided by the average symbols per second the SNR falls in the interval associated with state S_j [16] [37]. The transition probability of state S_j to state S_k is:

$$\begin{cases} p_{S_j,S_{k(j\neq k)}} = \mid \dfrac{L_k - L_{k+1}}{P(j) * R(t)} \mid = \mid \dfrac{(L_k - L_{k+1}) * T}{P(j)} \mid \\ p_{S_j,S_j} = 1 - \displaystyle\sum_k p_{S_j,S_{k(j\neq k)}}, \end{cases} \tag{4.5}$$

where $R(t)$ is the transmission rate at time t, T is the time duration of a MAC frame, and L_j is the level crossing rate at γ_j defined in Eq. (4.4).

So the transition probabilities of the layered multi-step FSMC model can be generated as the matrix in the following, each element in the matrix p_{S_j,S_k} represents the transition probability from state S_j to S_k defined in Eq. (3.2).

$$p = \{p_{S_j,S_k}, j, k\epsilon(0, n)\}, \tag{4.6}$$

where j, k are index of states S_j, S_k.

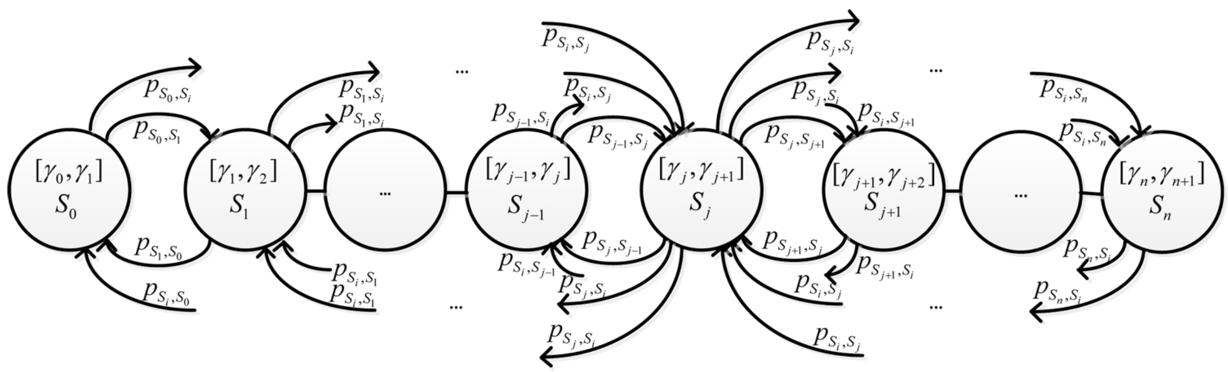

Figure 4.1: Proposed layered multi-step FSMC model.

Figure 4.1 gives the general representation of the proposed layered multi-step FSMC model. As shown each state of the proposed model has a range of SNR values, due to the fact that the symbol in this framework is the superposition of multi-layer SPC symbol. The SNR of each layer can be obtained using Eq. (3.2). Depending on the power allocation and QoS of each layer, state probability and transition probability of each layer can be calculated by equations defined above.

Accuracy and complexity are concerns of the proposed layered multi-step FSMC model, complexity factor α was introduced to represent the achievable accuracy and complexity, where α is in range $[3n+1,(n+1)^2]$ and means the number of connections between the model states.

Given α and p_{S_j,S_k}, a unique layered multi-step layered FSMC model can be generated. the layered multi-step FSMC model will choose $1th$ to αth maximum transition probabilities in Eq. (4.5). If p_{S_j,S_k} is chosen, S_j, S_k are said to be connected and there would be a direct connection from state S_j to state S_k in the model.

The value of α need to be chosen carefully, If α is large enough as n^2, any two states in the layered multi-step FSMC model will be connected, The resulting amounts of calculation need to be carried out which would require an unreasonable amount of time. Conversely if the complexity factor α is small enough, the layered multi-step FSMC model accuracy will not be guaranteed. An acceptable value of α must be chosen to adequately satisfy both requirements for complexity and precision for network throughout.

With both stationary and transition probabilities derived for the proposed layered AMC framework, it is important to identify the challenge in selecting key optimization parameters, such as the step size and the complexity factor of the layered multi-step FSMC model, to demonstrate the model's practical feasibility in terms of computation complexity. Using the model defined by Eq. (4.2) - Eq. (4.6), as long as the channel parameters, including f_d, m, and $\bar{\gamma}$, fluctuate slowly, the accuracy of the estimation model should be subject to an acceptable error rate for increased time intervals between necessary model regeneration and reduced computation complexity. The choice of an appropriate step size and model complexity factor will be further studied and analyzed in Chapter 5.

4.2 Model objective

Spectrum efficiency can be calculated for the proposed model to measure the system performance. There are N symbols in every MAC frame. Each symbol has the same modulation and coding scheme in the MAC frame with $r(c)$ and the symbol durations of T_s. For a modulation and coding scheme c chosen for each MAC frame, denote the corresponding number of information bits per frame by $r_f(c)$. The N symbols in the MAC frame, each with symbol durations of T_s with $r(c)$ bits/symbol, allow the information rate R to be expressed in bits/second as:

$$R = \frac{r_f(c)}{T} = \frac{Nr(c)}{NT_s} = \frac{r(c)}{T_s}, \tag{4.7}$$

Assuming the adoption of ideal Nyquist signal pulses with a fixed symbol period $T_s = 1/B$ for all modulation schemes [26] and using Eq. (4.6), the spectrum efficiency η_f is given by:

$$\eta_f = \frac{R}{B} = \frac{r(c)}{T_s} T_s = r(c), \tag{4.8}$$

The AMC scheme adaptively changes according to the CSI from feedback path. Before transmission, the layered AMC algorithm has the transmitter estimate the current receiver channel condition based on the previous feedback CSI from receiver and the previous FSMC state, denoted by S_j, using which the best modulation and coding scheme for each data layer is selected from a collection of predefined candidate modulation and coding sets each denoted by $M_j = \{c_1, ..., c_l, ..., c_L\}$, where c_l represents the ID corresponding to the modulation and coding choice optimally selected for the lth layer.

For each possible set of M_j, the expectation of spectrum efficiency, denoted by $\bar{\eta}_f(M_j)$, is expressed as:

$$\begin{aligned} \eta_f(\bar{M}_j) &= \sum_{k, p_{s_j,s_k} > \alpha} \sum_{l=1}^{L} p_{s_j,s_k} r(c_l)[1 - e_M(c_l, \gamma_k, l)] \\ &= \sum_{k, p_{s_j,s_k} > \alpha} \sum_{l=1}^{L} -p_{s_j,s_k} r(c_l) * [1 - [1 - 2(\frac{1}{M(c_l)}) * \\ &\quad Q(\sqrt{\frac{3}{M(c_l) - 1}\gamma_k})]^2, \end{aligned} \tag{4.9}$$

where $r(c_l)$ is the number of information bits in a symbol using c_l, p_{S_j,S_k} is the transition probability from state S_j to state S_k, and $e_M(c_l, \gamma_k, l)$ is the symbol error rate if the modulation and coding choice corresponding to the ID c_l is selected for layer l under channel state S_k with an SNR of $(\gamma_k + \gamma_{k+1})/2$. Eq. (4.9) is used to evaluate the spectrum efficiencies of all predefined modulation and coding sets, including all the situation such as upper layers is eliminated without assignment to maintain potential BER targets necessary in providing reliable service for lower layer(s).

