CHAPTER 2

LITERATURE REVIEW

In this chapter, a brief summary of the Literature survey and review for the current research work is provided. The review of the ensuing papers motivate in building this research work.

2.1 REVIEW OF EARLIER WORK

In this section, a detailed summary of Literature review of spectrum efficiency of various diversity schemes under different adaptation policies, and interference cancellation techniques, is discussed.

2.1.1 Capacity Analysis of MIMO

The increasing demand for transmitting information over a wireless channel has led to the emergence of Multiple Input Multiple Output (MIMO) technology. The use of multiple antennas at both ends of a wireless link enables the opening of multiple spatial data pipes between the transmitter and the receiver within the frequency band of operation for no additional power expenditure. This leads to a dramatic increase in spectral efficiency, known as spatial multiplexing gain. MIMO technology has materialised its promise of providing high information rates without additional spectral requirements, which has been well explained in the pioneering works of Foschini and Gans [13] and Telatar [14]. There is a considerably large amount of literature on
Rayleigh fading which considers only Non-Line-Of-Sight (NLOS) components. However, in reality, there are Line-Of-Sight (LOS) components between the transmitter and receiver which are best described by the Rician fading distribution. In [15], the author investigates the capacity limits of MIMO communication system following Rician distribution. In [16], the authors arrived at an exact expression for average Mutual Information (MI) rate of MIMO Rician fading channels when the fading coefficients are independent, but not necessarily identically distributed.

Research work in [17] has established that the presence of strong LOS components correlates with the channel sparsity, thereby reducing the number of Degrees of Freedom (DoF). The presence of NLOS components reduces the correlation between the signals thereby increasing the rank of the channel matrix. Capacity of spatially correlated MIMO channels has been obtained in [18]. Both single-sided and double-sided correlation has been considered in [18]. In [19], the author analyses ergodic capacity for MIMO channels with rank-1 mean matrices. Upper and lower bounds on the ergodic capacity have been presented in [19]. Upper bound on ergodic capacity for a system undergoing Rician fading for arbitrary Signal-to-Noise Ratio (SNR) and rank of matrix is derived in [20].

Researchers have analysed ergodic capacity for MIMO channels with rank-1 mean matrices, upper and lower bounds on the ergodic capacity. Moreover, upper bound on ergodic capacity for a system undergoing Rician fading for arbitrary SNR, and rank of a matrix was also derived.
2.1.2 Spectrum Efficiency of various fading channels

Shannon capacity for fading channels was obtained initially with channel side information at the transmitter and receiver [12]. The capacity of a single-user fading channel was obtained when the channel fade level is tracked by both the transmitter and the receiver, and by the receiver alone. In particular, fading channel capacity with channel side information at both the transmitter and receiver is achieved when the transmitter adapts its power, data rate, and coding scheme to the channel variation. The optimal power allocation is “water-pouring” in time, analogous to water-pouring used to achieve capacity on frequency-selective fading channels [21], [22]. It has been proved that for independent and identically distributed (i.i.d.) fading, using receiver side information only, has a lower complexity and the same approximate capacity as optimally adapting to the channel for the three fading distributions examined. However, correlated fading, not adapting to the transmitter, causes both a decrease in capacity and an increase in encoding and decoding complexity. Also, consider two suboptimal adaptation techniques: channel inversion and truncated channel inversion policy, which adapts transmit power, but keeps the transmission rate constant. These techniques have very simple encoder and decoder designs, but exhibit a capacity penalty which can be large in severe fading. Capacity analysis for all these techniques neglects the effects of estimation error and delay, which will generally degrade capacity. The tradeoff between these adaptive and nonadaptive techniques is therefore one of both capacity and complexity.

Assuming that the channel is estimated at the receiver, the adaptive techniques require a feedback path between the transmitter and the receiver, and some complexity at the transmitter. The optimal adaptive technique uses variable-rate and variable-power transmission, and the complexity of its decoding technique is comparable to the complexity of decoding a sequence of Additive White Gaussian Noise (AWGN) channels in parallel. For the non-
adaptive technique, the code design must make use of channel correlation statistics, and decoder complexity is proportional to the channel decorrelation time. The optimal adaptive technique always has the highest capacity, but the increase relative to non-adaptive transmission using receiver side information only, is small when fading is approximately i.i.d. The suboptimal adaptive techniques reduce complexity at a cost of decreased capacity. This tradeoff between achievable data rates and complexity is examined for adaptive and non-adaptive modulation in [23], where adaptive modulation achieves an average data rate within 7–10 dB of the capacity derived herein (depending on the required error probability), while non-adaptive modulation exhibits a severe rate penalty. Trellis codes can be combined with adaptive modulation to achieve higher rates [24].

Capacity was obtained when the channel fade level is unknown to both the transmitter and the receiver for Gilbert–Elliot channel in [25], and for more general Markov channels models in [26]. If the statistics of channel variations are also unknown, then channels with deep fading will typically have a capacity close to zero. This is because data must be decoded without error, which is difficult when the location of deep fades are random. In particular, the capacity of a fading channel with arbitrary variation is at most the capacity of a time-invariant channel under worst case fading conditions. More details about the capacity of time-varying channels under these assumptions can be found in Literature on arbitrarily varying channels [27-28]. The capacity of the fading channel (Rayleigh, Lognormal, and Nakagami fading) under different side information conditions was obtained. The adaptive policy with transmitter side information requires more complexity at the transmitter (and it typically also requires a feedback path between the receiver and transmitter to obtain the side information). However, the decoder at the receiver is relatively simple. The nonadaptive policy has a relatively simple transmission scheme, but its code design must use channel correlation statistics (often unknown), and the decoder
complexity is proportional to the channel decorrelation time. The channel inversion and truncated inversion policies use codes designed for AWGN channels, and are therefore the least complex to implement, but in severe fading conditions, they exhibit large capacity losses relative to the other techniques.

