PERFORMANCE MODELING OF ADAPTIVE MODULATION CODING SCHEMES ON RAYLEIGH FADING CHANNELS

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To God Who lets His Wisdom unfolds,
To my family,
To all who have loved me and supported me unconditionally

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ABSTRACT

Adaptive modulation coding schemes (MCSs) are important techniques in wireless data communication to minimize the bit-error-rate (BER) and maximize throughput. Usually, the adaptive system consists a few MCSs that will intelligently adapt to channel variation. At the receiver, the MCS transition is decided by link quality analysis and the result is sent to transmitter via acknowledgement data. Therefore, the system performance cannot rely on a single MCS. This research developes a methodology to estimate an adaptive MCS performance using Markov model. The model concerns type I Hybrid automatic repeat request (ARQ) system which is a combination of forward error control (FEC) and ARQ under the Rayleigh fading condition. The two-state Markov model performance estimation (MMPE-2) and four-state Markov model performance estimation (MMPE-4) are proposed, where the system performance are estimated based on packet error probability and level crossing probability of the Rayleigh fading condition. Performance comparison between estimation models and simulation using International Radio Consultative Committee (CCIR) 520-2 channel model is made and the results shows that MMPE-4 are comparable for fade duration longer than the packet length. From the models, the analysis on traffic and acknowledgement data in term of bit BER and throughput can be done theoretically prior to any simulation and experiment. This can save a lot of time and the modification on the system can be done before proceeding for further evaluation or implementation. By using the estimation models as tools, several new adaptive MCSs are evaluated and the best adaptive system is proposed for high frequency data communication system.

ABSTRAK

Adaptif modulasi pengekodan (AMP) adalah teknik yang penting dalam komunikasi data tanpa wayar bagi meminimumkan kadar salah bit dan memaksimumkan perolehan data. Biasanya, sistem adaptif terdiri daripada beberapa AMP yang akan menyesuaikan sistem dengan variasi saluran. Pada penerima, peralihan antara AMP ditentukan berdasarkan analisis kualiti talian dan hasilnya dihantar kepada pemancar melalui maklum-balas data. Oleh itu, prestasi sistem tidak boleh diandaikan berdasarkan satu AMP sahaja. Penyelidikan telah membangunkan satu methodologi untuk menganggar prestasi adaptif AMP dengan menggunakan model Markov. Model yang dibangunkan memberi penekanan kepada Adaptif sistem automatik ulang semula Jenis 1 yang merupakan gabungan kawalan salah hadapan and automatik ulang semula di dalam keadaan pemudaran Rayleigh. Model Anggaran Prestasi Markov Dua Keadaan dan Model Anggaran Prestasi Markov Empat Keadaan telah dicadangkan dengan prestasi sistem dihitung berdasarkan kebarangkalian salah data dan kebarangkalian kadar tahap persimpangan bagi keadaan pemudaran Rayleigh. Perbandingan di antara model dan simulasi menggunakan Jawatankuasa Konsultif Radio Internasional 520-2 saluran model telah dilaksanakan dan keputusan menunjukkan Model Anggaran Prestasi Markov Empat Keadaan sama dengan simulasi untuk keadaan masa pemudaran lebih panjang daripada panjang data. Daripada model-model yang dibangunkan, analisis untuk trafik dan maklum-balas data dari segi kadar salah bit dan perolehan data dapat dilakukan secara teori sebelum ke peringkat simulasi atau ekperimen. Ini dapat menjimatkan masa dan pengubahsuaian pada sistem boleh dilaksanakan sebelum meneruskan penilaian rekabentuk ke peringkat seterusnya. Dengan menggunakan model sebagai alat pengukur, beberapa AMP yang baru telah dinilai dan adaptif sistem yang paling baik telah dicadangkan untuk sistem komunikasi data frekuensi tinggi.

