# SEVERE FADING AND OUTDATED CHANNEL CONDITION MODELS IN RELAY COMMUNICATION NETWORKS

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# SEVERE FADING AND OUTDATED CHANNEL CONDITION MODELS IN RELAY COMMUNICATION NETWORKS

**by**

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# LIST OF SYMBOLS

| | |
|---|---|
| $\alpha$ | Fraction of the block time for energy harvesting |
| $B$ | Channel bandwidth |
| $C$ | Ergodic capacity |
| $c$ | Weibull severity parameter |
| $d_1$ | Distance between the source and the relay terminals |
| $d_2$ | Distance between the relay and the destination terminals |
| $div_1$ | Diversity order of outage probability |
| $div_2$ | Diversity order of error probability |
| $D$ | Destination terminal |
| $\eta$ | Constant for specific modulation schemes BPSK ($\eta = 2$) and QPSK($\eta = 1$) |
| $\mathbb{E}\{\cdot\}$ | Expected value operator |
| $\exp(\cdot)$ | Exponential function |
| $f_d$, $f_m$ | Maximum Doppler frequency |
| $F_\gamma(\gamma)$ | CDF of $\gamma$ |
| $\Gamma(\cdot)$ | Gamma function |
| $G_{p,q}^{m,n}(z\,|\ \ )$ | Meijer's G-function |
| $\mathcal{G}$ | Amplification gain |
| $h_0(k)$ | Channel coefficient of the source-destination link |
| $h_1(k)$ | Channel coefficient of the source-relay link |

|  |  |
|---|---|
| $h_{i,k}(t)$ | Actual channel on the $i$-th hop of the $k$-th relay |
| $h_{i,k}(t-T_d)$ | Delayed version of the actual channel on the $i$-th hop of the $k$-th relay |
| $\hat{h}$ | Estimated $i$-th hop of the $k$-th relay |
| $I_0(\cdot)$ | Zeroth order modified Bessel function of the first kind |
| $I_\nu(\cdot)$ | $\nu$-order modified Bessel function of the first kind |
| $J_0(\cdot)$ | Zeroth order Bessel function of the first kind |
| $\mathcal{L}^{-1}(\cdot)$ | Inverse Laplace transform |
| $M_{a,b}(\cdot)$ | Whittaker function |
| $\mathcal{M}_\gamma(s)$ | MGF of $\gamma$ |
| $m$ | Path loss exponent |
| $m$ | Nakagami-$m$ severity parameter |
| $N_0$ | Variance of $z_0$ |
| $N_1$ | Variance of $z_1$ |
| $N_2$ | Variance of $z_2$ |
| $\Omega_1$ | Mean value of the random variable $\lvert h_1(k)\rvert^2$ |
| $\Omega_2$ | Mean value of the random variable $\lvert h_2(k)\rvert^2$ |
| $\bar{P}_b$ | ABEP |
| $P_{out}$ | Outage probability |
| $p_\gamma(\gamma)$ | PDF of $\gamma$ |
| $P_s$ | Transmitted symbol power of the source terminal |
| $P_r$ | Transmitted symbol power from the relay terminal |

| | |
|---|---|
| $\Phi(\alpha,\gamma;z)$ | Confluent hypergeometric function |
| $R$ | Relay terminal |
| $Q_1(\cdot)$ | First-order Marcum Q-function |
| $Q(x)$ | Gaussian Q-function |
| $\rho_{i,k}$ | Correlation coefficients between the envelope of the actual channel and its delayed version |
| $S$ | Source terminal |
| $T$ | Block time |
| $T_c$ | Coherence time |
| $T_d$ | Time difference between the actual and estimate channel values |
| $T_s$ | Symbol period |
| $\bar{\gamma}$ | Average SNR |
| $\gamma$ | Instantaneous SNR |
| $\gamma_{th}$ | SNR threshold value |
| $\gamma_0$ | Instantaneous SNR between $S$ and $D$ |
| $\gamma_1$ | Instantaneous SNR between $S$ and $R$ |
| $\gamma_2$ | Instantaneous SNR between $R$ and $D$ |
| $z_0$ | AWGN at the destination during the first time slot |
| $z_1$ | AWGN at the relay |
| $z_2$ | AWGN at the destination during the second time slot |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ABEP | Average Bit Error Probability |
| AF | Amplify-and-Forward |
| AWGN | Additive White Gaussian Noise |
| BEP | Bit Error Probability |
| BPSK | Binary Phase Shift Keying |
| CDF | Cumulative Distribution Function |
| CLT | Central Limit Theorem |
| CSI | Channel State Information |
| DF | Decode-and-Forward |
| DSTC | Distributed Space-Time Coding |
| EGC | Equal Gain Combining |
| IEEE | Institute of Electrical and Electronics Engineers |
| LoS | Line-of-Sight |
| MGF | Moment Generating Function |
| MIMO | Multiple-Input Multiple-Output |
| M-PSK | $M$-Phase Shift Keying |
| MRC | Maximal Ratio Combining |
| MRS | Multiple Relay Selection |
| PDF | Probability Density Function |

| | |
|---|---|
| QPSK | Quadrature Phase Shift Keying |
| $RD$ | Relay-to-Destination |
| RF | Radio-Frequency |
| RV | Random Variable |
| SC | Selection Combining |
| $SD$ | Source-to-Destination |
| SNR | Signal-to-Noise Ratio |
| $SR$ | Source-to-Relay |
| SRS | Single Relay Selection |
| SWIPT | Simultaneous Wireless Information and Power Transfer |
| TS | Time-Switching |