Spectrum efficiency for Rayleigh fading channels under different adaptation policies with selection combining and maximal ratio combining are derived in [29]. Link spectral efficiency, defined as the average transmitted data rate per unit bandwidth for a specified average transmit power and Bit Error Rate (BER) was discussed. Over the last three decades, researchers have looked at various ways to improve link spectral efficiency of wireless systems. The theoretical spectral efficiency limit of adaptive modulation in Rayleigh fading channels was investigated. This fading channel model applies to land mobile radio channels without a LOS path between the transmitter and receiver antennas, as well as to ionospheric and tropospheric scatter channels. The analyses can also be generalized to Nakagami fading channels. Shannon capacity of a channel defines its theoretical upper bound for the maximum rate of data transmission at an arbitrarily small BER without any delay or complexity constraints. Therefore, Shannon capacity represents an optimistic bound for practical communication schemes, and also serves as a benchmark against which to compare spectral efficiency of all practical adaptive transmission schemes. The general theory developed was applied to obtain closed-form expressions for the capacity of Rayleigh fading channels under different adaptive transmission and diversity-combining techniques. In particular, three adaptation policies were considered: Optimal simultaneous Power and Rate Adaptation (OPRA), Constant power with Optimal Rate Adaptation (ORA), and Channel Inversion with Fixed Rate (CIFR). The relative impact of Maximal Ratio Combining (MRC) and Selection Combining (SC) diversity schemes were discussed in conjunction with each of these
adaptive transmission schemes. The capacity of a Rayleigh fading channel (with and without diversity) was derived for the optimal adaptation policy, constant transmit power policy, and channel inversion policy. The capacity of an AWGN channel is compared to the capacity of a Rayleigh fading channel with optimal rate adaptation, constant transmit power, and various diversity combining techniques. It was proved that Optimal power and rate adaptation policy yields a small increase in capacity over optimal rate adaptation policy, with increase in average received SNR and number of diversity branches. In addition, channel inversion suffers the largest capacity penalty relative to the other policies [29].

The capacity of Nakagami Multipath Fading (NMF) channels with an average power constraint for three adaptation policies has been studied. Theoretical spectral efficiency limits of adaptive modulation have been discussed in NMF channels. The assumptions are made such that the channel changes at a rate much slower than the data rate, so the channel remains constant over hundreds of symbols. NMF channel was assumed so that the Probability Density Function (PDF) of the received signal amplitude is statistically characterized by the Nakagami distribution. The time delay in this feedback path is also assumed to be negligible compared to the rate of channel variation. All these assumptions, which are reasonable for high-speed data transmission over a slowly-fading channel, allow the transmitter to adapt its power and/or rate relative to the actual channel state. Closed-form solutions for NMF channel capacity for each power and rate adaptation strategy are obtained. Also, closed-form expressions for outage probability, spectral efficiency and average BER assuming perfect channel estimation, and negligible time delay between channel estimation and signal set adaptation are derived. Results show that rate adaptation is the key to improve spectrum efficiency [30].
Closed-form expressions are derived for single-user capacity of MRC diversity systems taking into account the effect of correlation between the branches [31]. Both the cases of balanced and unbalanced branch SNRs are dealt with. A slow non-selective Rayleigh fading channel was considered with two kinds of correlation between branches: 1) equal branch SNRs and same correlation between any pair of branches; 2) unequal branch SNRs and arbitrary correlation between branches such that the eigenvalues of the branch covariance matrix are all distinct. The channel was assumed to be block-stationary and ergodic. Three adaptive transmission schemes are analyzed: 1) optimal simultaneous power and rate adaptation; (2) optimal rate adaptation with constant transmit power; and (3) channel inversion with fixed rate. The analysis assumes that the receiver has perfect knowledge of the branch amplitudes and phases for diversity combining, and that the transmitter has perfect knowledge of the combined SNR and can adapt to it. Closed-form expressions are derived for single-user capacity of maximal ratio combining diversity systems with the considered adaptive transmission schemes, assuming Rayleigh fading channel with two kinds of correlation. Plots of capacity per unit bandwidth show that for all schemes, spectrum efficiency decreases with increase in the correlation coefficient. The results show that capacity for OPRA policy outperforms capacity of ORA policy, capacity of CIFR policy, and capacity of TIFR policy.

The work of other researchers further extended by deriving closed form expressions for spectral efficiency in Rician fading channels with varying degrees of freedom [32]. The multipath Rician fading channels, which are used to model the statistics of signals transmitted through radio channels, such as cellular radio, have n degrees of freedom (n > 2). The methodology of computing the optimal cutoff level SNR is shown for generalized Rician fading channels with single antenna reception and L-fold MRC diversity reception. For successful data transmission, the received SNR must be at least equal to the
optimal cutoff level SNR. Closed-form expressions for spectral efficiency of Generalized Rician fading channels are derived for different adaptive transmission policies with and without diversity in [32]. Closed-form solutions are derived for single antenna reception (without diversity combining) and maximal ratio diversity combining cases. Results show that truncated channel inversion adaptation policy is the best policy for single antenna reception case, while channel inversion with fixed rate policy is the best policy for the MRC diversity case. Constant transmit power policy provides the lowest spectrum efficiency as compared to the other policies with and without diversity combining. Diversity combining yields large capacity gains for channel inversion with fixed rate policy as compared to the other policies.