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A - Signal Amplitude

C - Code Rate

d_k - Differential Encoded Sequence

d_{min} - Minimum Distance

f_b - Signal Bandwidth

f_m - Doppler Spread

f_n - Sub-carrier Frequency

$I(t)$ - In-phase Complex Signal

I_k - In-phase Bit

k - Information Bits

K - Number of States

l - Error Detection Capability

M - Number of Phases

m_k - Modulo Sum

n - Codeword

N - Packet Length

$N(\Gamma)$ - Level Crossing Rate

N_0 - Gaussian Noise Power

P - State Transition Matrix

P_b - Uncoded Bit Error Rate

P_c - Coded Bit Error Rate

P_e - Symbol Error Rate

P_{est} - Estimated BER

P_{ij} - Transition Probability

PL_{ij} - Level Crossing Probability

P_r - Binomial Distribution

$Q(\,)$ - Q Function

$Q(t)$ - Quadrature Complex Signal

Q_k - Quadrature Bit

r - Number of Repetition

$R(t)$ - Received Signal Envelop

R_s - Symbol Rate

$\underline{S}$ - State Probability Vector

$S(f)$ - Power Spectrum

$S_{\pi/4\ DQPSK}(t)$ - $\pi/4$ DQPSK Modulated Signal

t - Error Correction Capability

T_b - Symbol Duration

T_D - Total Transmission Time

T_h - Average Throughput

T_h/R_s - Normalized Throughput

T_p - Packet Duration

T_R - Average Duration Fade

w - Hamming Weight

$x(t)$ - Transmit Signal

$x_n(t)$ - Sinusoid Signal

$y(t)$ - Received Signal

γ - Average Signal to Noise Ratio

Γ - SNR Threshold

η - Effective Symbol Duration

Λ_p - Product Distance

π - Utilization Probability

$\rho_r(r)$ - Rayleigh Distribution

$\rho_z(z)$ - Exponential Distribution

φ_k - Phase Shift

$\Psi(\gamma)$ - Packet Error Probability

LIST OF ABBREVIATIONS

4SMM - Four-state Markov Model
ACK - Acknowledgement
ADF - Average Duration Fade
ADSL - Asymmetric Digital Subscriber Line
ALE - Automatic Link Establishment
APCO P25 - Association of Public-Safety Communications Officials Project 25
ARQ - Automatic Repeat Request
ASK - Amplitude Shift Keying
AWGN - Additive White Gaussian Noise
BER - Bit Error Rate
CCIR - International Radio Consultative Committee Recommendation
CDMA - Code Division Multiple Access
CLPC - Close Loop Power Control
CP - Cyclic Prefix
CRC - Cyclic Redundancy Check
CS - Coding Scheme
CSI - Channel-State Information
DECT - Digital Enhanced Cordless Telecommunications
DFB - Decision Feedback
DFT - Discrete Fourier Transform
DPSK - Differential Phase Shift Keying
DQPSK - Differential Quadrature Phase Shift Keying
DSTM - Differential Space-Time Modulation

DVB	-	Digital Video Broadcasting
EDGE	-	Enhanced General Packet Radio
EM	-	Electromagnetic
FEC	-	Forward Error Correction
FFT	-	Fast Fourier Transform
FH	-	Frequency Hopping
FSK	-	Frequency Shift Keying
FSMC	-	Finite State Markov Channel
GBNARQ	-	Go-Back-N ARQ
GI	-	Guard Interval
GM	-	Graphical Model
GMSK	-	Gaussian Minimum Shift Keying
GPRS	-	General Packet Radio Service
GPS	-	Global Positioning System
GSM	-	Global System for Mobile Communications
HARQ	-	Hybrid Automatic Repeat Request
HF	-	High Frequency
HSDPA	-	High Speed Downlink Packet Access
ICI	-	Inter sub-Carrier Interference
IDFT	-	Inverse Discrete Fourier Transform
IFB	-	Information Feedback
IFFT	-	Inverse Fast Fourier Transform
ILP	-	Institut Latihan Perindustrian
IMT	-	International Mobile Telecommunications
IP	-	Interference Projection
ISI	-	Intersymbol Interference
ITU	-	International telecommunication Union
JPDF	-	Joint Probability Density Function
LCP	-	Level Crossing Probability
LCR	-	Level Crossing Rate
LPF	-	Low Pass Filter
LQA	-	Link Quality Analysis
LS	-	Least Square
LSB	-	Left Significant Bit