# MODEL KEADAAN SALURAN YANG KABUR TERUK DAN KETINGGALAN MASA DALAM RANGKAIAN PERHUBUNGAN GEGANTI

## ABSTRAK

Sistem komunikasi kerjasama adalah kaedah yang menarik yang meningkatkan kepelbagaian prestasi dengan memperkenalkan geganti perantaraan bagi membantu komunikasi utama di antara terminal punca dan terminal matlamat. Terdapat dua isu utama mengenai saluran komunikasi. Pertama, saluran kabur teruk di mana analisis dilakukan terutamanya untuk menyiasat saluran terus punca ke matlamat (saluran $SD$) dalam rangkaian koperasi tanpa wayar. Kebanyakan kajian mengabaikan saluran $SD$ dengan menganggap sebagai kabur dalam, tanpa memberi pertimbangan sumbangan separa terhadap kepelbagaian sistem secara keseluruhan. Ini disebabkan klasifikasi yang tidak tepat bagi saluran Rayleigh sebagai kabur teruk. Isu kedua adalah pergerakan relatif dalam terminal komunikasi menyebabkan lengah dalam menyebarkan isyarat yang dikirimkan yang tertakluk kepada model autosekaitan Jakes yang telah tertubuh. Ini juga dikenali sebagai keadaan saluran ketinggalan masa. Ia menyebabkan terminal matlamat tidak dapat menganggar atau memulihkan maklumat punca dengan betul seterusnya akan merosotkan prestasi sistem. Untuk isu pertama, ungkapan analisis model saluran kabur teruk memerlukan pendekatan menggunakan fungsi penjanaan momen (MGF). Ungkapan MGF untuk model taburan Weibull harus berurusan dengan fungsi Meijer G yang kompleks dan kerana kerumitan dan keterbatasan dalam ungkapan MGF yang ada, sangat jarang untuk menjumpai analisis berdasarkan ungkapan ini. Untuk mengatasi halangan ini, ungkapan MGF yang siri tak terhingga bagi model Weibull dicadangkan. Ungkapan ini kemudiannya digunakan untuk menilai kesan saluran kabur teruk pada saluran terus $SD$ dalam rangkaian koperasi tiga-terminal geganti skema menggunakan skema besarkan-dan-ke depan (AF) untuk terminal geganti, dan skema nisbah maksimum tergabung (MRC) dan pemilihan tergabung (SC) untuk terminal matlamat. Dengan penetapan parameter yang dipratentukan, didapati apabila saluran terus $SD$ berada dalam kabur dalam, keuntungan kepelbagaian untuk kedua-dua MRC dan SC bagi sistem AF adalah 0.771. Apabila saluran terus $SD$ berkelakuan sebagai saluran Rayleigh maka keuntungan kepelbagaian yang dicapai adalah; MRC: 1.660, SC: 1.602. Isu kedua dikaji dalam sistem koperasi dua-hop AF berasaskan penuaian tenaga tanpa wayar tiga-terminal dengan andaian pergerakan terminal dinamik, di mana ia diandaikan bahawa terminal geganti adalah kekangan tenaga. Protokol pensuisan-masa yang baru yang mengambil kira jumlah lengah yang disebabkan pergerakan terminal dicadangkan. Kemudian, dua jenis mod penghantaran yang berbeza dipertimbangkan; lengah-terhad, DL (memerlukan penilaian kebarangkalian bocoran) dan lengah-had terima, DT (memerlukan penilaian keupayaan ergodik). Didapati bahawa apabila semua terminal berada dalam keadaan statik, sistem mencapai keluaran maksimum (DL: 0.83 bit/sec/Hz, dan DT: 1.59 bit/sec/Hz).

# SEVERE FADING AND OUTDATED CHANNEL CONDITION MODELS IN RELAY COMMUNICATION NETWORKS

## ABSTRACT

Cooperative communication system is an attractive method which enhances the performance diversity by introducing an intermediate relay for assisting the primary communication between the source and the destination terminals. There are two main issues regarding to the communication channel. The first one is the severe fading channel where the analysis is performed mainly for investigating the direct source-to-destination ($SD$) link in wireless cooperative network. Most of the works omits $SD$ link by simply assuming deep fade with no consideration of partial contribution to the overall system diversity. This is due to the imprecise classification of Rayleigh fading as severe fading. The second issue is a relative movement in communication terminals cause some delay in propagating the transmitted signals which is subject to the established Jakes' autocorrelation model. This is also known as outdated channel condition. It causes the destination terminal unable to estimate or recover the source's information properly that will deteriorate the system performances. For the first issue, the analytical expressions based on this severe fading channel model has come to an approach of utilizing the moment generating function (MGF). The MGF expression of the Weibull distribution model has to deal with a complex Meijer's G-function and due to the complexity and limitation in the existing MGF expression, it is scarce to have performance analysis based on the expression. To overcome this limitation, infinite series of MGF expression for the Weibull model is proposed. This expression is then, utilized for evaluating the impact of severe fading channel on the direct

SD link in a three-terminal cooperative network by employing approximated variable-gain and fixed-gain amplify-and-forward (AF) relaying schemes associates with the maximal ratio combining (MRC) and the selection combining (SC) schemes. Under predefined parameters setting, it is found that when the direct $SD$ link is in deep fade, the diversity gain for both MRC and SC for AF variable-gain relaying system is 0.771. While the $SD$ link behaves as Rayleigh channel then diversity gain is given by; MRC:1.660, SC:1.602. The second issue is investigated in a three-terminal wireless energy harvesting-based AF dual-hop cooperative system along with the assumption of dynamic terminals' movement where it is assumed that the relay terminal is energy-constrained. New time-switching relaying protocol which considers the amount of propagation delay due to the terminal's movement is proposed. Then, two different types of transmission mode are considered; delay-limited, DL (requires outage probability evaluation) and delay-tolerant, DT (requires ergodic capacity evaluation). It is found that when all the terminals are in static, the system achieves the maximum throughput (DL: 0.83 bit/sec/Hz, and DT: 1.59 bit/sec/Hz).

# CHAPTER 1

# INTRODUCTION

In the last three decades, with the advancements of science and technologies, wireless communication systems have been greatly evolved which has served as indispensable merits in various fields of people's daily lives. Recent technologies support the communication features of low or high mobility, over short and long distances with rapid and global information transmissions as well as the capability of reliable information access at any time. Although many wireless applications have been successfully established such as satellite systems, mobile cellular systems, television broadcasting, and wireless local area networks, still, these technologies will face the challenges of the increasing future communication requirements.

## 1.1 Research Background

The revolution of wireless communication systems have been accompanied along with the advance in electronic circuit technology which allows the development of complex processing of wireless devices with lower power consumptions and smaller in sizes. By having tremendous enhancement than their predecessors, the third generation and the fourth generation cellular networks offer high-speed services for mobile applications such as Internet access, video streaming, and online games (Wang, 2015). However, all the communication devices which are based on wireless technologies would have similar problems to face in general; one of the most problems in wireless communication is that the information signals transmitted over the wireless channel are subject to a natural phenomenon of *fading* (Shankar, 2012). The two types of small-scale and large-scale fading which create the following effect to the transmitted signals; multipath, pathloss and shadowing, undoubtedly lead to attenuation, fluctuation and even deep fade to the channel powers. This surely impairs the transmitted signals that will cause unreliable and compromised information transmissions.