Using the PDF of a Rayleigh fading channel with Equal Gain Combining (EGC) diversity, closed-form expressions for capacities per unit bandwidth are derived for various adaptation policies in [33]. It is assumed throughout our analysis that the variation in the combined output SNR is tracked perfectly by the receiver. It is also assumed that the variation in the received signal is sent back to the transmitter via an error-free feedback path. The time delay in this feedback path is also assumed to be negligible compared to the rate of channel variations. Results prove that channel inversion with fixed rate policy is best suited for EGC diversity reception, and constant transmit power policy provides lowest capacity as compared to the other policies. When diversity combining is used, deep channel fades are generally absent, and so, a limited amount of transmit power is enough to compensate for fading. Thus, channel inversion with fixed rate policy which incorporates a fixed modulation and code design technique proves to be the best adaptation policy for the EGC diversity case. A simulation is performed for each of the adaptation policies, and compared with the analytical results. Analytical results closely match with the simulated results.
Asymptotic error rate expressions are derived for multi-branch equal gain combining and selection combining schemes, operating on arbitrarily correlated Rayleigh fading channels [34]. These closed-form solutions are used to provide rapid and accurate estimation of error rates in large SNR regions. More importantly, they reveal additional insights into the transmission characteristics of linear diversity combining schemes operating on correlated Rayleigh fading channels. It is shown that the asymptotic error rates over correlated branches can be obtained by scaling the asymptotic error rates over independent branches with a factor, \( \det(M) \), where \( \det(M) \) is the determinant of the normalized channel correlation matrix. This relationship is valid for both coherent and non-coherent signaling. A similar relationship is also established for outage probabilities of fading channels employing multi-branch diversity reception. In this work, asymptotic error performance of EGC and SC were studied over N-branch correlated Rayleigh channels. Of practical value, new compact analytical results were derived that can be used to provide rapid and accurate error rate and outage probability estimation. Simple analytical expressions have been developed and have been used to assess the asymptotic error performance of EGC and SC schemes operating over N-branch arbitrarily correlated Rayleigh fading channels. Simple relationships between the asymptotic error rates and outage probabilities of MRC, EGC, and SC diversity operating over correlated channels and independent channels have been established. It has been shown analytically that the logarithmic error performance over correlated channels with fixed correlation behaves like the error performance over independent channels in large SNR regions.

Closed-form expressions for single-user capacity of MRC systems in the presence of Gaussian channel estimation errors are obtained, taking into account the effect of imperfect channel estimation at the receiver [35]. The channel considered is slowly varying flat Rayleigh fading that is also spatially independent. The combiner weights are assumed to be affected by Gaussian
errors at the receiver. Also, closed-form expressions for system capacity when employing different adaptive transmission schemes, such as (1) optimal power and rate adaptation, (2) constant power with optimal rate adaptation, and (3) channel inversion with fixed rate are derived. In addition, channel capacity statistics of MRC schemes are investigated, which are valid for arbitrary number of receive antennas, including Moment Generating Function (MGF), Cumulative Distribution Function (CDF) and PDF. The contributions of this paper are two-fold. Firstly, the capacity statistics of MRC receiver subject to Rayleigh fading for arbitrary number of diversity branches was derived in the presence of Gaussian estimation errors. Secondly, closed-form expressions for the channel capacity of MRC in independent and identically distributed (i.i.d.) Rayleigh fading channels was derived with the following adaptive transmission schemes (1) OPRA; (2) ORA with constant transmit power; and (3) CIFR. Numerical results are shown to illustrate the mathematical derivation of channel capacity per unit bandwidth as a function of the average received SNR in dB for different adaptation policies with MRC over slow Rayleigh fading channel with weight estimation errors. Results show that capacity for OPRA policy outperforms capacity of ORA policy and capacity of TIFR policy when compared to the other policies. However, capacity of TIFR policy performs the worst among other policies because it suffers large capacity penalty due to the estimation error, whereas it is less complex to implement.

2.1.3 Mitigation of Co-Channel Interference

Optimal Transmit/Receive Diversity (TRD) is one of the most important configurations for wireless MIMO systems, due to its good performance and ease of implementation [36]. Though investigated intensively, the performance of optimal TRD in general correlated fading with co-channel interference (CCI) still not well understood. Since the output optimal of the TRD instantaneous Signal-to-Noise-plus-Interference Ratio (SNIR) is equal to
the largest sample eigenvalues of a quadratic form involving signal and interference channel matrices, directly determining the PDF of this eigenvalue has been a prevailing approach in Literature. Given the nonlinearity involved in the quadratic form, however, finding such a PDF is not simple except for some special channel conditions. This problem is formulated in a totally different framework, as testing the positive-definiteness of a random matrix, whereby the theory of matrix-variate distributions can be invoked to obtain exact solutions in terms of special functions. The solutions are very general, including most of the existing results as a special case, and allowing for the correlation structures of both signal and interferers to be arbitrary at both transmitter and receiver ends. The performance issue of MIMO systems was tackled with optimal TRD over general Rician/Rayleigh and Rayleigh/Rayleigh fading channels in a unified framework. No attempt is made to compute the distribution function of the largest eigenvalue of the relevant quadratic form. But rather, the outage problem is formulated as testing the positive-definiteness of a random matrix. The philosophy behind this is that determining the joint PDF of this random matrix is much easier than its counterpart for the aforementioned largest sample eigenvalue.

An analytical framework is developed to characterize the capacity of MIMO communication systems in the presence of multiple MIMO co-channel interferers and noise [37]. The situation is considered in which transmitters have no channel state information, and all links undergo Rayleigh fading. The determinant representation is first generalized of hypergeometric functions with matrix arguments to the case when the argument matrices have eigenvalues of arbitrary multiplicity. This enables the derivation of the distribution of the eigenvalues of Gaussian quadratic forms and Wishart matrices with arbitrary correlation, with applications to both single-user and multiuser MIMO systems. In particular, ergodic mutual information for MIMO systems was derived in the presence of multiple MIMO interferers. This analysis is valid for any number
of interferers, each with arbitrary number of antennas having possibly unequal power levels. This framework, therefore, accommodates the study of distributed MIMO systems and accounts for different spatial positions of the MIMO interferers. In this work, rich scattering environments were considered in which transmitters have no CSI, the receiver has perfect CSI, and all links undergo frequency flat Rayleigh fading. The joint PDF of the eigenvalues of complex Gaussian quadratic forms and Wishart matrices are derived, with arbitrary multiplicities for the eigenvalues of the associated covariance matrix. The ergodic capacity of single-user MIMO systems are also derived that accounts for arbitrary power levels and arbitrary correlation across the transmit antenna elements, or arbitrary correlation at the receiver side.