For state S_j, the modulation set yielding the highest expected spectrum efficiency is assigned. Assuming there are L layers in transmitter and receiver, corresponding modulation and coding scheme for each layer is c_l, where $l, (0 \leq l \leq L)$ is an integer, $M_j^* = \{c_1^*, c_2^*, \ldots, c_L^*\}$ is assigned to S_j, if:

$$\bar{\eta}_f(M_j^*) = \max_{c_1, c_2, \ldots, c_L} \bar{\eta}_f(M_j), \tag{4.10}$$

Without loss of generality, when number of layers is $L = 2$, each modulation and coding set can be denoted as $M_j = \{c_1, c_2\}$, where c_1 and c_2 is the modulation and coding scheme selected for layer 1 and layer 2, respectively. For state S_j, the modulation set yielding the highest expected spectrum efficiency is assigned, such that $M_j^* = \{c_1^*, c_2^*\}$ is assigned to S_j if:

$$\begin{aligned} \bar{\eta}_f(M_j^*) &= \max_{c_1, c_2} \bar{\eta}_f(M_j) \\ &= \sum_{k, p_{s_j, s_k} > \alpha} (p_{s_j, s_k}(r(c_1)[1 - e_c(c_1, \gamma_k, l)] + r(c_2)[1 - e_c(c_2, \gamma_k, 2)])), \end{aligned} \tag{4.11}$$

To evaluate the system as a whole, the expected spectrum efficiency, denoted as $\bar{\eta}$, is evaluated over all states in the FSMC as follows:

$$\bar{\eta} = \sum_{j=0}^{n} P(j) \bar{\eta}_f(M_j^*), \tag{4.12}$$

where $P(j)$ is the stationary probability of state S_j as defined in Eq. (3.1).

It could be noted that the determined optimal modulation and coding set for each state are valid as long as the statistical fading parameters fluctuate slowly, allowing high reusability of each employed layered multi-step FSMC model depending on application scenarios to further the effectiveness of the proposed scheme.

4.3 Search strategy for optimal power and coding schemes

The number of coding schemes and power ratios are fixed in the optimal process for selecting power and coding schemes, and the formulation obviously becomes a discrete and nonlinear problem which is subject to a serious scalability problem when an optimal solution is desired. Thus, an optimal search strategy is introduced in this section to lower the search process complexity. The basic idea of the proposed approach lies in two folds:

(1) the number of coding schemes is much less than that of the power ratio allocated to each layer. Instead of choosing power ratios and coding schemes randomly, the focus in this section is to give every state a coding scheme.

(2) Lower layer rates should be less than the rates of higher layers, represented as $r_1 < r_2 < \ldots < r_L$ in the sense that lower layer information data can have more chance to recover even when the higher layer data cannot be recovered successfully.

The selection process is subject to the constrains of whole power restrictions and QoS (BER) requirements for each layer. Mathematically this is represented as:

$$\begin{aligned}
\max \bar{\eta} &= \max_{c_1,c_2,\ldots,c_L;\pi_1,\pi_2,\ldots\pi_L} \sum_{j=0}^{n} P(j)\bar{\eta}_f(M_j^*) \\
&= P(j) * \max_{c_1,c_2,\ldots,c_L;\pi_1,\pi_2,\ldots\pi_L} \sum_{j=0}^{n} \bar{\eta}_f(M_j^*), \\
&subject\ \ to \\
&\quad \begin{cases} \pi = \pi_1 + \pi_2 + \ldots + \pi_L \\ e_M(c_l, \gamma_l, l) \leq BER, for\ layer\ l, \end{cases}
\end{aligned} \tag{4.13}$$

where in the optimization procedure the modulation and coding scheme c_l and the allocated power π_l of layer l are dynamic variables to maximize the network spectrum efficiency. Using Eq. (4.13), it is easy to maximize overall spectrum efficiency by maximizing the spectrum efficiency of each state in the layered multi-step FSMC model. Figure 4.1 gives the flowchart for this optimal power and coding scheme search process through CSI. Before the selection process, the corresponding channel SNR that can achieve the QoS can be calculated using the reverse process of Eq. (2.2) for each coding scheme. The Focus is on the change of coding scheme when predicating channel status from the current FSMC model. The coding scheme that can satisfy the QoS (BER) can be calculated by following available transition states where at least the lowest rate coding scheme would be selected. In the layered multi-step FSMC model, the least power that can achieve this coding selection must be allocated. Based on that, after determining the minimal power ratio of each layer

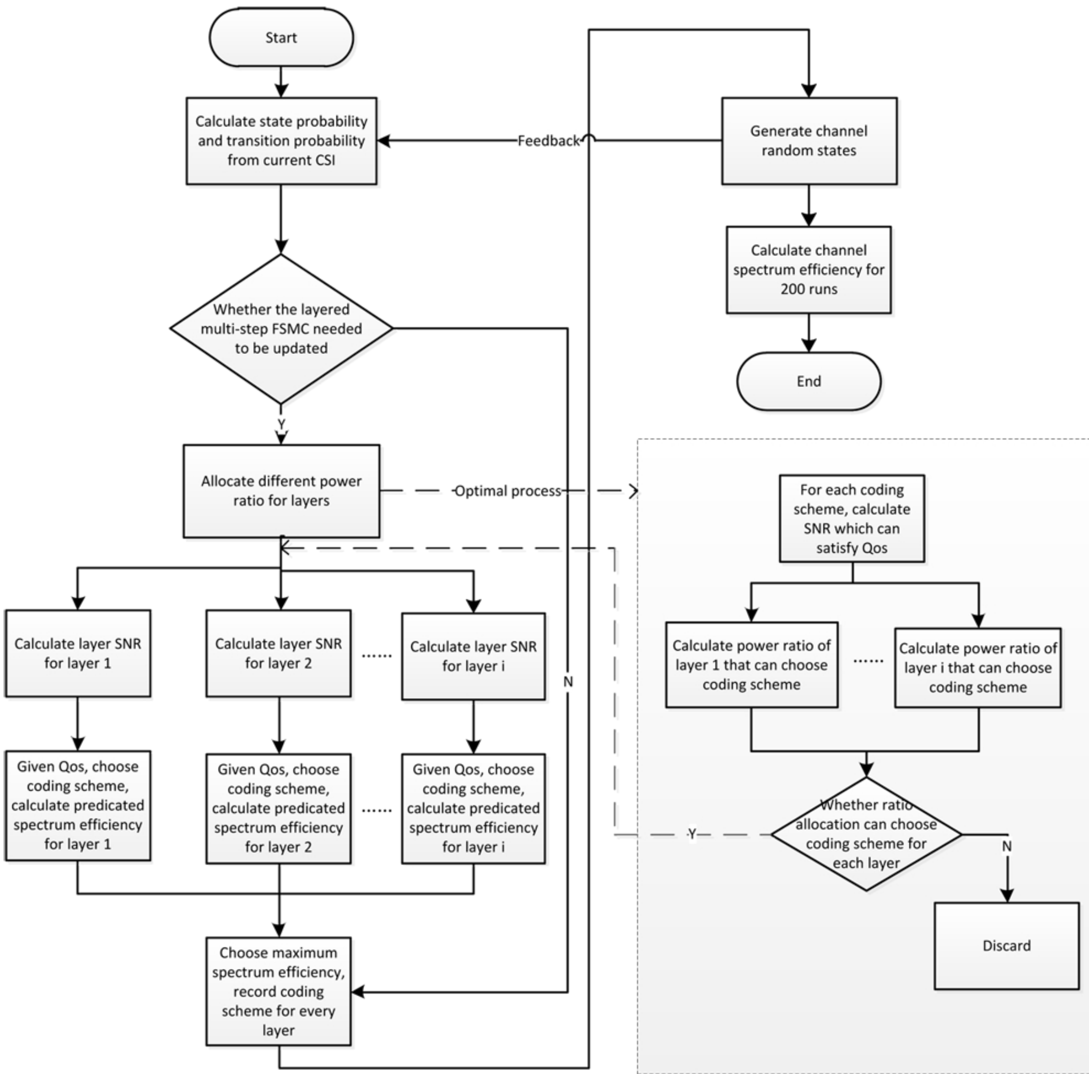

Figure 4.2: Flowchart for optimal power and coding scheme search.

in current channel status, the search space is narrowed. This improves the search process efficiency compared with an exhaustive search scheme.