MCM - Multi sub-Carrier Modulation
MCS - Modulation Coding Scheme
MEDLL - Multipath Estimating Delay Lock Loop
MIL-STD - Military Standard
MIMO - Multi-Input Multi-Output
ML - Maximum Likelihood
MMPE - Markov Model Performance Estimation
MMSE - Minimum Mean Square Error
MPSK - M-ary Phase Shift Keying
MRRC - Maximal-Ratio Receiver Combining
NACK - Negative Acknowledgement
OFDM - Orthogonal Frequency Division Multiplexing
OLPC - Outer Loop Power Control
PAPR - Peak to Average Power Ratio
PC - Power Control
PDF - Probability Density Function
PEM - Pseudo-Error Monitoring
PEP - Packet Error Probability
PER - Packet Error Rate
PMC - Pseudo-Markov Compression
PN - Pseudo Noise
PSK - Phase Shift Keying
QAM - Quadrature Amplitude Modulation
QoS - Quality of Service
QPSK - Quadrature Phase Shift Keying
RF - Radio Frequency
SB - Subspace-Based
SDR - Software Defined Radio
SER - Symbol Error Rate
SIMO - Single-Input Multiple-Output
SINR - Signal Interference to Noise Ration
SIR - Signal Interference Ration
SISO - Single-Input Single-Output
SLS - Scaled Least Square

SNR - Signal to Noise Ratio
SP - Signal Projection
SRARQ - Selective-Repeat ARQ
STANAG - Standardization Agreement
STBC - Space-Time Block Code
SWARQ - Stop-Wait ARQ
TETRA - Trans European Trunked Radio
UHF - Ultra High Frequency
UMTS - Universal Mobile Telecommunications System
US - Uncorrelated Scattering
UTM - Universiti Teknologi Malaysia
VHF - Very High Frequency
W-CDMA - Wideband Code Division Multiple Access
WSS - Wide-Sense Stationary
WSSUS - Wide Sense Stationary Uncorrelated Scattered
π/4 DQPSK - π/4 Differential Quadrature Phase Shift Keying

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CHAPTER 1

INTRODUCTION

1.1 Research Background

An adaptive modulation coding scheme (MCS) is a method that is widely used in digital wireless communication to maximize the reliability and throughput due to variation of channel conditions. Usually, an adaptive MCS consists of several MCS with different level robustness and it varies accordingly depending on current channel condition. In poor condition, robust MCS with lower throughput is utilized to ensure reliability and it changes to another MCS with less robust in good condition [1].

Typically, MCS is a combination of modulation and forward error correction (FEC) that merge together in a packet format before data transmission. Any error due to channel propagation will be corrected by the FEC. However, there is a limitation of FEC since errors are still present after the correction and this will corrupt the information. Therefore, Automatic Repeat Request (ARQ) is used as a second layer protection where the retransmission of previous data is required until no error presents in the transmission. The combination of FEC and ARQ is known as hybrid error correction.

The great demand for higher data rate leads further research on adaptive system in various communication environments. In Global System for Mobile Communications (GSM), an adaptive MCS is employed in General Packet Radio Service (GPRS) and Enhanced General Packet Radio (EDGE) for data exchange.

Since the adaptive method capable of maximizing the system performance, it is extended further and adopted in 3G technology. High Speed Downlink Packet Access (HSDPA) is among of the recognized 3G technology that widely used for broadband data communication.

Similar to mobile communication, an adaptive system is also adopted in HF communication. Various data formats that are available for commercial use are PACTOR I, PACTOR II, PACTOR III, GTOR and CLOVER2000. For military operation, MIL-STD-188-110A and MIL-STD-188-110B are considered as standards for HF data format. Both data formats were then adopted by NATO for alliance countries which recognized as STANAG 4285 and STANAG 4539. The data format either for commercial or military contains several modulation coding schemes with different robustness that alternately changes depend on channel conditions to maximize the reliability and throughput.