The performance of dual branch Switch and Stay Combining (SSC) diversity receivers operating over correlated Rician fading channels were studied in the presence of correlated Rayleigh distributed CCI [38]. Fast convergent infinite series representations for both the joint PDF of the SSC input Signal-to-Interference Ratios (SIRs) and the PDF of the SSC output SIR were derived. The last one is applied to semi-analytically study the Average Bit Error Probability (ABEP) of Differential Binary Phase Shift Keying (DBPSK). In this work, a dual SSC receiver was considered, operating over correlated Rician fading channels in the presence of correlated Rayleigh CCI. SSC diversity system over correlated Rician fading channel in the presence of Nakagami-m CCI is considered. This work focussed on Rayleigh CCI and branch correlation with detailed derivation of formulae needed for assessment of system performance. Actually, closed-form expressions for both the joint PDF of input SIRs and the PDF of the output SIR at the SSC receiver were derived. Capitalizing on the last of these expressions, ABEP for DBPSK was obtained. Moreover, optimal switching threshold that minimizes ABEP was obtained numerically in order to analyze the effects of fading severity and branch correlation on the minimized ABEP. First, closed-form expressions of
the joint PDF of SSC input SIRs was derived, and it has been used to derive an infinite series representation of the PDF of the SSC output SIR. Further, ABEP as an important performance criterion was evaluated for DBPSK. The switching threshold that minimizes the considered ABEP was obtained numerically and presented for different values of fading severity and branch correlation coefficient. Rapid convergence of the PDF of the output SIR enables high accuracy of the obtained ABEP.

An algorithm was proposed to reject CCI in 3GPP Long Term Evolution (LTE) Multiple Input Multiple Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems [39]. An improved channel estimation method and interference rejection algorithm was discussed. The interference information is measured on the pilot sub-carriers which are sent regularly in time and frequency. An improved model averaged interference mitigation method parameterizes the interference and noise spatial-covariance-matrix on each carrier as a combination of several low-rank models, each associated with probability soft information. A reduced complexity aposteriori receiver was derived based on the low-rank spatial covariance model. Parameterizing the interference and noise covariance matrix helps in adapting the receiver for different interference scenarios. Simulation results are provided to demonstrate the efficacy of the model averaged over interference rejection method applied to MIMO-OFDM system. In this paper, a CCI mitigation method applicable to a MIMO-OFDM system with time varying interference was considered. An advanced MIMO detector, an improved channel estimator and adaptive CCI suppression algorithms were discussed. An improved channel estimator was proposed and performance results are applicable to 3GPP-LTE. Due to adaptive resource allocation algorithms, interference and also the number of interferers experienced by different subcarriers are different and vary with time. The conventional methods do not account for time variation of the number of interferers, and hence their performance varies with different
interference scenarios. A model averaged interference rejection method and an improved channel estimation method was proposed for interference limited MIMO-OFDM systems like 3GPP-LTE.

CCI cancellation strategy was proposed based on Successive Interference Cancellation (SIC) for cooperative communication systems [40]. The performance is evaluated in terms of BER in a Rayleigh fading channel. One of the primary factors in the design of cooperative communication systems is spectrum efficiency. Frequency reuse is typically employed to provide a high capacity system due to limited amount of radio frequency spectrum resource. In the frequency reuse system, cancellation strategy of CCI is very much required to maintain a permissible range of interference for the system. In order to mitigate the effect of CCI, Clean-and Forward (CF) and Minimum Mean Square Error (MMSE) algorithms have been proposed and analyzed. In this paper, CCI cancellation performance was analyzed and simulated for cooperative communication systems. MMSE and Zero-Forcing (ZF) algorithm was employed to cancel the interfering signals in cooperative communication systems. Moreover, SIC scheme was employed with optimal ordering to choose one of the estimated symbols. BER performance is evaluated. From simulation results, it was demonstrated that the SIC with optimal ordering achieves better performance compared to other conventional interference cancellation algorithms. Also, the SIC scheme with optimal ordering offered performance improvement compared to simple SIC without optimal ordering. Additionally, it was confirmed that the CCI cancellation algorithm became more effective for rejection of CCI if it was combined with a channel coding scheme, such as convolutional coding.

2.1.4 Effects of Co-Channel Interference in MIMO systems

In [41], considering channel estimation error and the presence of CCI, the performance of multiuser MIMO systems was analyzed in wireless systems
employing transmit beamforming and maximum ratio combining. Exact
closed-form cumulative distribution function expressions of the SNIR were
derived. Secondly, average capacity of MIMO-MRC systems was presented
with multiuser diversity. In a MIMO-MRC system, Channel State Information
(CSI) is perfectly known at the transmitter and the receiver, and the signals are
combined in such a way that the SNR at the output receiver combiner is
maximized. The performance of MIMO-MRC systems with the assumption of
perfect channel estimation in the presence of CCI was considered in which the
authors first analyzed the performance of MIMO-MRC systems with channel
estimation error. Also, the authors derived exact closed-form expressions for
the statistical distribution of SNIR, the outage probability of SNIR, and the
Average Symbol Error Rate (ASER) with channel estimation error and the
presence of CCI.