Chapter 5

Result analysis

To measure the performance of the proposed framework which incorporates multi-step F-SMC model prediction and multi-layer SPC scheme. Comprehensive numerical simulation is conducted. The results from comprehensive numerical evaluations are presented in this section to: 1) compare the legacy non-layered AMC scheme with the proposed framework with and without FSMC estimation. The scheme without the FSMC estimation simply uses the average CSI feedback based on the several previous transmissions in the window to choose the optimal modulation and coding set; 2) study the behavior of the proposed framework when subject to various BER targets and fading conditions; 3) determine the impact of the step size parameter and model complexity factor in the layered FSMC model for exploiting the implementation compromise between performance and computation complexity.

Numerical experiments are conducted using MATLAB, where the presented results are calculated based on the average of 200 executed simulations. For a fair comparison, total transmission power and wireless channel properties are assumed to be equal in all experiments such that the SNR of each layer are expressed in Eq. (2.4). Various channel fading conditions and QoS targets are tested to evaluate the behavior of the proposed scheme. Channel fading effects are evaluated by using $m = 0.7$ for fast fading and $m = 1$ for slow fading (Rayleigh).

Figure 5.1 - Figure 5.4 show the spectrum efficiency under different average receiver SNRs when a minimum BER target is enforced for the non-layered conventional AMC, as well as for all layers of the proposed framework for a fair comparison in terms of QoS. Two layers are used to simplify the proposed model. In layered AMC framework with multi-step FSMC model prediction, each layer of one state will choose the optimal power and coding scheme to maximize spectrum efficiency for current fading channel characteristics. While in non-layered scheme, only one state keeps the optimal coding scheme. To accelerate the

search process for the optimal power and coding scheme, this chapter proposes a search strategy.

5.1 Impact of BER target

Firstly, Figure 5.1- Figure 5.4 demonstrate that the spectrum efficiency of layered AMC generally have superior performance over non-layered AMC under diverse BER targets regardless of the channel fading characteristics. Take an example at average channel SNR 10 dB, the spectrum efficiency of layered AMC with FSMC prediction scheme is 1.2 b/s/HZ higher than non-layered with FSMC prediction scheme, and 1.5 b/s/HZ higher than non-layered AMC without FSMC prediction scheme in slow fading channel for required $BER = 10^{-4}$. These verify that layered AMC with FSMC estimation can better utilize the receiver channel due to more accurate channel estimation, with all four figures exhibiting certain common characteristic. Moreover, it is observed that the spectrum efficiency increases with looser BER constraints under the same receiver average SNR. However, the improvements in non-layered AMC with or without FSMC estimation are less in magnitude because all the power can only be allocated to a particular choice of modulation and coding scheme for a single layer, even though the BER target has already been fulfilled. this exhibits the advantages of layered AMC.

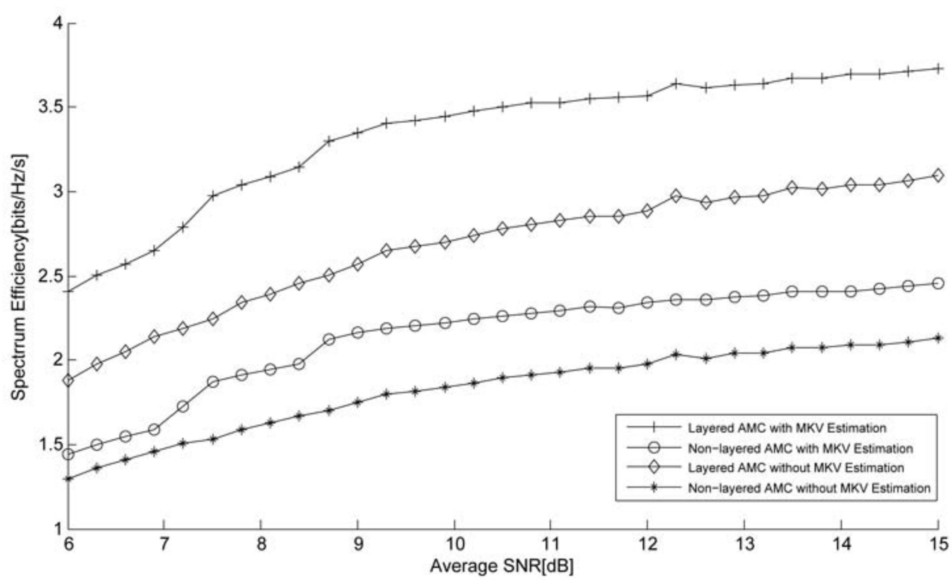

Figure 5.1: Spectrum efficiency at $m = 0.7, BER = 10^{-6}$.

There is a common drop-and-increase trend of spectrum efficiency in layered AMC results. The reduction is produced by the enforcement of the BER target in the lowest