The fading effect, however, can be mitigated by employing a technique of diversity where multiple independent scaled copies of the source's messages are received and processed by the receiver by utilizing certain algorithms. Several common diversity schemes that have been implemented in many wireless systems are known as time diversity, frequency diversity, and spatial diversity (Shankar, 2012). Spatial diversity has been successfully investigated in the literature and even in practice, there are wireless applications and standards which bring a technique known as multiple-input multiple-output (MIMO) system. It has been shown that with the increasing diversity gain, a remarkable enhancement to the system performances such as outage probability and channel capacity are obtained (Xu et al., 2017). MIMO system employs several transmit and/or receive antennas in every wireless transceiver which allows exploitation of the randomness feature of fading channels. Particularly, with the use of antenna arrays, the probability of information loss is reduced significantly. This comes to the fact that when few communication channels are bad, the rest of active channels may assist in delivering the copies of the source's information (Wang, 2015).

To have independent distribution to each source's message replicas that are received by a receiver, the antenna arrays must be placed according to the separation distance rule, where the distance is related to the order of the wavelength of the carrier signal.

For a carrier frequency of 1 GHz, according to the basic half-wave antenna, it requires a minimum separation distance of 15 cm between the antennas (Posluszny, 2019). This situation, however, might benefit for a large infrastructure like a cellular base station, but this is not possible for designing today's mobile devices. Hence, hardware limitation is the key factor that hinders the effectiveness of MIMO system implementation to pocket-sized devices, in the future for diversity harnessing.

The intensive researches for communication diversity lead to the development of a new technique, known as cooperative communication systems (Laneman et al., 2004). In early time, this idea is pioneered and improved by Cover and Gamal (1979) where they presented the information-theoretic properties of the relay channel. The capacity in an additive white Gaussian noise channel of the three-terminal network is analyzed with the assumption that all terminals operate in the same band where this allows the operations of broadcasting and multiple access from viewpoints of the source and the destination terminals, respectively. This work has great potential to be extended into various wireless practical implementations such as in ad hoc, peer-to-peer and wide-area cellular networks (Stallings, 2004).

User cooperation is a concept in a cooperative communication system (Sendonaris et al., 2003) where it is possible when there is at least a single neighboring terminal willing to assist in communication. For example, there are two users in a network that have information to transmit. Then, for communication to take place, each of the two partners is responsible to transmit his information and his partner's information to a particular destination(s). The relaying concept is that there is an intermediate terminal has not owned any information and only willing to forward the source's information to the destination. A relay receives a faded version of the source's information in the first half of the time and then forwards the information in the second half of the time. This provides spatial diversity that offers fading effect mitigation, signal reliability enhancement, signal coverage extension and power consumption reduction (Laneman et al., 2004; Sendonaris et al., 2003). These advantages surpass the benefit in the MIMO system including no separation distance rule need to be observed in a cooperative communication system.

Fading channels are usually described through statistical modeling of the channel distributions. It allows wireless communication system performances to be measured for the particular channel behaviors and presented in terms of analytical evaluations. For a small-scale fading, the channel might be represented by non-line-of-sight Rayleigh or line-of-sight Rician (Blaunstein and Andersen, 2002) and the distribution of the channels must conform to the condition of a great number of signal paths in order to follow the criterion of central limit theorem (CLT). However, there are several practical situations which violate this CLT criterion in term of wireless applications such as the enclosed or cavity environments (Frolik, 2008). Several examples to these enclosed environments include aircraft, buses, shipping containers, and trains (Rabelo et al., 2009; Sofotasios and Freear, 2011). In (Frolik, 2007), it has shown the empirical evidence demonstrated in the wireless sensor networks with strict setups of static-sensors deployment and static-cavity structures. From the setups, the phenomenon of channels that severe than Rayleigh is characterized and it is referred to as hyper-Rayleigh fading. This occurs due to the fact that this kind of environment is described by a few numbers of propagating paths, which leads to severe fading conditions.

It is prominent for future mobile communication systems to offer reliable communications although experience mobility environment. The movements in communicating terminals cause the transmitted signals to experience frequency shift in each multipath components, and this is known as Doppler shift. At the same time, this induces Doppler spread that is the spectral broadening due to the change in the time rate of the channel (Rappaport, 2002). Consequently, this realizes the phenomenon of outdated or imperfect channel conditions. It is found in (Haykin and Moher, 2005; Rappaport, 2002), a relative movement of the terminals does not only cause the event of Doppler spread but it also produces a certain delay to particular communication channels, in which relate to the well-known Jakes' autocorrelation model (Michalopoulos et al., 2012). The transmitted information that encounters fading and distortion may face serious impairment and overall system performance loss.

Furthermore, there is an attractive way to extend the power duration of energy-constrained wireless devices which is known as *energy harvesting*. It has become an appealing solution due to the harvesting energy that can be acquired from any ambient radio-frequency (RF) signals especially for the low-powered devices, in spite of recharging or replacing the power supply which incurs high cost and time consumption. The reason behind this is the RF signals are not only bringing the information but at the same time carrying energy (Zhang and Ho, 2013). Hence, the idea of simultaneous wireless information and power transfer (SWIPT) has been proposed and pioneered in (Popovski et al., 2013; Varshney, 2008). However, SWIPT technique is not compatible with a particular network setup with single-antenna terminals. To this type of terminals, wireless energy harvesting can be carried out either in, 1) time-sharing protocol, where the receiver utilizes a portion of time duration for harvesting energy and the remaining time for information processing, or 2) power-splitting protocol, where the receiver uses a portion of received signal power for harvesting energy and the remaining power for information processing (Gu and Aïssa, 2015; Ku et al., 2016; Nasir et al., 2013; Xiang and Tao, 2012; Zhang and Ho, 2013; Zhou et al., 2013).

## 1.2 Problem Statements

In this thesis, the severe fading analysis is intended to be primarily investigated towards the direct source-to-destination ($SD$) link in wireless cooperative network. Since majority in the literature that omits $SD$ link simply presumes that the link is in deep fade without even considering partial contribution of channel diversity that may provide to the network just before it goes to actual deep fade. One of the reasons is that the imprecise classification of Rayleigh fading as severe fading, and hence, any channel that undergoes severe than Rayleigh can be merely thought as deep fade. This severe-than-Rayleigh channel is described as severe fading and it can be represented by using the Weibull distribution model (Ikki and Aissa, 2012b).