Exact closed-form expressions were determined for the outage
probability of MIMO systems in Rayleigh fading with maximal ratio diversity
combining and CCI [42]. In this work, assuming arbitrary-power interferers
and an arbitrary number of transmit and receive antennas, the SNIR PDF, and
an exact closed-form expression were obtained for the outage probability of
MIMO-MRC systems with CCI. These formulas were given as a finite sum of
simple terms that are easily evaluated. A second analytical approach was also
presented to obtain the Moment Generating Function (MGF) of the SNIR,
which was used for the analysis of average probability of error. Numerical
results for system outage probability and average error rate indicated that
performance was degraded in the presence of dominant interferers, and an
unbalanced number of antennas at the transmitter and receiver for a fixed total
interference power. In addition, for a fixed total number of transmit and receive
antennas, outage probability and average BER decrease when the transmitter
and receiver have the same number of antennas.
Turbo packet combining for single carrier broadband MIMO hybrid-Automatic Repeat reQuest (ARQ) transmission with unknown CCI was studied in [43]. A new frequency domain soft MMSE-based signal level combining technique was proposed, where received signals and Channel Frequency Responses (CFRs) corresponding to all retransmissions are used to decode the data packet. Also, a recursive implementation algorithm was provided for the introduced scheme, and show that both its computational complexity and memory requirements were quite insensitive to ARQ delay, i.e., maximum number of ARQ rounds. Furthermore, it was analyzed that the asymptotic performance showed that under a sum-rank condition on the CCI MIMO ARQ channel, the proposed packet combining scheme is not interference-limited. In this work, efficient turbo receiver techniques were investigated for SC Space Time-Bit Interleaved Coded Modulations (ST–BICM) transmission with Chase-type ARQ over broadband MIMO channel with unknown CCI. By using an identical Cyclic Prefix (CP) word for multiple retransmissions of a symbol block, transmission combining was performed at the signal level. The frequency domain soft MMSE packet combiner performed soft Inter Symbol Interference (ISI) cancellation and retransmission combining in the presence of unknown CCI jointly over all received signal blocks. The complexity order is only cubic in terms of the number of transmit antennas. Received signals and CFRs corresponding to all ARQ rounds are used without being required to be stored in the receiver. Interestingly, it was shown that under a rank-condition on the MIMO ARQ channel corresponding to unknown CCI, the proposed combining scheme is not interference-limited, i.e., unknown CCI can be completely removed.

An analysis method for determining downlink data throughput was presented in interference-limited MIMO systems [44]. This approach does not lead to an explicit single formula which covers all system design parameters. However, cell-wide mean throughputs for any particular design can be
computed using the method described here. The overall impact of the assumptions made is minor, in terms of getting realistic estimates of cell-wide throughput; and this holds for a wide range of channel and system parameters besides the set used. The key novelties in this work were that (1) it treated the total multipath-averaged CCI power as being that of additive Gaussian noise (the first conjecture noted above); and (2) it exploited the near-Lognormality of Lognormal sums to obtain a Lognormal distribution for the total CCI power (the second conjecture). Taken together, these steps permitted a very simple analytical framework; it requires only a small amount of simulation and curve fitting to obtain key analysis inputs for a given set of system and channel parameters.

In communication systems that use OFDM and multiple transmit and receive antennas, Beam Forming (BF) is conventionally carried out on a subcarrier basis. The computational requirements are high as dedicated Discrete Fourier Transform (DFT) processors are needed for each antenna. Considerable complexity reductions can be achieved by symbol-wise BF, which performs transmit and receive BF operations in the time domain, and therefore requires only one DFT processor per terminal. Symbol-wise BF for mitigation of CCI was investigated on spatially correlated channels, which are modeled with the Kronecker model [45]. A generalized framework was considered for symbol-wise BF that also takes CCI into account. From an information theoretic perspective, it is desirable to maximize mutual information. Since its maximization in the context of symbol wise BF is infeasible, an alternative optimization metric, the SNIR before OFDM demodulation was introduced. The analytic optimization of this metric is not tractable either, but an algorithm is proposed that performs maximization iteratively. Convergence to local maxima is rare and if it occurs, the local maximum is generally close to the global maximum. It was confirmed analytically that symbol-wise BF is the optimal BF scheme when the channel is
frequency flat. An iterative algorithm was presented for antenna weight computation, which converges to the global maximum in most cases. Computer simulations have demonstrated that this algorithm clearly outperforms a Single Input and Single Output (SISO) system and a conventional phased array, both of which have no, or only limited ability to mitigate interference and to exploit spatial diversity. Compared to subcarrier-wise BF, symbol-wise BF significantly reduces computational requirements. The relative performance gap between the two schemes reduces with increase in spatial correlation, and disappears completely for full correlation.

2.1.5 Effects of Adjacent Channel Interference

Frequency channels are a scarce resource in Industrial, Scientific and Medical (ISM) radio bands used by IEEE 802.11 WLANs. Current radio resource management is often limited to a small number of non-overlapping channels, which leaves only three possible channels in the 2.4 GHz band used in IEEE 802.11b/g networks. The presence of Adjacent Channel Interference (ACI) reduces the effective SINR and therefore, the number of errors in reception is increased. The effect of ACI was studied and quantified, which is caused by transmissions in partially overlapping channels [46 - 47]. A model was proposed that is able to determine under what circumstances the use of adjacent channels is justified. The model can also be used to assist different radio resource management mechanisms (e.g. transmitted power assignments). The results obtained from simulations, analytical models and practical measurements justify the use of partially overlapped channels instead of 3-coloring allocations traditionally applied to IEEE 802.11b networks.

The market is demanding higher data throughput rates for new WLAN applications like multimedia audio and video, streaming media, voice over WLAN, and others that require very good Quality of Service (QoS) capabilities
and lower packet error rates. As a consequence of an increasing amount of in-band and adjacent band interference in the environment for WLAN equipment, the design of radios and digital filtering has become critical. This white paper analyzes the sources of ACI and radio design practices that can improve a WLAN's Adjacent Channel Rejection (ACR) for better overall performance [48]. By following careful design practices, IEEE 802.11 receivers can be developed with adequate ACR in order to overcome much of the ACI encountered in WLAN deployments. In addition, power control and other strategies can be designed into WLAN receivers and transmitters to drastically improve data throughput and range performance of Access Points (APs) and clients in the presence of in-band RF interference.