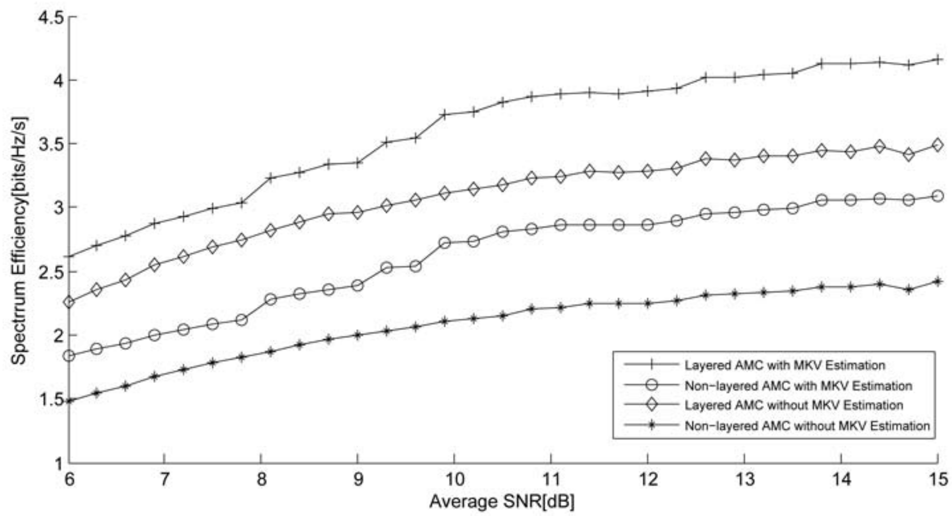

Figure 5.2: Spectrum efficiency at $m = 0.7, BER = 10^{-4}$

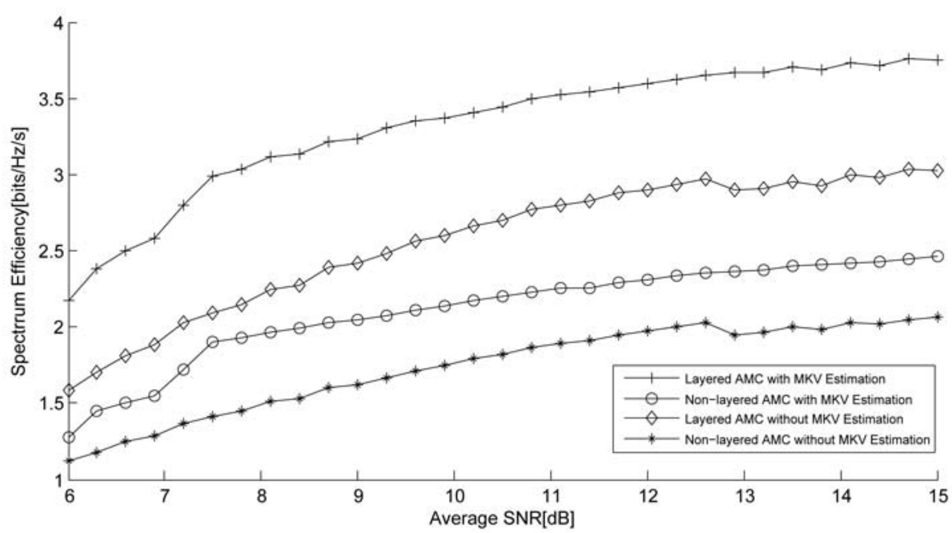

Figure 5.3: Spectrum efficiency at $m = 1, BER = 10^{-6}$.

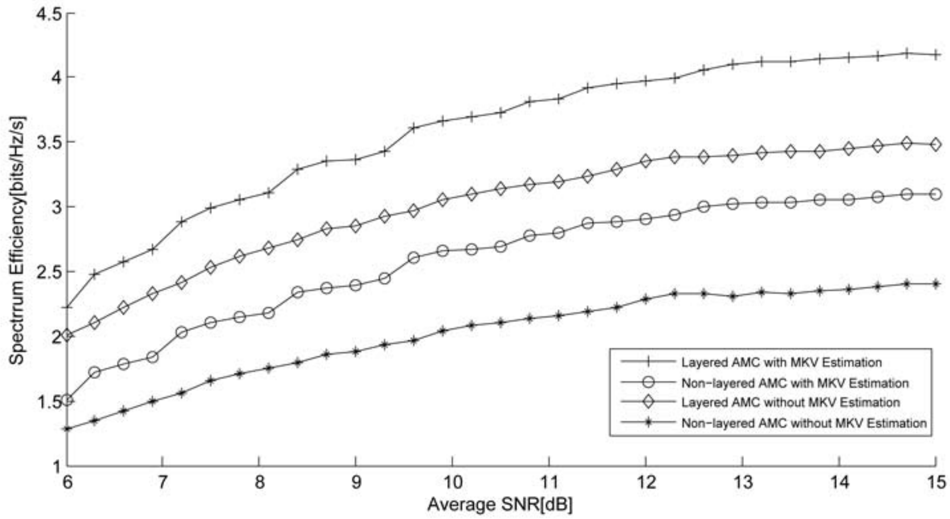

Figure 5.4: Spectrum efficiency at $m = 1, BER = 10^{-4}$.

layer, causing the inability to create the upper layer(s) due to insufficient power when both the lowest layer of layered AMC and the single layer in non-layered AMC switch to a higher rate while maintaining the BER target. Such scenario exhibiting the described trend occurs at the channel boundaries between link adaptations to a higher coding level. For example when the average SNR is 8.5 dB at $BER = 10^{-6}$ for fast fading channel, the corresponding spectrum efficiencies are 2.8 b/s/HZ, 1.7 b/s/HZ and 1.5 b/s/HZ. It is then more likely that the channel state be around 8.5 dB, which results in a higher occurrence of state transitions where lower layer will choose higher modulation, and the upper layer must be silenced since 8.5 dB is a boundary SNR. Once the average SNR of the channel improves, scenarios where the power is required to fulfill the BER target of the lowest layer are more likely to occur, allowing higher probabilities to allow sufficient power allocation to create the upper layers. Therefore, beyond an average SNR of 8.5 dB, the trends of spectrum efficiency increasingly become larger and continue to provide superior performance over non-layered AMC. Moreover, for layered AMC with multi-step FSMC estimation, the drop-and-increase trend is less pronounced, this is because the channel being estimated for scenarios where the instantaneous channel is actually higher than 8.5dB to support the creation of the upper layer for coding selection.

5.2 Impact of Fading

Comparing Figure 5.1 - Figure 5.4, it is similarly concluded that the spectrum efficiency of the proposed layered AMC framework always achieves better performance than that of the conventional non-layered AMC under very different fading situations, regardless of the

BER target. In the range of the low SNR regime, more gains in spectrum efficiency can be obtained earlier for fast fading channel conditions when utilizing layered AMC, even with a more stringent BER target. This is because there are more opportunities for layered AMC in mitigating the stale CSI feedback with the higher layer utilization. At $BER = 10^{-6}$ for the proposed layered AMC with FSMC scheme the spectrum efficiency can be achieved at SNR 8.3 dB for a fast fading channel. However, at SNR of 9.5 dB the same spectrum efficiency is achieved for slow fading. Further observation demonstrates that for fast fading channel performance of AMC with the layered multi-step FSMC degrades quite a bit while the layer scheme supplementally results in the increase of whole spectrum efficiency.

5.3 Impact of step Size and system complexity

The influence of step size between different adjacent states in the proposed layered multi-step FSMC model is evaluated in Figure 5.5 - Figure 5.8 for two diverse fading situations under different BER targets. Figure 5.5 and Figure 5.7 show the spectrum efficiency under various average channels SNR, Figure 5.6 and Figure 5.8 are the specific situation when the average SNR is 10 dB. Whatever the average SNR, the figure will exhibit the same characteristics. An average SNR of 10 dB stepped from 1 dB to 3 dB in increments of 0.1 dB is employed. With larger BER targets, the expected spectrum efficiency increases, with the proposed framework providing higher spectrum efficiency than non-layer AMC in both diverse fading and BER target scenarios. Although larger step sizes reduce the accuracy of the FSMC results, it is observed from these figures that the spectrum efficiency is generally in a declining trend with increasing step sizes.

For example in Figure 5.6, if the step size is increased from 1 dB to 3 dB spanning an SNR range from 0 to 30 dB, the number of states would decrease from 30 to 10; such tripling of the step size only decreases the spectrum efficiency by approximately 10%, or 0.5 bits/HZ/s, while reducing the number of states in the FSMC by three times. Hence, the performance of the proposed framework is relatively insensitive to step size variations, allowing reduced computational overhead through the use of larger step size for practical system implementations.