Compare to VHF and UHF communication system, HF communication provides nearly global connectivity at low power and low cost without any repeaters. HF communication also offers free air time to users and this privilege is not applicable for either cellular or satellite communication where the users have to pay to the service provider. Besides voice and telegraphy, services that are available today on HF include short messaging, email[2], fax and telemetry. The applications either in broadcast or point-to-point communication do not require third party service provider and completely under national control.

Various type of adaptive system with several MCS will ensure the connectivity although at poor channel condition. Since the system changes the MCS rapidly, the system performance is contributed from multiple MCS and cannot be represented by single MCS. Therefore, an appropriate estimation model is required to predict the performance of adaptive system mathematically prior to any simulation and experimental. The model can be used as a tool for design process where the performance of new adaptive system can be evaluated theoretically. Any modification to improve the system design can be done directly without the need of simulation results. By using this approach, the simulation is required after final modification for system verification and this reduce time and energy consumption.

1.2 Problem Statements

In digital wireless communication, the signals between two stations are characterized by wide sense stationary uncorrelated scattered (WSSUS) channel where it includes multipath fading, path lost and interference due to additive white Gaussian noise (AWGN). Multipath fading occurs when the radio signal is reflected and refracted by terrestrial objects such as buildings and mountains and as a result the signal reaching the receiver antenna by two or more paths. For HF communication, the refraction is due to variability in the electron density in the electron density layers in the ionosphere [3]. These propagation phenomena which also known as Rayleigh fading will attenuate the signal amplitude and introduced error burst. This will increase the bit error rate (BER) and minimize the reliability.

Typically, problem of multipath fading can be categorized as time selective fading or flat fading and time delay spread. Time selective fading introduced by Doppler spread and Doppler shift can be further classified as slow and fast fading. This results in the presence of error burst within a packet of transmitted data. Time delay spread limits data transfer rate and under worst case condition will cause interference between transmitted symbols knows as intersymbol interference (ISI). In frequency domain, time delay spread can be viewed as frequency selective fading which causes attenuation within a range of frequencies within a given bandwidth.

Due to channel variations introduced by multipath fading, the instantaneous SNR at certain instances is either lower or higher compared to average SNR. Therefore, digital wireless communication system cannot rely on a single MCS but requires few MCS with different modulations and code rates to adapt with SNR variations. With a multiple MCS that operates adaptively, the system is capable in delivering high throughput and robustness in either good or poor channel conditions.

Usually, an adaptive digital communication includes additional features such as sounding or control channel and link quality analysis (LQA) that are used to estimate the channel conditions. LQA determines which MCS is suitable for the appropriate situation. Since an adaptive system contains multiple MCS, the average system performance cannot be represented by an individual MCS. In normal practice, the performance of average system is verified by simulation and experimental where both consumed time. The modification is required to overcome any weaknesses on system design and the process for system verification repeats until the desired result is achieved.

For the given defined problem, the research interest is to develop a model to estimate the average system performance of adaptive system in terms of bit error rate (BER) and throughput. The developed system model can be utilized as a tool to verify and optimize the system design prior to any simulation or experiment. From the model, adaptive data communication system which is suitable for the HF radio frequency spectrum is proposed. The design is more concerned on flat fading or time selective fading since it can be overcome by using forward error correction (FEC) coding. Provided with the link quality analysis, the system is capable for estimating the channel conditions and an appropriate MCS is chosen for data transmission. Even though the proposed system looks for a specific solution related to HF communication, the developed system models are applicable for other types of wireless communication where the effect of multipath fading is a significant problem.