Moreover, symmetric fading in both indirect links (i.e., source-to-relay, $SR$ and relay-to-destination, $RD$) is not a realistic assumption in cooperative system since wireless links may undergo different fading conditions in every link, where the situation has been identified and documented in the WINNER II project (Meinilä et al., 2009). Several renowned works consider cooperative networks with different kind of asymmetric links such as in (Kapucu et al., 2013; Ouyang et al., 2012; Peppas et al., 2013). In order to demonstrate the impact of severe fading in the direct $SD$ link and asymmetric fading to the indirect $SR$ and $RD$ links, a baseline three-node amplify-and-forward (AF) relaying system is constructed with system receive diversity at the destination terminal.

The Weibull model can characterize the severe fading condition of a wireless channel. It is used to model the $SD$ link which is in a severe fading in a cooperative system. However, in the process of the derivation of the analytical expressions for system performance evaluations, it comes to the necessity of utilizing the moment generating function (MGF). It should be noted that the common statistical distributions are cumulative distribution function (CDF) and probability density function (PDF). The issue arises since the MGF expression of the Weibull distribution model has to deal with a complex Meijer's G-function (Jeffrey et al., 2007). Due to the complexity and limitation in the existing MGF expression, this is the reason why it is scarce to have performance analysis based on the Weibull model.

Besides, in a recent wireless energy harvesting-based cooperative communication system, a different perspective of channel issue namely the outdated channel condition is highlighted. Due to the relative movement of the wireless terminals, it will cause an effect known as Doppler spread and at same time, a particular delay is produced in the time-switching protocol and it is associated with the Jakes' autocorrelation model (Michalopoulos et al., 2012). Besides, this type of channel condition is subject to the first-order autoregressive model (Khattabi and Matalgah, 2016) in which relies on the Jakes' autocorrelation model.

## 1.3 Research Objectives

1. To develop a new MGF expression for the Weibull distribution model, where from this expression, tractable expressions for common statistical distribution (CDF and PDF) of the instantaneous signal-to-noise ratio (SNR) at the destination terminal is obtained.

2. To evaluate the impact of severe fading channel on the direct source-to-destination ($SD$) link in a baseline cooperative network by employing approximated variable-gain and fixed-gain amplify-and-forward (AF) relaying schemes associate with selected diversity combining scheme.

3. To propose a new channel delay model which is based on the first-order autoregressive model associated with Jakes' autocorrelation model and evaluate the impact on the system performance of a wireless energy harvesting-based AF cooperative communication system.

## 1.4 Research Scope

The research is about to analyze the performance of a baseline structure of a three-node wireless cooperative communication system. It consists of a source ($S$), a relay ($R$) and a destination ($D$) terminals. The communication between $S$ and $D$ is assisted by $R$ where $R$ amplifies and forwards the scaled version of the source's signals to $D$. When $D$ receives more than one copy of the source's signal, a diversity combining scheme such as maximal ratio combining (MRC) is employed. This idea is illustrated in Figure 1.1. Two types of practical channel issues are analyzed. The first is the event of severe fading channel between the terminals of the conventional cooperative

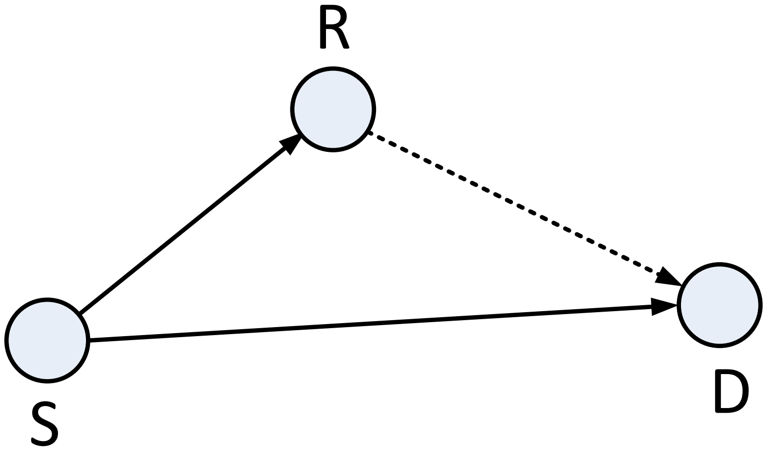

Figure 1.1: Illustration of three-node structure of wireless cooperative communication system. Solid line denotes the first time phase, dashed line denotes the second time phase.

communication system, and the second is the event of the outdated channel condition to the wireless energy harvesting-based cooperative communication system.

Regarding the first type of the channel issue, the direct source-to-destination ($SD$) link is assumed to experience the severe fading channel due to undergo a particular environment as mentioned earlier in Background. This kind of fading condition is characterized by the Weibull model where the Matlab $m$-file for Weibull channel model is included in Appendix A. The performance analysis is based on the system model simulations whereby the verifications are done through the respective mathematical equations.

To obtain certain simulation results (e.g. outage probability), random symbols are fed into $S$, then, after several processes of signal processing (e.g., modulation and demodulation through the random coefficient of the channel models of source-to-relay ($SR$), relay-to-destination ($RD$), and $SD$ links), the output is measured at $D$. For the case of outage probability performance, the SNR at $D$ is compared to a predefined threshold value, and the operation is repeated to acquire the average value outage probability for a given SNR value. Based on the system model criteria such as type of channel model for a particular link, relaying type and diversity combining scheme type, the mathematical expressions are derived, then, the final line of the mathematical derivations are written in *m*-file and plotted.

According to the second type of the channel issue, the direct $SD$ link does not exist. This means the communication between $S$ and $D$ is solely through $R$. Since the $S$ and $D$ terminals are assumed of having slow dynamic mobility, hence, the channels $SR$ and $RD$ are subject to the first-order autoregressive model. Due to the employment on the wireless energy harvesting-based cooperative communication system, the time-switching protocol which is based on time structure is subject to the Jakes' autocorrelation model. In this case, no severe fading channel is considered between the terminals but the communication links experience a particular delay (the outdated channel environment) due to the movement of the terminals. The channel characteristic is associated with the correlation coefficient (based on the Jakes' autocorrelation model). The correlation coefficient is unit when all terminals are stationary, and this coefficient reduced from one once the terminal is having motions. The system performance considered is the achievable throughput, measured in bit/second per unit bandwidth. The performance analysis is based on the simulations and it is verified through the respective mathematical derivations. For both cases of the channel issues, there is no hardware implementation along with the simulation and mathematical expressions.