The influence of system complexity for AMC with layered multi-step FSMC model is evaluated in Figure 5.9 - Figure 5.12 for two diverse fading situations under different BER targets. Figure 5.9 and Figure 5.11 show the spectrum efficiency under various average channels SNR, Figure 5.10 and Figure 5.12 is the specific situation when the average SNR is 10 dB. With the complexity factor stepped from factor 20 to factor 70 in increments of factor number 3, whatever the average SNR, the figure exhibits the same characteristics for the varying complexity factor. Similarly results show the advantage of proposed framework in the spectrum efficiency under both diverse fading and BER target scenarios. Higher

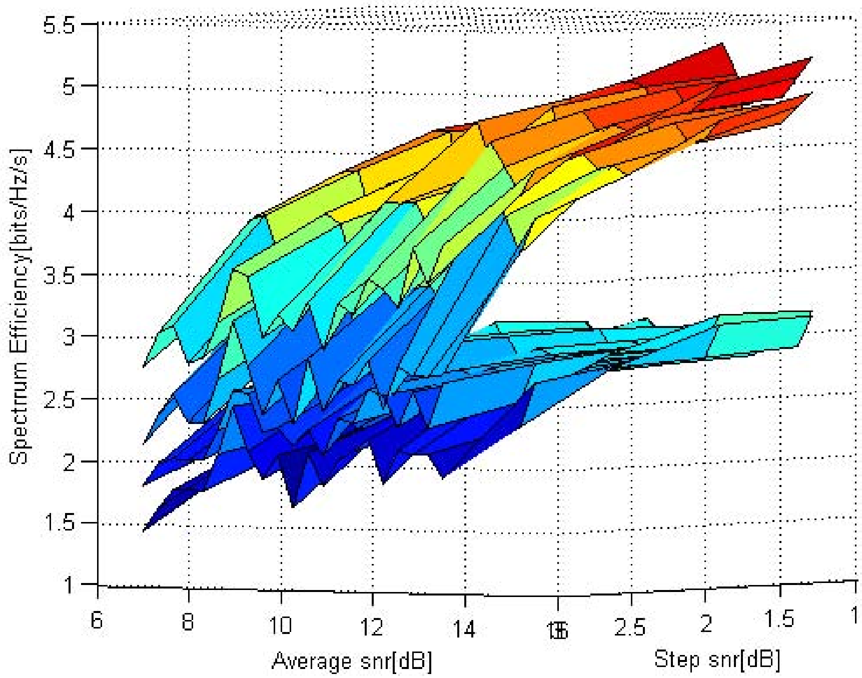

Figure 5.5: Spectrum efficiency at $BER = 10^{-6}$ for varying step size.

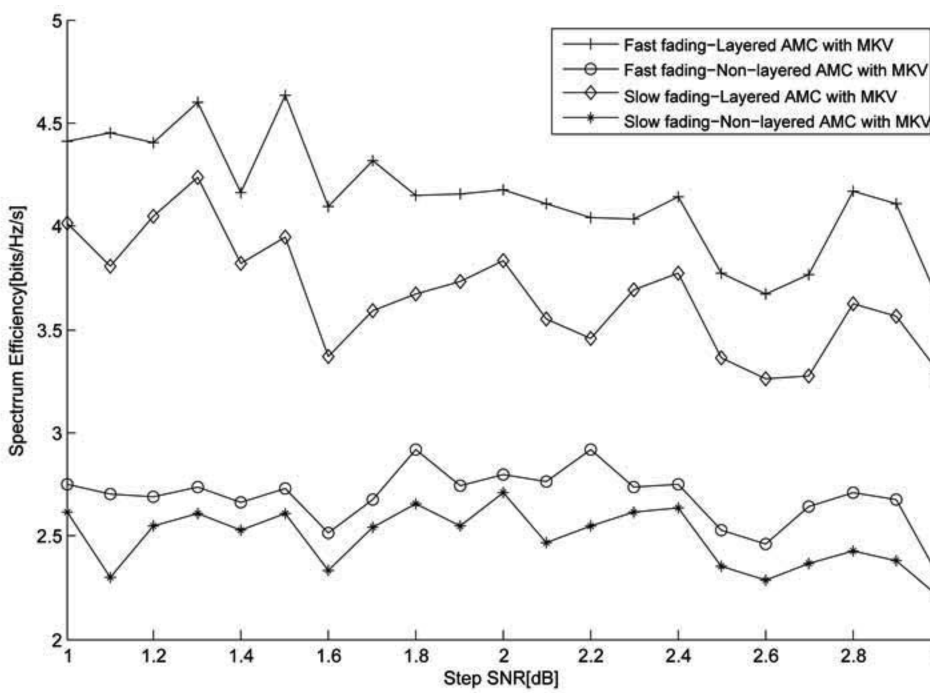

Figure 5.6: Spectrum efficiency at $BER = 10^{-6}$ for varying step size at SNR 10dB.

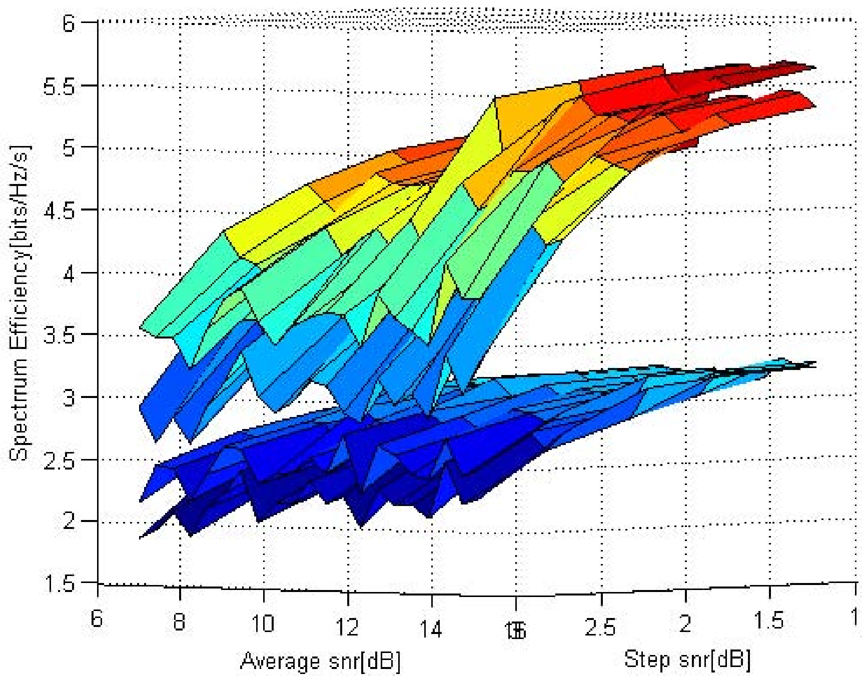

Figure 5.7: Spectrum efficiency at $BER = 10^{-4}$ for varying step size.

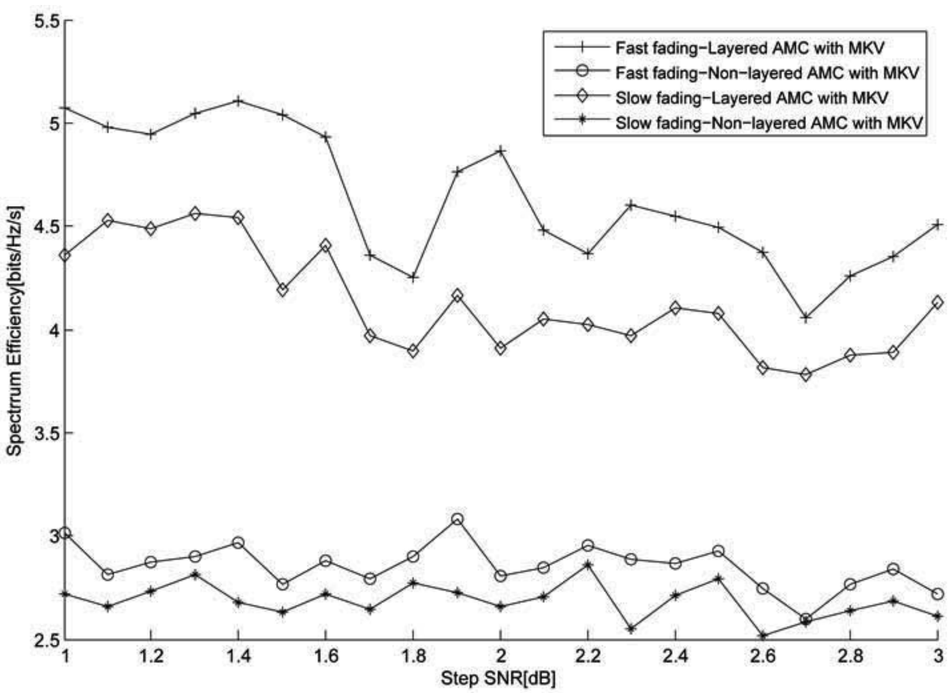

Figure 5.8: Spectrum efficiency at $BER = 10^{-4}$ for varying step size at SNR 10dB.