To design a highly reliable system, potential interference to the system has to be identified and taken into consideration. One of the major interference sources is that coming from other IEEE 802.15.3c devices occupying adjacent channels, commonly known as ACI. The ACI resistance of a multi-Gbps single carrier Wireless Personal Area Network (WPAN) operating in the 60 GHz millimeter-wave band has been discussed in [49]. The significance of performance degradation due to ACI is investigated corresponding to varying factors such as types of modulation and Radio Frequency (RF) hardware impairments. The level of modulation scheme is found to change the system resistance against ACI considerably.

The performance impact of ACI was evaluated in multi-hop wireless networks based on dual-radio 802.11a nodes [50]. Although these nodes use chipsets that satisfy transmit-mask requirements set by the IEEE 802.11 standard, multi-hop performance is still significantly affected by ACI. That is, the transmitter of a node can interfere with its own receiver on a different channel; as a result, multi-hop throughput is severely degraded. This
degradation is especially pronounced for IEEE 802.11a. A spectrum analyzer was used with a signal combiner to quantify ACI under various conditions and propose solutions to mitigate the effect of such interference on multi-hop forwarding. The technique used, such as increasing channel separation and antenna distance, mitigates ACI. Field experiments with multi-hop relay have validated these findings as well as the effectiveness of the solutions.

An adaptive ACI technique was proposed, which improves the system performance under higher levels of interference [51]. Basically, the idea was to send pilot signals and then to use them in estimating the amount of ACI in frequency domain. The estimated spectral error was used to modify tap weights of an adaptive frequency-domain filter. Simulation results reported suggest that ACI can be effectively reduced with the proposed technique. At the system level, the requirements of analog front-end channel-select and other filters can be relaxed, resulting in a cost-effective receiver design.

Adjacent channel interference can result in a reduced network capacity in a multi-operator Wideband Code Division Multiple Access/Frequency Division Duplexing (WCDMA/FDD) environment. When considering two wide Base Stations (BSs) grids that lie close to each other to cover a specific area, it was observed that the main interference source is not ACI, but interference from the neighbouring BSs working on the same channel [52]. It was noted that macro BS is more likely to suffer from ACI when new hotspots are covered with micro BS by a competitor operator. This fact is due to the longer distance between the user and the macro BS, as compared to the latter. As the macro carrier may suffer a greater impact on capacity, it should be protected and placed in the centre channel of the allocated spectrum. This choice is independent of the number or type of carriers used, assuming that the operator launching a service uses at least one macro carrier.
2.1.6 WiMAX and its Standards

Worldwide Interoperability for Microwave Access (WiMAX) offers wireless access as an alternative to fixed access, e.g. Digital Subscriber Line (DSL) at high data rate Internet services, and extends broadband services with mobility to areas where currently no fixed broadband access is feasible due to excessive costs on the last mile. The demand for broadband mobile services continues to grow. Conventional high-speed broadband solutions are based on wired-access technologies such as DSL. This type of solution is difficult to deploy in remote rural areas; further it lacks support for terminal mobility. Mobile Broadband Wireless Access (MBWA) offers a flexible and cost-effective solution to these problems [53].

IEEE WiMAX/802.16 is a promising technology for broadband Wireless Metropolitan Area Networks (WMANs), as it can provide high throughput over long distances and can support different Qualities of Service (QoS). WiMAX/802.16 technology ensures broadband access to the last mile. It provides a wireless backhaul network that enables high speed Internet access to residential, small, and medium business customers, as well as Internet access for Wi-Fi hot spots and cellular base stations [54]. It supports both Point-to-MultiPoint (P2MP) and multipoint-to-multipoint (mesh) modes.

WiMAX will substitute other broadband technologies competing in the same segment and will become an excellent solution for the deployment of well-known last mile infrastructures in places where it is very difficult to obtain with other technologies, such as cable or DSL, and where the costs of deployment and maintenance of such technologies would not be profitable. In this way, WiMAX will connect rural areas in developing countries as well as underserved metropolitan areas. It can even be used to deliver backhaul for carrier structures, enterprise campus, and Wi-Fi hot-spots. WiMAX offers a
good solution for these challenges because it provides a cost-effective, rapidly deployable solution [55].

Additionally, WiMAX will represent a serious competitor to 3G (Third Generation) cellular systems as high speed mobile data applications will be achieved with 802.16e specification. The IEEE 802.16-2004 standard specifies OFDM as the transmission method for NLOS connections. OFDM signal is made up of many orthogonal carriers, and each individual carrier is digitally modulated with a low symbol rate. This method has distinct advantages in multipath propagation, because in comparison with the single carrier method at the same transmission rate, more time is needed to transmit a symbol. BPSK, QPSK, 16-QAM, and 64-QAM modulation modes are used and modulation is adapted to the specific transmission requirements. Transmission rates of up to 75 Mbps are possible. It addresses the following needs which may answer the question of closing the digital divide [56]:

- It is cost effective.
- It offers high data rates.
- It supports fixed, nomadic and mobile applications, thereby converging fixed and mobile networks.
- It is easy to deploy and has a flexible network architecture.
- It supports interoperability with other networks.
- It is aimed at being the first truly global wireless broadband network.

IEEE 802.16 aims to extend wireless broadband access up to kilometers in order to facilitate both Point-to-Point (P2P) and P2MP connections [57].

2.1.7 Background on IEEE 802.16 and WiMAX

The IEEE 802.16 group was formed in 1998 to develop an air-interface standard for wireless broadband. The initial focus of the group was the
development of a LOS-based P2MP wireless broadband system for operation in the 10 GHz - 66 GHz millimeter waveband. The resulting standard—the original 802.16 standard, completed in December 2001—was based on a single-carrier physical (PHY) layer with a burst time division multiplexed (TDM) MAC layer. Many of the concepts related to the MAC layer were adapted for wireless from the popular cable modem Data Over Cable Service Interface Specification (DOCSIS) standard [58].