1.3 Thesis Objectives

There are two main objectives that need to be achieved in this research as follows:

i. Develop an estimation model to predict the average performance of adaptive MCS in terms of BER and throughput. From the characteristic of adaptive

MCS due to WSSUS channel, the performance estimation models are developed. This model considers both traffic and acknowledgement data since those are complement to each other to ensure an adaptive system to work accordingly. Errors in those transmitted data will influence the average system performance. With a complete knowledge of modulation and error coding scheme, the estimation parameters such as packet error probability (PEP) and level crossing probability (LCP) are obtained. And by using Markov process, the probability of each MCS used in data communication is determined. For verification, the adaptive MCS based on hybrid ARQ system is introduced and comparison is made for various channel conditions.

ii. Design and propose the adaptive MCS that contain set of modulation and error correction coding for HF data communication. Associated with estimation model, several MCS are evaluated mathematically and only selected systems design are simulated for verification. By using this approach, any weaknesses of the system design can be overcome immediately without requires simulation or experiment and can minimize time consumption. This second objective is to demonstrate the advantage of developed estimation model as a design tool. The proposed system will include the LQA capability to estimate given channel condition and choose the appropriate MCS to ensure maximum throughput and reliability. The LQA is based on error detection method using cyclic redundancy check (CRC) and it does not require training data. An acknowledgement or feedback from the receiver is an important component to ensure the adaptive system operates appropriately since it carries the LQA results. Besides choosing which MCS should be used, the LQA also informs the transmitter whether retransmission of previous data is required or not. Errors on acknowledgement will disturb the chosen MCS according to LQA and this can reduce the system performance. The importance of an acknowledgement is addressed in estimation model and applied in proposed system.

1.4 Scope of Work

The research intention is on performance modeling of adaptive system, modulation and error correction schemes. Due to multipath fading characteristic, the envelope of the received signal will vary and the adaptive system attempts to find the suitable MCS for the given SNR. Since the present MCS depends on its previous, the Markov process is used to describe the overall system behavior. Each MCS is represented as a state and the number of state depends on number of MCS that are employed in an adaptive system. The transition between the states depends on LQA's result that carried by an acknowledgement data. Two major factors that contribute to the LQA's result are packet error and Doppler spread. Therefore, both parameters are considered during the calculation of system performance. As a result of performance estimation, the theoretical estimation of BER and throughput will compare with the simulation for verification.

In wireless communication, interference from unwanted signal and white noise contributes to errors in the received data. Error correction schemes are introduced to overcome this problem and can be classified as forward error correction and automatic repeat request [4] or a combination of both. For wide sense stationary channel, where the channel characterizes by time selective fading, the errors not only occur in random but it also appears in burst. This reduces FEC performance due to limitation of error correction capability. Therefore, the interleaving with appropriate depth is utilized together with the FEC as it randomized the error burst. Sometimes, a very long burst could cause both FEC and interleaving failure to correct the error. Here, second layer of protection is required and it is done by an ARQ scheme. Therefore, a hybrid or concatenated error is evaluated to as the design of the adaptive MCS.

Besides concentrating on traffic data which contain several MCS, the research also gives an intention on acknowledgement data and LQA. As part of adaptive system, the LQA is more on processing unit that estimates the channel conditions [1] while the acknowledgement is a medium to convey the LQA's results.

It is to ensure that the transmitter utilizes the correct MCS according to channel conditions. For that reason, analysis of acknowledgement is conducted to observe the effect on system performance. This result will be applied to complete the structure of the proposed system design.

Defining a suitable channel model is essential to ensure the analysis result is close to actual channel environment. For VHF and UHF spectrum, Jakes channel model [5] is appropriate while for HF spectrum Watterson channel model also known as CCIR 520-2 is preferred since it is recommended by International Telecommunication-Union [6, 7]. Since the proposed adaptive MCS is for HF data communication, CCIR 520-2 is chosen as a channel model for analysis and simulation. The proposed system does not consider frequency selective fading problem and the performance verification between estimation models and the proposed adaptive MCS is based on simulation using MATLAB software. The system design follows the standard bandwidth given by International Telecommunication Union (ITU) for HF communication channels which is 3 kHz. And according to Nyquist theorem, the sampling frequency is set to 8000 Hz. In additional, the proposed estimation model is also applicable for VHF application. This is because the parameters that used for calculation is also relevant for VHF channel propagation.