model complexity results more calculation which is sometimes unachievable during MAC frame time, while lower model complexity results the inaccuracy of channel prediction. When tighter BER constrains need to be enforced, more system complexity should be chosen to predict an accurate result due to the more rapidly decrease of spectrum efficiency for larger BER.

Furthermore, Figure 5.9 - Figure 5.12 show that when same complexity is selected in channel prediction, for fast fading channel situation the spectrum efficiency decreases faster regardless of the BER constrains. This indicates more system complexity is needed to obtain more accurate results for the fast fading channel. Through the observations in Figure 5.9 - Figure 5.12, when fast fading channel is considered, empirical complexity is the threshold which can be used to keep the model accurate while decreasing the model complexity at the expense of a 0.3 b/s/HZ decrease (around 10%).

5.4 Impact of layer number in layered multi-step F-SMC model

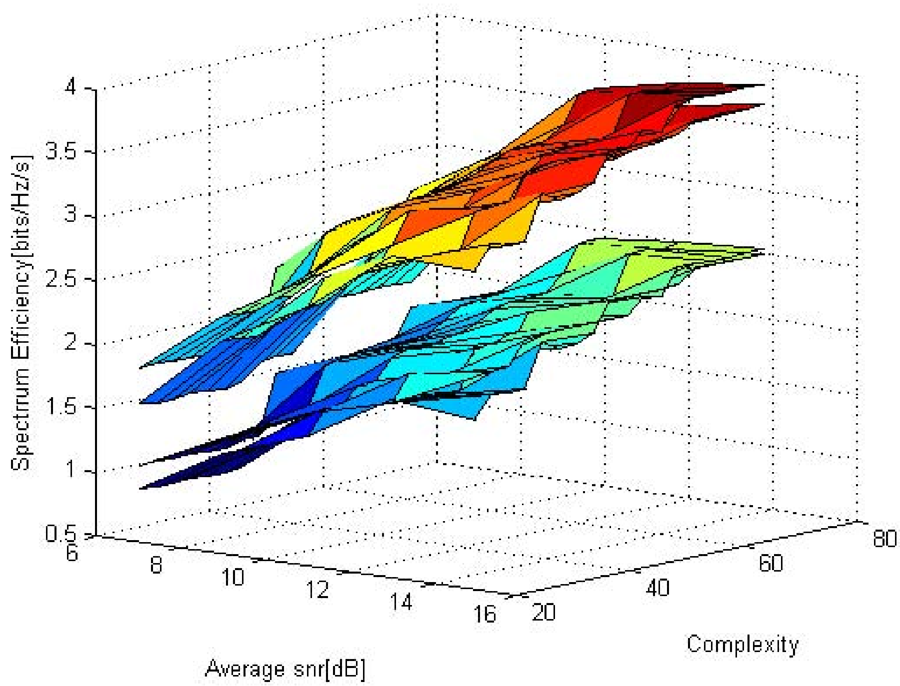

Figure 5.9: Spectrum efficiency at $BER = 10^{-6}$ for varying complexity.

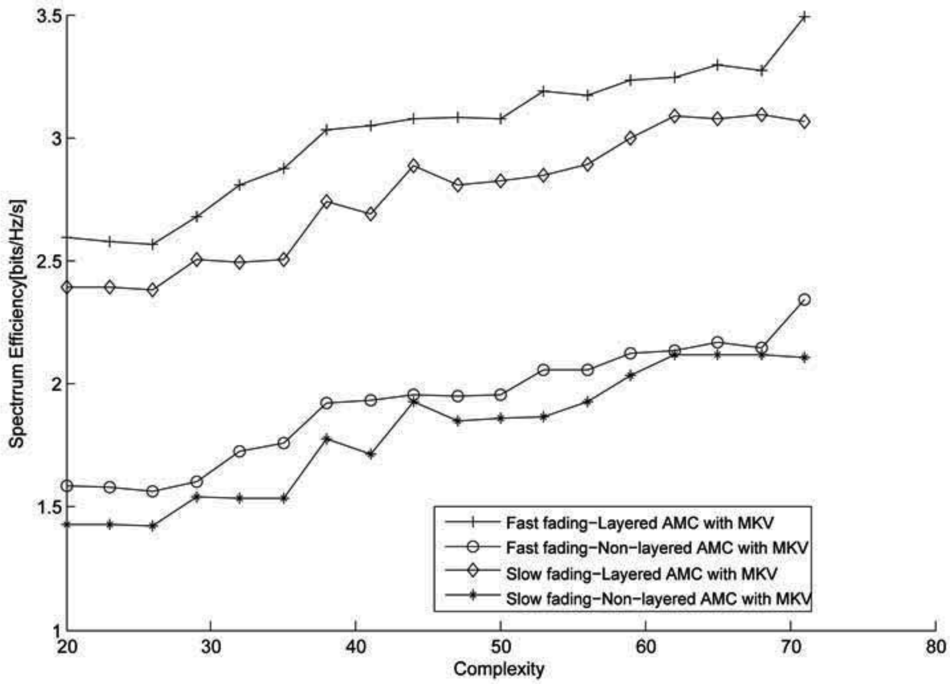

Figure 5.10: Spectrum efficiency at $BER = 10^{-6}$ for varying complexity at SNR 10dB.

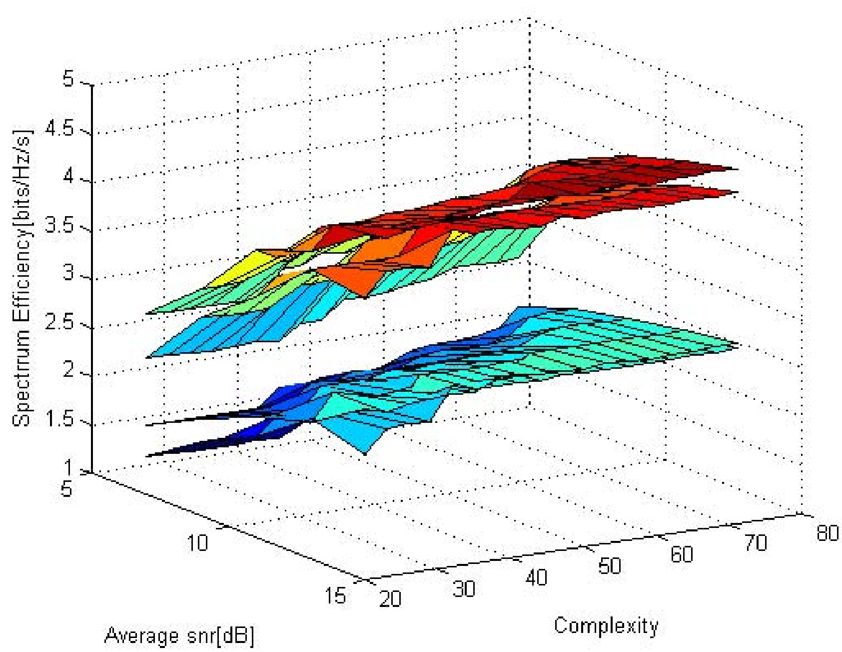

Figure 5.11: Spectrum efficiency at $BER = 10^{-4}$ for varying complexity.