The IEEE 802.16 group subsequently produced 802.16a, an amendment to the standard, to include NLOS applications in the 2GHz-11GHz band, using OFDM based PHY layer. Additions to the MAC layer, such as support for Orthogonal Frequency Division Multiple Access (OFDMA), were also included. Further revisions resulted in a new standard in 2004, called IEEE 802.16-2004, which replaced all prior versions and formed the basis for the first WiMAX solution. These early WiMAX solutions based on IEEE 802.16-2004 targeted fixed applications, and referred as fixed WiMAX [59]. In December 2005, the IEEE group completed and approved IEEE 802.16e-2005, an amendment to the IEEE 802.16-2004 standard that added mobility support. The IEEE 802.16e-2005 forms the basis for the WiMAX solution for nomadic and mobile applications and is often referred to as mobile WiMAX [60].

The basic characteristics of the various IEEE 802.16 standards are summarized in Table 2.1. Note that these standards offer a variety of fundamentally different design options. For example, there are multiple PHY layer choices: a single-carrier-based PHY layer called Wireless-MAN-SCa, an OFDM-based PHY layer called WirelessMAN-OFDM, and an OFDMA-based PHY layer called Wireless-OFDMA. Similarly, there are multiple choices for MAC architecture, duplexing, frequency band of operation, etc. These standards were developed to suit a variety of applications and deployment scenarios, and hence offer various design choices for system developers. In
Table 2.1 Basic Data on IEEE 802.16 Standards (page 35 of [58]).

<table>
<thead>
<tr>
<th></th>
<th>802.16</th>
<th>802.16d-2004</th>
<th>802.16e-2005</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency band</strong></td>
<td>10GHz-66GHz</td>
<td>2GHz-11GHz</td>
<td>2GHz-11GHz for fixed; 2GHz-6GHz for mobile applications</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Fixed LOS</td>
<td>Fixed NLOS</td>
<td>Fixed and mobile NLOS</td>
</tr>
<tr>
<td><strong>MAC architecture</strong></td>
<td>Point-to-multipoint, mesh</td>
<td>Point-to-multipoint, mesh</td>
<td>Point-to-multipoint, mesh</td>
</tr>
<tr>
<td><strong>Transmission scheme</strong></td>
<td>Single carrier only</td>
<td>Single carrier, 256 OFDM or 2048 OFDM</td>
<td>Single carrier, 256 OFDM or scalable OFDM with 128,512,1024 or 2048 subcarriers</td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td>BPSK, QPSK, 16 QAM, 64 QAM</td>
<td>BPSK, QPSK, 16 QAM, 64 QAM</td>
<td>BPSK, QPSK, 16 QAM, 64 QAM</td>
</tr>
<tr>
<td><strong>Gross data rate</strong></td>
<td>32 Mbps - 134.4 Mbps</td>
<td>1 Mbps - 75 Mbps</td>
<td>1 Mbps - 75 Mbps</td>
</tr>
<tr>
<td><strong>Multiplexing</strong></td>
<td>Burst TDM/TDMA</td>
<td>Burst TDM/TDMA/OFDMA</td>
<td>Burst TDM/TDMA/OFDMA</td>
</tr>
<tr>
<td><strong>Duplexing</strong></td>
<td>TDD and FDD</td>
<td>TDD and FDD</td>
<td>TDD and FDD</td>
</tr>
<tr>
<td><strong>Channel bandwidth</strong></td>
<td>20MHz, 25MHz, 28MHz</td>
<td>1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz</td>
<td>1.75MHz, 3.5MHz, 5MHz, 7MHz, 14MHz, 1.25MHz, 10MHz, 15MHz, 8.75MHz</td>
</tr>
<tr>
<td><strong>WiMAX implementation</strong></td>
<td>None</td>
<td>256-OFDM as Fixed WiMAX</td>
<td>Scalable OFDMA as Mobile WiMAX</td>
</tr>
</tbody>
</table>

\(^a\)WirelessHUMAN (Wireless High-speed Unlicensed MAN) is similar to OFDM-PHY, but mandates dynamic frequency selection for license-exempt bands.
fact, one could say that IEEE 802.16 is a collection of standards, not one single interoperable standard.

For practical reasons of interoperability, the scope of the standards needs to be reduced, and a smaller set of design choices for implementation need to be defined. The WiMAX forum does this by defining a limited number of system profiles and certification profiles. A system profile defines the subset of mandatory and optional physical-and MAC-layer features selected by the WiMAX Forum from the IEEE 802.16-2004 or IEEE802.16e-2005 standard. It should be noted that the mandatory and optional status of a particular feature within a WiMAX system profile may be different from what it is in the original IEEE standard. Currently, the WiMAX Forum has two different system profiles: one based on IEEE 802.16-2004, OFDM PHY, called the fixed system profile; the other one based on IEEE 802.16e-2005 scalable OFDM PHY called the mobility system profile. A certification profile defined as a particular instantiation of a system profile where the operating frequency, channel band width, and duplexing mode are also specified. WiMAX equipment is certified for interoperability against a particular certification profile.

2.1.8 Features of WiMAX

WiMAX is a wireless broadband solution that offers a rich set of features with a lot of flexibility in terms of deployment options and potential service offerings. Some of the most salient features that deserve highlighting are as follows [58]:

**OFDM-based physical layer:** The WiMAX physical layer (PHY) is based on OFDM, a scheme that offers good resistance to multipath, and allows WiMAX to operate in NLOS conditions. OFDM is now widely recognized as the method of choice for mitigating multipath for broadband wireless.
Very high peak data rates: WiMAX is capable of supporting very high peak data rates. In fact, the peak PHY data rate can be as high as 74 Mbps when operating using a 20 MHz wide spectrum. More typically, using 10 MHz spectrum operating using a TDD scheme with a 3:1 downlink-to-uplink ratio, the peak PHY data rate is about 25 Mbps and 6.7 Mbps for the downlink and the uplink, respectively. These peak data rates are achieved when using 64 QAM modulation with rate 5/6 error-correction coding. Under very good signal conditions, even higher peak rates may be achieved using multiple antennas and spatial multiplexing.