Besides modulation and error correction scheme, the transmission BER performance and throughput can be further enhanced by using channel equalizer [4] and compression techniques such as Huffman and Markov [8] code. All of the techniques are not included in this research because the main objective of the research is to model and analyze the performance of adaptive system based on modulation and coding schemes.

1.5 Research Methodology

In order to achieve the objectives, the research is organized as follows:

i. Literature review on problems and trends in HF communications in order to understand the problem with wide sense stationary channel and the existing solution. Utilize the facilities that are available at DSP Lab, UTM, the experiments and analysis are conducted to observe and monitor the HF, VHF and UHF communication traffic. From the analysis, the advantages and limitation of existing data format are determined and the knowledge is essential for developing of new adaptive modulation coding scheme.

ii. The CCIR 520-2 channel model is developed using the MATLAB software. The model verification is done by comparing the simulation and theoretical computation in terms of Level Crossing Rate (LCR) and Average Duration Fade (ADF) for appropriate Doppler spread condition.

iii. By considering error in traffic data, acknowledgement and fading conditions, the estimation models for adaptive MCS are developed. The developed models are capable to predict the average system performances in terms of BER and throughput. Comparison between the estimation and simulation is performed for various channel conditions for verification.

iv. Further, the analyses of various acknowledgement schemes are conducted to observe the effect of acknowledgement for adaptive system. Several acknowledgements are introduced and for each analysis, the simulation is made for verification. By using developed model, the analysis is extended to other application such as adaptive close loop power control (CLPC), adaptive orthogonal frequency division multiplexing (OFDM) and adaptive multiple input multiple output (MIMO) system.

v. Next, several adaptive modulation coding scheme with different capacity are designed to overcome time selective fading problem and all of them are evaluated using the estimation model. From the prediction results, the best performance of adaptive MCS is proposed for HF data communication. Simulation of proposed system is made for verification.

vi. Instead of modulation and coding scheme, other parameters that influence the system performance such as packet length, number of coding scheme, interleaving and acknowledgement are also considered in the development of adaptive system. The simulation in only performed for the chosen adaptive MCS due to prediction results. Others are not required because they are not achieving the target. This approach can minimize time consumption because only selected system is chosen for further evaluation. Otherwise the simulation for each adaptive MCS is required.

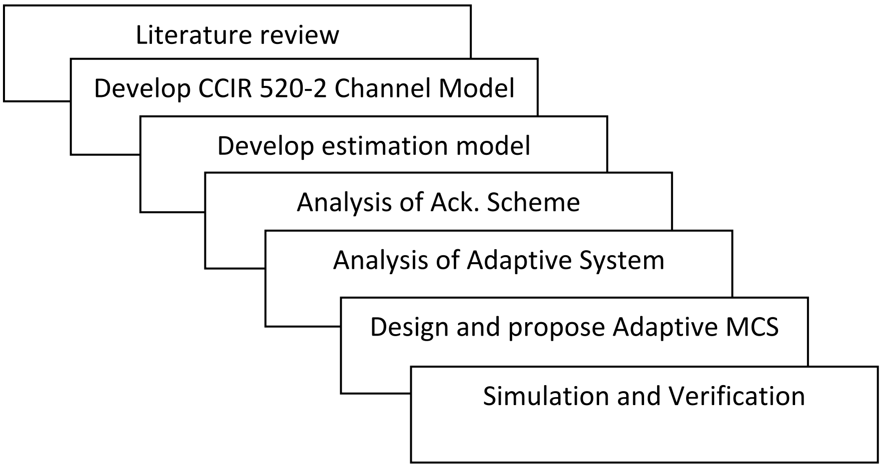

Figure 1.1 Summary of Research Methodology

1.6 Contributions of Work

The research work is performed accordingly as described in section 1.5 such as to achieve research objectives. The aims of the works and their contributions are as follows:

i. The estimation models for an adaptive system are proposed by using Markov chain model. With a complete knowledge of modulation and error correction schemes, a systematic methodology to predict the average BER and throughput for an adaptive MCS is developed. The model assumes error is present in both traffic and acknowledgement data. Since each MCS is represented as a state, the complexity of estimation model depends on number of MCS that is employed in adaptive system. Comparison between simulation and estimation is done where both are comparable for fade duration longer than a packet length.