## 1.5 Overview of Research Methodology

The objectives of this thesis are to analyze the issues in the wireless communication channels, in terms of severe fading and outdated channel environments. Figure 1.2 presents the flow diagram of the research methodology.

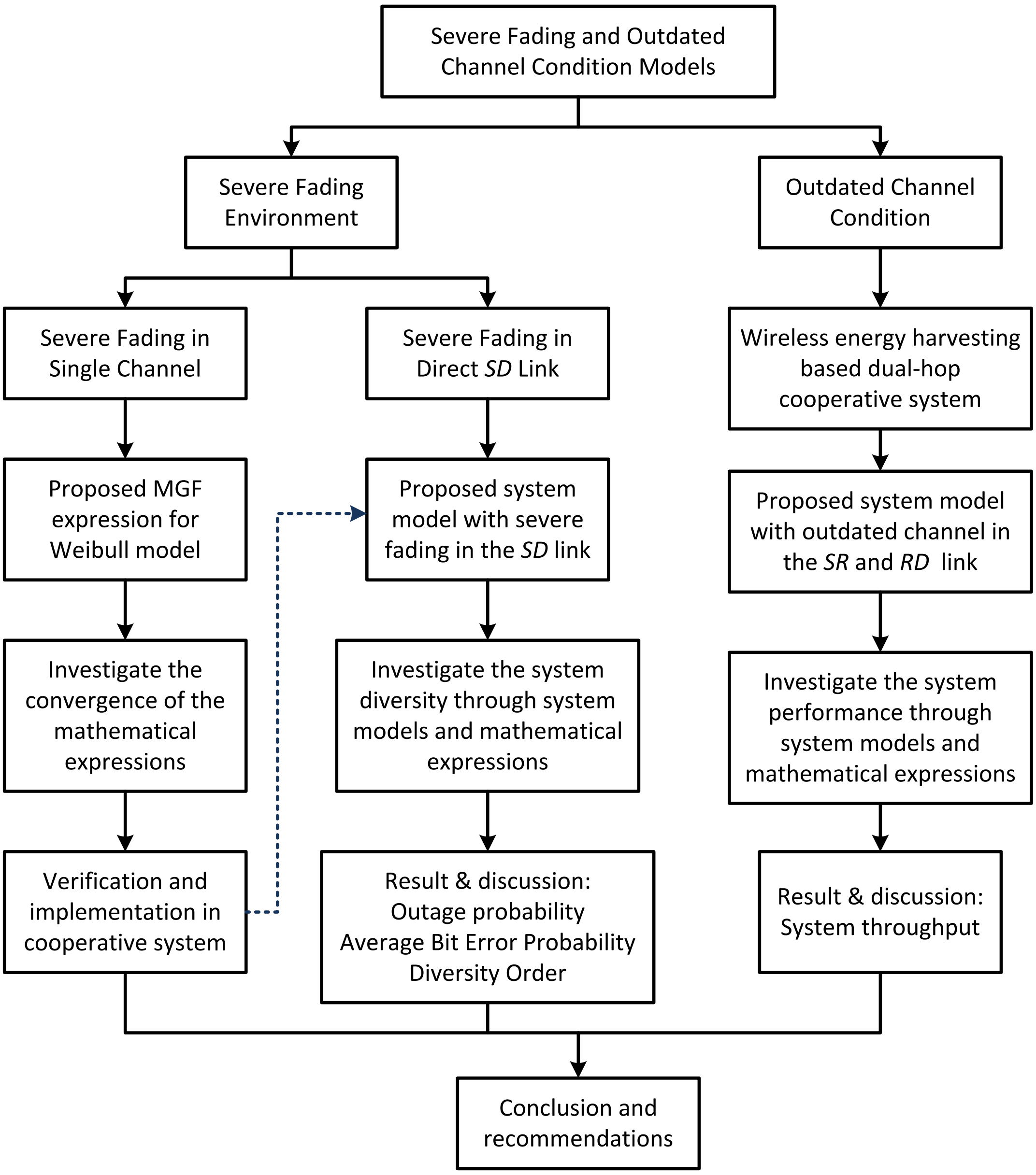

Figure 1.2: Flow diagram of the research methodology.

For the first objective, a new mathematical expression namely moment generating function (MGF) that indicates the distribution of the Weibull model is proposed. This expression represents the behavior of a single channel in terms of fading severity by manipulating the fading parameter. It is crucial to have this MGF expression since it is mathematically tractable, especially when representing a complex structure of the channel. It should be noted that this proposed expression can be converted into different distributions such as cumulative distribution function (CDF) and probability density function (PDF). The proposed MGF expression of Weibull distribution for a single channel consists of an infinite series term. Therefore, it is important to ensure that this series is converged. Then, this MGF expression is used in the second objective.

For the second objective, an amplify-and-forward (AF) cooperative system with a severe fading channel on its $SD$ link is analyzed. The severe fading is a channel condition where it has the level of a fading amount greater than Rayleigh has, but not reach the deep fade situation. It can be characterized by utilizing the Weibull distribution model. The aim is to evaluate the impact of considering the severe fading $SD$ link towards the system diversity and performances. Two types of AF protocols are considered; fixed-gain and variable-gain relaying protocols which are referred to as the amplification gain used during forwarding the signals at the second time phase. The system performances are measured based on the outage probability and average bit error probability.

For the third objective, an AF dual-hop wireless energy harvesting based cooperative system is analyzed. The time-switching relaying protocol is employed for the energy harvesting mechanism at the relay terminal. The outdated channel environment is considered to have occurred on both $SR$ and $RD$ links when the source and destination terminals are not static. Therefore, these channels are subject to the first-order autoregressive model while the time switching protocol is expected some delays which is subject to the Jakes' autocorrelation model. The system performances are computed based on the system throughput in bit/second per unit bandwidth, where these require the performances of outage probability and the ergodic capacity.

## 1.6 Thesis Chapter Outline

The thesis is organized as follows. Chapter 2 consists of two main parts. The first part describes the fundamental theories. They consist of the system parameters and frameworks, the relaying protocols and diversity combining schemes, several fading channel models and descriptions of severe fading and outdated channel conditions, energy harvesting protocols and related transmission modes, and definitions of advanced mathematical functions. The second part emphasizes on the related research works that pertaining to severe fading channel, outdated channel environment and energy-constrained relay terminal in a research scope of relaying network.