Scalable bandwidth and data rate support: WiMAX has a scalable physical-layer architecture that allows for the data rate to scale easily with the available bandwidth. This scalability is supported in the OFDMA mode, where the Fast Fourier Transform (FFT) size may be scaled based on the available channel bandwidth. For example, a WiMAX system may use 128, 512, or 1048 bit FFTs based on whether the channel bandwidth is 1.25MHz, 5MHz, or 10MHz, respectively. This scaling may be done dynamically to support user roaming across different networks that may have different bandwidth allocations.

Adaptive Modulation and Coding (AMC): WiMAX supports a number of modulation and Forward Error Correction (FEC) coding schemes and allows the scheme to be changed on per user and per frame basis, based on channel conditions. AMC is an effective mechanism to maximize throughput in a time-varying channel. The adaptive algorithm typically calls for the use of the highest modulation and coding scheme that can be supported by the SNIR at the receiver such that each user is provided with the highest possible data rate that can be supported in their respective links.

Link-layer retransmissions: For connections that require enhanced reliability, WiMAX supports Automatic Retransmission reQuests (ARQ) at the link layer. ARQ-enabled connections require each transmitted packet to be
acknowledged by the receiver; unacknowledged packets are assumed to be lost and are retransmitted. WiMAX also optionally supports hybrid-ARQ, which is an effective hybrid between FEC and ARQ.

**Support for TDD and FDD:** IEEE 802.16-2004 and IEEE 802.16-2005 supports both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD), as well as half-duplex FDD, which allows for a low-cost system implementation. TDD is flavored by a majority of implementations because of its advantages: (1) flexibility in choosing uplink-to-downlink data rate ratios, (2) ability to exploit channel reciprocity, (3) ability to implement in nonpaired spectrum, and (4) less complex transceiver design. All the initial WiMAX profiles are based on TDD, except for two fixed WiMAX profiles in 3.5 GHz.

**Orthogonal Frequency Division Multiple Access (OFDMA):** Mobile WiMAX uses OFDM as a multiple-access technique, whereby different users can be allocated different subsets of the OFDM tones. OFDMA facilitates the exploitation of frequency diversity and multiuser diversity to significantly improve system capacity.

**Flexible and dynamic per user resource allocation:** Both uplink and downlink resource allocation are controlled by a scheduler in the base station. Capacity is shared among multiple users on a demand basis, using a burst TDM scheme. When using OFDMA-PHY mode, multiplexing is additionally done in the frequency domain, by allocating different subsets of OFDM subcarriers to different users. Resources may be allocated in the spatial domain as well when using the optional Advanced Antenna Systems (AAS). The standard allows for bandwidth resources to be allocated in time, frequency, and space and has flexible mechanism to convey resource allocation information on a frame-by-frame basis.

**Support for advanced antenna technologies:** The WiMAX solution has a number of hooks built into the physical-layer design, which allows for the
use of multiple-antenna techniques, such as beamforming, space-time coding, and spatial multiplexing. These schemes can be used to improve overall system capacity and spectral efficiency by deploying multiple antennas at the transmitter and/or the receiver.

**Quality-of-service support:** The WiMAX MAC layer has a connection oriented architecture that is designed to support a variety of applications, including voice and multimedia services. The system offers for constant bit rate, variable bit rate, real-time, and non-real-time traffic flows, in addition to best-effort data traffic. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement.

**Robust security:** WiMAX supports strong encryption, using Advanced Encryption Standard (AES), and has a robust and key-management protocol. The system also offers a very flexible authentication architecture based on Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including username/password, digital certificates, and smart cards.

**Support for mobility:** The mobile WiMAX variant of the system has mechanisms to support secure seamless handovers for delay-tolerant full-mobility applications, such as VoIP. The system also has built-in support for power-saving mechanisms that extends the battery life of handheld subscriber devices. Physical-layer enhancements, such as more frequent channel estimation, uplink subchannelization, and power control, are also specified in support of mobile applications.

**IP-based architecture:** The WiMAX Forum has defined a reference network architecture that is based on all-IP platform. All end-to-end services are delivered over an IP architecture relying on IP-based protocols for end-to-end transport, QoS, session management, security, and mobility. Reliance on IP allows WiMAX to ride the declining cost curves of IP processing, facilitate
easy convergence with other networks, and exploit the rich ecosystem for application development that exists for IP.

Since, WiMAX is the developing future trend having the above mentioned features, WiMAX PHY layer with OFDM transmission scheme is selected for validating the results.

2.2 REVIEW OF PROPOSED WORK

Research has been carried out discussing the effects of CCI and ACI under various scenarios. Also, several algorithms were proposed, and receiver structures were designed to mitigate interference. System performance in the presence of Co-channel and Adjacent channel interference has not been addressed yet. This research work extends the analysis of system performance in the presence of the above mentioned interference scenarios. System performance under various diversity schemes when subjected to different adaptation policies have been discussed in several fading environments in this research work.

The system performance is analyzed by deriving analytical expressions for parametric measures considered under various scenarios in the presence of Co-channel and Adjacent channel interference. Analytical expressions derived are used to discuss results through various plots. Analytical results discussed are validated through simulation results of the system considered with real-time parameters. For simulation, the considered system specifications are taken from the WiMAX IEEE 802.16 standard.
2.3 SUMMARY

In this chapter, a detailed review of Literature survey was carried out along with the papers that motivate building the research ideas. This chapter explained the theory from various research papers and each paragraph gave a brief summary of the research papers. Each paper has its strong point and details more on the paper. Chapter 3 explains the SNIR produced in the presence of CCI and ACI.