ii. The proposed models can be extended further to N number of states depending on number of MCS in adaptive system. Although the number of states increases but the methodology for computing the transition probabilities between the states are still similar to the MMPE-4.

iii. The proposed estimation model is not only applicable for single sub-carrier adaptive system but also valid to predict the performance of adaptive outer loop power control (OLPC) system, adaptive orthogonal frequency division multiplexing (OFDM) system and adaptive multi input multi output (MIMO) system.

iv. The proposed model is very useful tool for design process where the system performance can be predicted theoretically prior to simulation and experimentation. Therefore, any modifications on system design can be performed immediately. This may reduces design turnaround time and computational resources.

v. An adaptive system that contains several MCS is proposed for wide sense stationary channel. The system utilized M-ary differential phase shift keying as modulation and hybrid type I error correction which a combination of cyclic block code and automatic repeat request to ensure error free transmission. By using short packet length for traffic data, the MCS changes for every data transmission to adapt with channel variations. At low SNR, the system utilizes robust MCS with lower code rate to ensure reliability and changes to higher code rate to increase the throughput at high SNR.

vi. Link quality analysis based on error detection of traffic data is proposed and included in design system to estimate the channel conditions and to choose the appropriate MCS for the next data transmission. The system will reduce the code rate for the next data transmission when the error is detected in traffic data. Since the Cyclic Redundancy Check (CRC) bits are included in traffic data for error detection, the LQA is done directly after the block code decoding. No training or other overhead data required for LQA.

vii. The proposed adaptive system is not completed without the acknowledgement data. The robust acknowledgement data is essential to ensure the information on the transmission status and the LQA results to return to the transmitter correctly. An error on acknowledgement data will jeopardize the communication due to the chosen MCS is not reflected to channel condition. Therefore, the analysis of various acknowledgements is conducted using the proposed estimation model. From the analysis, the most robust acknowledgement scheme is chosen to adopt into the proposed system.

1.7 Organization of Thesis

This thesis is divided into seven chapters, including the current one. Chapter 2 presents the literature survey that was done at the earlier stage of the research such as ionosphere properties, HF communication, adaptive system, channel estimation and also several models that used as a platform to estimate system performance

Chapter 3 presents the theory of digital communication including modulation, error correction and interleaving. It is also describing the wide sense stationary uncorrelated scattering channel in terms of first and second order statistic. Then follow by theoretical calculation to obtain steady state of Markov chain model. From the steady state value, the performance of the system can be predicted.

Chapter 4 explains the developed estimation model that can be used to estimate the performance of adaptive system in terms of BER and throughput. Initially, the model assumes the acknowledgement from the receiver that carries information about previous transmission is perfect without any errors. After that, the model is expended in order to include the effect of error on acknowledgement. Details analysis between both models is explained thoroughly. The methodology of developed model is described in last section in this chapter.

In Chapter 5, three types of adaptive system that utilize various diversity techniques are introduced and the performance for each system is predicted using developed models. They are adaptive outer loop power control (OLPC) system, adaptive orthogonal frequency division multiplexing (OFDM) system and adaptive multi-input multi-output (MIMO) system. The performance of each system is predicted and the simulations are conducted for verification.

Several adaptive MCS for HF data communication are designed in Chapter 6 and their performances are estimated using developed model. The best adaptive MCS is chosen based on the highest throughput it can deliver at various SNR conditions with reasonable BER performance. The selected system is verified by simulation before it is proposed for HF data communication. Finally, Chapter 7 consists of the conclusion of works and contributions made in this thesis. It also includes future works that can be done further from this research.

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