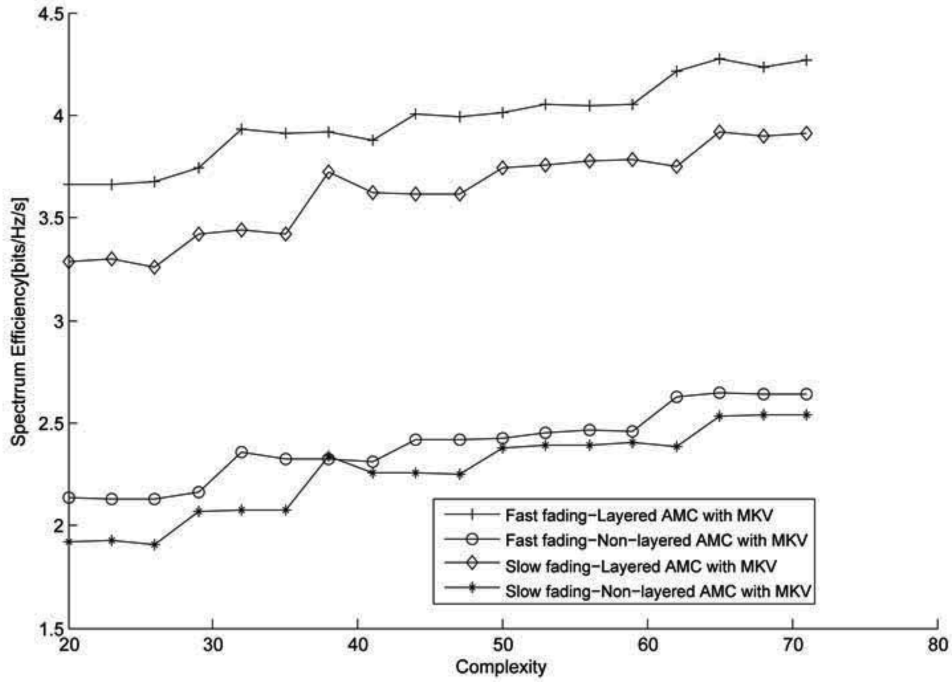

Figure 5.12: Spectrum efficiency at $BER = 10^{-4}$ for varying complexity at SNR 10dB.

In practice, for sufficiently large number of layers of power ratio allocations, impractical computations would be introduced, rendering the optimal search procedure unreasonable. Due to the complex formulations of the proposed framework, extensive simulations were performed to study the behavior of spectrum efficiency and system complexity to demonstrate the sufficiency of the two-layer scheme to achieve favorable results for power allocation.

The simulations were performed using an Intel Core 2 Duo processor clocked at 2.26 GHz with 3 GB of RAM. The study of increased allocated layers focused on the increased computation complexity of two and three layer schemes without losing generality. The QoS requirement was set to $BER = 10^{-6}$.

Table 5.1 summarizes the elapsed time for different units of allocated power for each layer. Simulation results show that when the total allocated power was set to 100, 200, or even 800 units, the spectrum efficiencies of the two and three layer schemes are very similar, while the elapsed time to perform the simulation increased up to 1000 times. Even for power workstations, such complexity is unacceptable. The unchanged results in spectrum efficiency with the addition of the third layer is reasonable, given that to maximize spectrum efficiency, most of the power will already have been allocated for base layer transmission, with the remainder left over for upper layers to increase spectrum efficiency. Thus, more precise power allocation can be employed while maintaining reasonable complexity in the two-layer scheme over the three-layer scheme for optimized power allocation.

Table 5.1: complexity calculation time for multi-layer scheme

layer scheme	unit	whole elapsed time (seconds)	each run elapsed time (seconds)
2 layers	100	27.556	0.138
3 layers	100	338.838	1.694
3 layers	200	1499.577	7.498
3 layers	400	6064.188	30.321
3 layers	800	25704.508	128.523

Chapter 6

Conclusion

This thesis introduced a novel framework by incorporating AMC with layered transmission through SPC to tackle the effects of decreased performance caused by the stale CSI problem. An efficient layered multi-step FSMC model is developed to assistant the system choose optimal modulation and coding scheme, as well as the power allocated for each layer in every multi resolution transmission under this framework.

Combining these two schemes allows superimposed layered data to be transmitted on the channel which is under the predication of the layered multi-step FSMC model. The results that from the lower-rate portion of an SPC transmission on overestimated CSI may still likely be secured instead of being completely lost, while both the lower-rate and higher-rate data of an SPC transmission can be decoded and obtained on an underestimated channel. In this sense, the whole system throughput can be enlarged.

The layered FSMC model in this thesis was designed to include multi-step transitions to help the system select a more accurate and relevant modulation and coding scheme for each layer in every multi-resolution unicast transmission. The multi-step transitions are calculated from the channel characteristic received from CSI. Moreover, in the proposed model, layer SPC symbols are incorporated in each state to give the model multi chances to recover information data.

To allow the proposed layered multi-step FSMC model to have close to reality performance, the layered multi-step FSMC model in this thesis was designed with constrains of a complexity parameter. Values of complexity factor and step size are discussed extensively in the thesis to better a predicate channel state. Additionally a search strategy on how to efficiently obtain optimal values for the power and modulation scheme is given.

Simulation results prove that this proposed framework generally achieves higher spectrum efficiencies over a system using non-layered AMC, even when the proposed framework simply uses average CSI feedback without FSMC estimation for optimal modulation and coding selections. Simulation results also demonstrated that two layer schemes is the good choice for allocating powers and more layers are not needed in practice for implementation. The proposed layered AMC framework is believed to be fundamentally applicable for incorporation into emerging 4G wireless technologies to reduce the gap between achievable channel performance and the Shannon capacity limit.