Chapter 3 presents new moment generating function (MGF) of the Weibull distribution model which allows complete derivations for the performance analytical expressions. The Weibull model is used to describe severe fading environment. Then, the impact of severe fading channel on the performance analysis of AF approximated variable-gain relaying and AF fixed-gain relaying networks are analyzed. This severe fading effect is mainly imposed on the direct $SD$ link in order to observe the contributions of the overall achievable diversity gain. Several diversity combining are considered such as maximal ratio combining and selection combining schemes.

Chapter 4 presents new channel delay for realizing the event of the outdated channel condition in the wireless energy harvesting-based cooperative communication system. The influence of the outdated channels towards throughput performances are observed accordingly. The delay caused by moving terminals affects the time-switching protocol time frame, and the channel itself is characterized by the first-order autoregressive model. In this chapter, no direct $SD$ link is considered and none of the links experience severe fading condition.

Chapter 5 concludes the thesis outcome and list out potential research recommendations.

# CHAPTER 2

# LITERATURE REVIEW

The cooperative communication system is a prominent way of enhancing the quality of transmitting information to the receiver by augmenting the system diversity. This can be achieved through generating multiple copies of original signals by each intermediate relaying terminal which are voluntarily delivering the signal information to the destination terminals. However, the wireless communication medium is susceptible to the quality of the operating channels.

Fading in wireless communication channels can be described as an attenuation in the signal strength at the receiver due to fluctuation over distance and time. When a signal is transmitted away from the antenna, it experiences reflection, scattering, diffraction or refraction by different structures in its path (Shankar, 2012) due to the natural behaviors of wireless signal propagations such as multipath, path loss and shadowing. The concept of multipath is the possibility of several broadcasting signal copies from the transmitter is fed into the receiver part of the communication. This is considered as a small-scale fading due to the significant change in attenuation level. Based on the behavior of the signal multipath, several statistical channels are described and explained in the following subsection. Path loss is the dissipation power concerning the distance between the transmitter and the receiver. But, in other cases, although the signal travels through the same distance from the transmitter, the signal received at different locations may vary due to random effect, and this is called as superposed of shadowing (Chiueh and Tsai, 2007; Goldsmith, 2005).

## 2.1 Fundamental Theories

This section presents the channel distribution models and attributes for characterizing certain wireless media. It follows with the types of system performance measures and the idea of cooperative and relaying systems. Then, several diversity combining schemes and the concept of energy harvesting in cooperative systems are described.

### 2.1.1 Fading Channel Environment

An accurate deterministic channel model to characterize the multipath propagation effects is impossible to develop. Usually, statistical models are employed to represent multipath channels and evaluate the system performance in radio propagation environments. Several statistical models are considered and listed in the following Table 2.1. The notations are given as follows: $p_X(x)$ is the PDF of magnitude $X$, where $X = |h|$, $p_Y(x)$ is the PDF of the channel power gain $Y$, where $Y = |h|^2$, $F_Y(x)$ is the CDF of the channel power gain $Y$, and $\Omega$ is the channel mean power, $\Omega = \mathbb{E}\{|h|^2\}$. All the details in the table can be referred to Blaunstein and Andersen (2002); Patzold (2003); Shankar (2012); Suraweera et al. (2009b).

Table 2.1: Well-known fading channel models

| Channel Model and Details | PDF and CDF of $Y$ |
|---|---|
| **Rayleigh Fading**<br>Characterizes a multipath channel environment with a large number of signal propagation paths and no line-of-sight (NLoS) path between the transmitter and the receiver.<br>According to the central limit theorem (CLT), the impulse response of the channel is modelled by a Gaussian random process, which leads to a symmetric circular complex Gaussian random variable or Rayleigh distribution. | $p_Y(x) = \frac{1}{\Omega}\exp\left(-\frac{x}{\Omega}\right), x \geq 0 \quad (2.1)$<br>$F_Y(x) = 1 - \exp\left(-\frac{x}{\Omega}\right), x \geq 0 \quad (2.2)$ |

Table 2.1: (continued)

| Channel Model and Details | PDF and CDF of $Y$ |
|---|---|
| **Rician Fading**<br>Characterizes a multipath fading channel when there is a line-of-sight (LoS) propagation path from the transmitter to the receiver, which means there is a dominant path as compared to other paths.<br>Note: $I_0(\cdot)$ is the zeroth order modified Bessel function of the first kind and $K$ denotes the Rician factor which represents the power ratio of the LoS component to the non-LoS components (i.e., $K = A^2/\Omega$, where $A$ is the peak amplitude of dominant path).<br>Special cases: If $K = 0$, it becomes Rayleigh fading, and when $K \longrightarrow \infty$, it is Gaussian channel. | $p_Y(x) = \frac{(1+K)}{\Omega}\exp\left(-K-\frac{(1+K)x}{\Omega}\right) \times I_0\left(2\sqrt{\frac{K(1+K)x}{\Omega}}\right), x \geq 0 \quad (2.3)$<br>$F_Y(x) = 1 - Q_1\left(\sqrt{2K}, \sqrt{\frac{2(K+1)x}{\Omega}}\right), x \geq 0 \quad (2.4)$ |
| **Nakagami-*m* Fading**<br>Describes a propagation environment in which the wavelength of the carrier is proportional to the cluster size of scatterer.<br>Note: $m$ is the fading severity parameter, ranged between 0.5 to $\infty$, and $\Gamma(\cdot)$ is the gamma function. | $p_Y(x) = \frac{m^m x^{m-1}}{\Omega^m \Gamma(m)}\exp\left(-\frac{mx}{\Omega}\right), x \geq 0 \quad (2.5)$<br>$F_Y(x) = 1 - \frac{\Gamma(m, mx/\Omega)}{\Gamma(m)}, x \geq 0 \quad (2.6)$ |
| **Weibull Fading**<br>Considers as an approximation of generalized Nakagami distribution.<br>Note: $c$ is the Weibull fading severity parameter.<br>Special case: When $c = 2$, the distribution represents Rayleigh fading.<br>Weibull fading can be used to model a channel environment that is severe than Rayleigh and this topic will be discussed in detail in Section 2.2.1. | $p_Y(x) = \frac{c}{2}\left(\frac{\Gamma(1+\frac{2}{c})}{\Omega}\right)^{\frac{c}{2}} x^{\frac{c}{2}-1} \times \exp\left[-\left(\frac{x}{\Omega}\Gamma\left(1+\frac{2}{c}\right)\right)^{\frac{c}{2}}\right], x \geq 0 \quad (2.7)$<br>$F_Y(x) = 1 - \exp\left[-\left(\frac{x}{\Omega}\Gamma\left(1+\frac{2}{c}\right)\right)^{\frac{c}{2}}\right], x \geq 0 \quad (2.8)$ |

#### 2.1.1(a) Outdated Channel

The condition of outdated channel impacts wireless communication systems performances. There are two distinguishable scenarios of the outdated channel conditions to happen, that is either the channel is having a feedback delay response or the estimation errors occur at the destination terminal. These two situations are presented here.