Bibliography

[1] K. Cheong W. Choi and J. Ciof. *Adaptive Modulation with Limited Peak Power for Fading Channels*. IEEE Proc., pp. 2568-2571, March. 2000. 1

[2] A. J. Goldsmith and S. G. Chua. *Adaptive Coded Modulation for Fading Channels*. IEEE Trans. Commun.,vol. 45, pp. 595-602, May 1998. 1

[3] V. Lau and M. Macleod. *Variable Rate Adaptive Trellis Coded QAM for High Bandwidth Efficiency Applications in Rayleigh Fading Channels*. IEEE Proc., pp. 348-352, Apr. 1998. 1

[4] S. M. Alamouti and S. Kallel. *Adaptive Trellis-Coded Multiple-Phased-Shift Keying for Rayleigh Fading Channels*. IEEE Trans. Commun., vol. 42, pp. 2305-2314, June 1994. 1

[5] K. J. Hole and G. E. ien. *Spectral Efficiency of Adaptive Coded Modulation in Urban Microcellular Networks*. IEEE Trans. Veh. Technol., vol. 50, pp. 205-220, Jan. 2001. 1

[6] 3GPP TS 25.201. *Physical layer general description*. http://www.3gpp.org/ftp/Specs/html-info/25-series.htm. 1, 5

[7] IEEE Standard 802.16e 2005. *IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air Interface for Fixed and Mobile Broadband Wireless Access Systems*. Feb. 2006. 1

[8] 3GPP TS 36.211. *Physical channels and modulation*. http://www.3gpp.org/ftp/Specs/html-info/36-series.htm. 1

[9] E. Bjrnson and B. Ottersten. *A Framework for Training-Based Estimation in Arbitrarily Correlated Rician MIMO Channels with Rician Disturbance*. IEEE Trans. on Signal Processing, vol. 58, pp. 1807- 1820., 2010. 2

[10] Abou Saleh and H.A. Hamouda. W. *Cross-Layer Criterion for MIMO Spatial Multiplexing Systems with Imperfect CSI*. IEEE Veh. Tech. Conference, pp. 1 - 5,, April 2009. 2, 5

[11] M Siva Ganga Prasad, P Siddaiah, and L Pratap Reddy. *Optimization of Training Sequence Length for Enhancement of Channel Capacity in Wireless Communications*. International Journal of Computer Science and Network Security,Vol. 8 No. 6 pp. 321-328. 2

[12] P.C. Cosman, K.O. Perlmutter, Olshen Perlmutter, S.M., R.A., and R.M. Gray. *Training Sequence Size and Vector Quantize Performance*. Signals, Systems and Computers, 1991. 1991 Conference Record of the Twenty-Fifth Asilomar Conference on, vol.1, pp. 434 - 438, Nov 1991. 2

[13] J. Yang, A.K Khandani, and N. Tin. *Statistical decision making in adaptive modulation and coding for 3G wireless systems*. IEEE Trans. on Veh. Tech., vol. 54, no. 6,pp. 2066-2073, Nov. 2005. 3, 11

[14] H.S. Wang and N Moayeri. *Finite-state Markov channel-a useful model for radio communication channels*. IEEE Trans. on Veh. Tech., vol. 44, no. 1,pp. 163-171, 1995. 3

[15] H.S. Wang and P.-C. Chang. *On verifying the first-order Markovian assumption for a Rayleigh fading channel*. IEEE Trans. on Veh. Tech., vol. 45, no. 2,pp. 353-357, May 1996. 3

[16] C. C. Tan and N. C. Beaulieu. *On first-order Markov modeling for the Rayleigh fading channel*. IEEE Trans. on Comm., vol. 48, no. 12,pp. 2032-2040, Dec. 2000. 3

[17] F. Hou, J. She, Pin-Han Ho, and Xuemin Shen. *Performance Analysis of ARQ with Opportunistic Scheduling in IEEE 802.16 Networks*. Proc. IEEE Global Communications Conference, pp. 4759-4763, Washington, DC, USA, Nov. 2007. 3

[18] Y. L. Guan and L. F. Turner. *Generalized FSMC model for radio channels with correlated fading*. IEE Proc. Part F, vol. 146, no. 2,pp. 133- 137, Apr. 1999. 3

[19] M. Zorzi, R. R. Rao, and L. B. Milstein. *ARQ error control for fading mobile radio channels*. IEEE Trans. on Veh. Technol., vol. 46, pp. 445-455, May 1997. 3

[20] F Babich and G Lombardi. *On verifying a first-order Markovian model for the multi-threshold success/failure process for Rayleigh channel*. IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications, vol. 1,pp.12 - 16., Sept. 1997. 3, 5, 11

[21] J. She, F. Hou, Pin-Han Ho, and Liang-Liang Xie. *IPTV OVER WiMAX: Key factors, challenges, and Solutions*. IEEE Commun, Magazine, vol 45, no. 8,pp. 87-93, Aug. 2007, Nov 1991. 5, 14

[22] J. She, Xiang Yu, Pin-Han Ho, and En-Hui Yang. *A cross-layer Design Framework for Robust IPTV Services over IEEE 802.16 Networks*. IEEE Journal of Selected Areas on Commun, vol. 27, no.2,, pp. 235-245, Feb.2009. 5

[23] M.J Hossain, Litthaladevuni, Alouini P.K, Bhargava M.S, V.K, and Goldsmith. *adaptive hierarchical modulation for simultaneous trans*. Veh. Tech, vol 55, pp., 1181-1194, Jul. 2006. 5, 14

[24] H. Suzuki. *A statistical model for urban multipath propagation*. IEEE Trans. On Commun., vol. COM-25, pp. 673-680, July 1977. 10

[25] T. Aulin. *Characteristics of a digital mobile radio channel*. IEEE Trans. on Veh. Technol.vol. VT-30, pp. 45-53, May 1981. 10

[26] W. R. Braun and U. Dersch. *A physical mobile radio channel model*. IEEE Trans. on Veh. Technol., vol. VT-40, pp. 472-482, May 1991. 10

[27] A. U. Sheikh, M. Handforth, and M. Abdi. *Indoor mobile radio channel at 946 MHz: measurements and modeling*. Proc. IEEE Veh. Technol. Conf. (VTC'93,)pp. 73-76, Secaucus, NJ, May 1993. 10

[28] E. J. Fremouw and H. F. Bates. *Worldwide behavior of average VHF-UHF scintillation*. Radio Sci., vol. 6,pp. 863-869, October 1971. 10

[29] H. E. Whitney, R. S. Allen J. Aarons, and D. R. Seeman. *Estimation of the cumulative probability distribution function of ionospheric scintillations*. Radio Sci., vol. 7, pp. 1095-1104, December 1972. 10

[30] E. J. Fremouw, R. C. Livingston, and D. A. Miller. *On the statistics of scintillating signals*. J. Atmos. Terr. Phys., vol. 42,pp. 717-731, August 1980. 10

[31] P. K. Banerjee, R. S. Dabas, and B. M. Reddy. *C-band and L-band transionospheric scintillation experiment: some results for applications to satellite radio systems*. Radio Sci., vol. 27,pp. 955-969, June 1992. 10

[32] C. Berrou, A. Glavieux, and P. Thitimajshima. *Near Shannon limit error-correcting coding and decoding: Turbo-codes*. Proc. ICC'93, pp. 1064-1070, May 1993.

[33] S. Vishwanath and A. J. Goldsmith. *Exploring Adaptive Turbo Coded Modulation for Flat Fading Channels*. Proc. VTC, vol. 4, pp. 1778-1783, Fall 2000.

[34] S. O. Rice. *Mathematical analysis of random noise.* Bell Syst. Tech. J., vol. 23, pp. 282-332, July 1944.

[35] K. B. Letaief, J. Lu, and M. L. Liou. *Robust video transmission over correlated mobile fading channels.* IEEE Trans. on Circ. and Syst. For Video Tech., vol. 9, no. 5, pp. 737-751, Aug. 1999.

[36] IEEE standard 802.16e 2005. *IEEE Standard for Local and Metropolitan Area Networks - Part 16: Air interface for Fixed and Mobile Broadband Wireless Access.* Feb. 2006.

[37] Jon W. Mark and Weihua Zhuang. *Wireless communications and networking.* Morgan Kauffmann publisher, San francisco, 2007.

[38] J. She, J. Ho, J. Mei, Pin-Han Ho, and H. Ji. *Layered Adaptive Modulation and Coding for 4G Wireless Networks.* IEEE Global Communications Conference, 2010.