**Channel Feedback Delay:**

The correlation coefficients between the envelope of the actual channel $h_{i,k}(t)$ and its delayed version $h_{i,k}(t-T_d)$ on the $i$-th hop of the $k$-th relay can be defined as $\rho_{i,k}$, where $T_d$ is the time lag between $h_{i,k}(t)$ and $h_{i,k}(t-T_d)$. Assuming that the distribution of the channel and its delayed version are jointly Gaussian, then, $h_{i,k}(t)$ can be written as follows (Kim et al., 2013; Michalopoulos et al., 2012)

$$h_{i,k}(t) = \rho_{i,k}\, h_{i,k}(t-T_d) + g_{i,k}(t), \tag{2.9}$$

where $g_{i,k}(t)$ is circularly symmetric complex Gaussian random variables (RVs) and follows the distribution as $g_{i,k}(t) \sim \mathcal{CN}(0,(1-\rho^2)\sigma_h^2)$. Under the assumption of a Jakes' autocorrelation model, the correlation coefficients, $\rho_{i,k}$ is written as (Michalopoulos et al., 2012)

$$\rho_i = J_0(2\pi f_m T_{d_i}), \tag{2.10}$$

where $J_0(\cdot)$ denotes the zeroth order Bessel function of the first kind, $f_d$ is the maximum Doppler frequency and $T_d$ is the time difference between the actual and estimate channel values.

**Channel Estimation Error:**

Let the estimated $i$-th hop value of the $k$-th relay be $\hat{h}_{i,k}(t)$. With the assumption that $h_{i,k}(t)$ and $\hat{h}_{i,k}(t)$ are jointly ergodic and stationary Gaussian process as well as having the orthogonality between the estimated channel and the estimation error values, the following relationship (Han et al., 2009; Ikki and Aissa, 2012a; Seyfi et al., 2012) is obtained as

$$h_{i,k}(t) = \hat{h}_{i,k}(t) + e_{i,k}(t) \tag{2.11}$$

where $e_{i,k}(t)$ is the channel estimation error, which is complex Gaussian with zero mean and variance of $\sigma^2_{e_{i,k}} = E\{|h_{i,k}|^2\} - E\{|\hat{h}_{i,k}|^2\} = \Omega_h - \Omega_{\hat{h}}$, where $E\{\cdot\}$ is the expectation operator and $|\cdot|$ is the absolute value operator. Similar to $h_{i,k}(t)$, the term $\hat{h}_{i,k}(t)$ is also complex Gaussian with zero mean and variance of $\Omega_{\hat{h}} = \Omega_h - \sigma^2_{e_{i,k}}$. The parameter of $\sigma^2_{e_{i,k}}$ reveals that the quality of the channel estimation and can be decided depending on the channel dynamics and estimation schemes.

### 2.1.1(b) Time and Frequency Dispersion Parameters

To describe the time dispersive nature of the channel, the parameters of delay spread and coherence bandwidth, $B_c$ are introduced. Delay spread is caused by multipath propagation and $B_c$ is an analogous of root mean square (rms) delay spread ($\sigma_\tau$) in the frequency domain which can be viewed through Fourier transform. Although, there is no exact relationship between $B_c$ and $\sigma_\tau$, generally, they are inversely proportional to each other (Rappaport, 2002). If the definition is relaxed so that the frequency correlation function is above 0.5, then, $B_c$ is given by (Rappaport, 2002)

$$B_c \approx \frac{1}{5\sigma_\tau} \tag{2.12}$$

Furthermore, to describe the time varying nature of the channel, the parameter of Doppler spread, $B_D$ and coherence time, $T_c$ are used. $B_D$ is the spectral broadening measure caused by changing time rate of the channel. Meanwhile, $T_c$ is the Doppler spread's time domain dual for characterizing the time varying nature of the frequency dispersiveness of the channel. The relationship between $T_c$ and $B_D$ is given by (Rappaport, 2002)

$$T_c \approx \frac{1}{B_D} = \frac{1}{f_m} \tag{2.13}$$

where $B_D$ is also recognized as $f_m$, or the maximum Doppler shift.

### 2.1.1(c) Slow Fading Channel

When impulse response of a channel changes at a rate much slower than the transmitted baseband signal, the channel is slow fading. It can be assumed to be static over one or several symbol period intervals. From the perspective of its frequency domain, the Doppler spread of the channel is much less than the baseband signal bandwidth. Hence, the condition for slow fading is summarized as (Rappaport, 2002)

$$\text{symbol period } (T_s) \ll \text{coherence time } (T_c) \tag{2.14}$$

$$\text{signal bandwidth } (B_s) \gg \text{Doppler spread } (B_D) \tag{2.15}$$

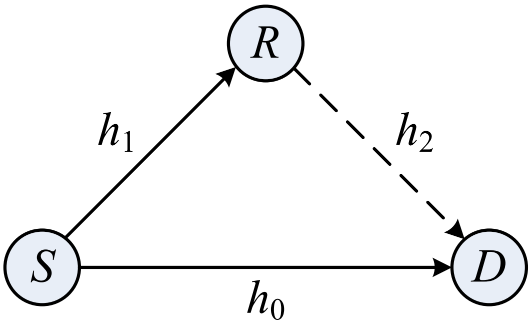

Figure 2.1: A baseline relaying network with single relay that helps the communication between $S$ and $D$. Solid and dashed lines represent the first and the second time slots, respectively.

### 2.1.2 System Parameters and Performance Measures

A fundamental cooperative relaying network requires at least three important terminals; known as source ($S$), relay ($R$) and destination ($D$) as shown in Figure 2.1. The communication between $S$ and $D$ is assisted by $R$ while at the same time, $S$ and $D$ may have their communication link. The channel coefficients of source-to-destination ($SD$), source-to-relay ($SR$) and relay-to-destination ($RD$) links are denoted by $h_0$, $h_1$ and $h_2$ respectively. The relaying network can be extended into a more complex network such as by having multiple $S$ or multiple $R$ or multiple $D$ or any combination of these terminals. Other relevant and extended network topologies as presented are shown in Section 2.1.4.

Assume that $R$ always agree to cooperate and $SD$ link always exists, each cycle of communication can be achieved by orthogonal transmission of two time slots. In the first time slot, $S$ broadcasts its signal and both $R$ and $D$ receive this attenuated or scaled version of the signal. Then, $R$ performs signal processing using certain relaying protocol. In the second time slot, $R$ transmits the processed signal to $D$. In this case, $D$ receives two copies of the source's message and using certain algorithms, $D$ attempts to recover the information, resulting in diversity gain that improves the signal reliability. Several relaying protocols may be applied to $R$ and different kinds of diversity combining techniques can be employed by $D$. The details on relaying protocol and diversity combining schemes are included in Section 2.1.3(a) and 2.1.5, respectively. It is assumed that the communications are carried out in half-duplex (e.g., in Wireless Local Area Network) where the terminals cannot transmit and receive information data on similar frequency band simultaneously (Laneman et al., 2004).

The received signal power randomly changes over time and distance. Thus, the received signal-to-noise ratio (SNR) is a random variable that requires certain fading distributions of cumulative distribution function (CDF), probability density function (PDF) and moment generating function (MGF) for performance evaluations. In Table 2.2, several performance measures are put into consideration. Details are obtained from Abouelseoud and Nosratinia (2011); Goldsmith (2005); Gurung et al. (2010); Papoulis and Pillai (2002); Simon and Alouini (2005); Suraweera et al. (2009b).

Table 2.2: Critical system performance measures

| Types of Performance Measures | Mathematical Expressions |
|---|---|
| **Signal-to-Noise Ratio (SNR), $\gamma$**<br>An average SNR, $\bar{\gamma}$ is obtained by averaging the probability distribution of the channel fading. | $\bar{\gamma} = \int_0^\infty \gamma p_\gamma(\gamma) d\gamma \qquad (2.16)$ |
| The instantaneous SNR can be represented in term of MGF ($\mathcal{M}_\gamma(s)$) as a unified approach of performance evaluation. | $\mathcal{M}_\gamma(s) = \int_0^\infty p_\gamma(\gamma) e^{-s\gamma} d\gamma \qquad (2.17)$ |
| $\gamma$ is not only represented from a single channel, but it is often considered as a sum of independent individual branches or fading composite channels. | |

Table 2.2: (continued)

| Types of Performance Measures | Mathematical Expressions |
|---|---|
| **Outage Probability ($P_{out}$)**<br>A critical measure of performance which computes the service quality of the wireless system over fading channel. It is defined as the probability that instantaneous output SNR falls beyond a given specified threshold value, $\gamma_{th}$. | $P_{out} = \Pr(\gamma_d < \gamma_{th}) = F_{\gamma_D}(\gamma_{th})$ (2.18a)<br>$P_{out} = \int_0^{\gamma_{th}} p_{\gamma_D}(\gamma) d\gamma$ (2.18b) |
| Alternatively, $P_{out}$ can be evaluated by an MGF-based approach. | $P_{out} = \mathfrak{L}^{-1}\left\{ \frac{\mathcal{M}_{\gamma_D}(s)}{s} \right\}\Big\vert_{\gamma_{th}}$ (2.19) |
| where $\mathfrak{L}^{-1}(\cdot)$ denotes the inverse Laplace transform and the computing operation of $P_{out}$ can be obtained numerically as presented in (Ko et al., 2000). The Matlab *m*-file code is included in Appendix B. | |
| **Average Bit Error Probability (ABEP)**<br>One of the most informative indicators in wireless communication system. It can be obtained by averaging the conditional Bit Error Probability (BEP) over fading statistics.<br>Based on $M$-phase shift keying modulation ($M$-PSK), the evaluation of ABEP, $\bar{P}_b$ can be obtained. | $\bar{P}_b = \frac{1}{2\sqrt{2\pi}} \int_0^{\infty} F_{\gamma_D}\left(\frac{u}{\vartheta}\right) e^{-\frac{u}{2}} u^{-\frac{1}{2}} du.$ (2.20) |
| where $\vartheta$ is a constant to a specific modulation schemes used in communication system such as binary phase shift keying (BPSK) ($\vartheta = 2$) and quadrature phase shift keying (QPSK) ($\vartheta = 1$). | |
| Alternatively, $\bar{P}_b$ can be evaluated by the MGF-based approach. | $\bar{P}_b = \frac{1}{\pi} \int_0^{(M-1)\pi/M} \mathcal{M}_{\gamma_D}\left(-\frac{g_1}{\sin^2\psi}\right) d\psi,$ (2.21) |
| where $g_1 = \sin^2(\pi/M)$ is a function of the $M$-PSK constellation size. | |

Table 2.2: (continued)

| Types of Performance Measures | Mathematical Expressions |
|---|---|
| **Ergodic capacity ($C$)**<br>Also known as Shannon capacity in which having an average power constraint and the knowledge on the receiver channel. | $$C = \mathbb{E}\{B\log_2(1+\gamma_D)\}, \quad (2.22a)$$<br>$$C = \int_{\gamma=0}^{\infty} B\log_2(1+\gamma)\, f_{\gamma_D}(\gamma)\, d\gamma, \quad (2.22b)$$ |
| where $\mathbb{E}\{\cdot\}$ is the expected value operator, $B$ is the channel bandwidth and the capacity unit is bits per second ($b/s$).<br>Usually, $B$ is normalized into unit bandwidth of 1 Hz and the capacity is viewed in bits per second per Hertz (b/s/Hz). | |
| **Diversity Order ($div$)**<br>A helpful tool that provides additional information to the plotted graphs at the high SNR regime for $P_{out}$ and ABEP performance evaluations.<br>By assuming the transmission intervals are sufficiently long, the diversity order-based outage probability can computed as on the right. | $$div_1 = -\lim_{\xi\to\infty} \frac{\log P_{out}(\xi)}{\log \xi}, \quad (2.23)$$ |
| where $\xi$ is the SNR. Commonly, the diversity order-based error probability is obtained as on the right. | $$div_2 = -\lim_{\xi\to\infty} \frac{\log P_b(\xi)}{\log \xi}. \quad (2.24)$$ |

### 2.1.3 Cooperative and Relaying System

This section presents several important concepts in cooperative communications including the relaying protocols, relaying technique, network configurations with selection schemes and diversity combining schemes. Conventionally, the multiple-antenna transceiver is employed for the purpose of achieving improved diversity gain. However, due to limitations of cost and hardware, its development has been hindered. Cooperative communication can provide diversity gain when the source's messages are