PERFORMANCE ANALYSIS OF COOPERATIVE DIVERSITY IN LAND MOBILE SATELLITE SYSTEMS

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November 2013

Dissertation submitted in fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN ENGINEERING: ELECTRONIC ENGINEERING

In the Discipline of Electrical, Electronic and Computer Engineering

UNIVERSITY OF KWAZULU-NATAL

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DECLARATION - PLAGIARISM

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ACKNOWLEDGEMENTS

I wish to sincerely appreciate the great efforts put into this work by my supervisor, Dr Tom Walingo and co-supervisor, Prof. Fambirai Takawira. Your fatherly role, tireless personal commitments and continuous impetus made this work possible. I am most grateful.

My parents and siblings quickly come to mind as I put together this acknowledgement. You guys are the best in the whole wide world! Though very far away, yet you kept so near. We went through the hurdles and the challenges together. I am forever indebted to you all.

Special appreciation goes to the following sweethearts: Dr Oluwafemi Ilesanmi and family (who God used not only to make my coming to SA a possibility but who also stood as great mentors and builders of destiny!); Dr Oyerinde Olutayo and family (who were not just spiritual guides but also encouraged, motivated and challenged me towards great achievements); My colleagues (Olugbenga Imole, Sithembiso Gama, Abdulrahman Mogbonjubola and Maria Sefuba) who helped me in all capacities than I could ever imagine. We kept moving on through the hard and difficult times, yes, together! Thanks a bunch guys; Fellow brethren in the Deeper Life Campus Fellowship house (lovely brothers and sisters who are making my stay in SA enjoyable). Thank you all for showing me much love.

To the staff and students (both post grads and under grads) of the School of Electrical, Electronic and Computer Engineering, UKZN Howard College who through their constant love and many sacrifices keep challenging me to keep going forward. I appreciate you all!

And the utmost gratitude goes to the Almighty God who indeed makes all things beautiful in His time. Thank you Lord.

ABSTRACT

Land Mobile Satellite Systems (LMSS) generally differ from other terrestrial wireless systems. The LMSS exhibit unique characteristics with regard to the physical layer, interference scenarios, channel impairements, propagation delay, link characteristics, service coverage, user and satellite mobility etc. Terrestrial wireless systems have employed the spatial diversity or MIMO (Multiple Input Multiple Output) technique in addressing the problem of providing uninterrupted service delivery to all mobile users especially in places where non-Line-of-Sight (NLoS) condition is prevalent (e.g. urban and suburban environments). For the LMSS, cooperative diversity has been proposed as a valuable alternative to the spatial diversity technique since it does not require the deployment of additional antennas in order to mitigate the fading effects. The basis of cooperative diversity is to have a group of mobile terminals sharing their antennas in order to generate a "virtual" multiple antenna, thus obtaining the same effects as the conventional MIMO system. However, the available cooperative diversity schemes as employed are based on outdated channel quality information (CQI) which is impracticable for LMSS due to its peculiar characteristics and its particularly long propagation delay. The key objective of this work is therefore to develop a cooperative diversity technology model which is most appropriate for LMSS and also adequately mitigates the outdated CQI challenge.

To achieve the objective, the feasibility of cooperative diversity for LMSS was first analyzed by employing an appropriate LMSS channel model. Then, a novel Predictive Relay Selection (PRS) cooperative diversity scheme for LMSS was developed which adequately captured the LMSS architecture. The PRS cooperative scheme developed employed prediction algorithms, namely linear prediction and pattern-matching prediction algorithms in determining the future CQI of the available relay terminals before choosing the most appropriate relay for cooperation. The performance of the PRS cooperative diversity scheme in terms of average output SNR, outage probability, average channel capacity and bit error probability were simulated, then numerically analyzed. The results of the PRS cooperative diversity model for LMSS developed not only showed the gains resulting from introducing cooperative techniques in satellite communications but also showed improvement over other cooperative techniques that based their relay selection cooperation on channels with outdated quality information (CQI). Finally, a comparison between the results obtained from the various predictive models considered was carried out and the best prediction model was recommended for the PRS cooperation.

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LIST OF ACRONYMS

3G	Third Generation
ACK	Positive Acknowledgement
AF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BSS	Broadcasting Satellite Service
CC	Coded Cooperation
CD	Cooperative Diversity
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Check
CQI	Channel Quality Information
dB	Decibels
DF	Decode-and-Forward
DVB-SH	Digital Video Broadcasting – Satellite Handheld
FSS	Fixed Satellite Service
i.i.d	Independent and identically distributed
i.n.d	Independent but non-identically distributed
IRS	Incremental Relay-Selection
IRS-DF	Incremental Relay-Selection Decode-and-Forward
ITU-R	International Telecommunication Union - Recommendation
LMSS	Land Mobile Satellite Systems
LoS	Line-of-Sight
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output

MGF	Moment Generating Function
MRC	Maximum Ratio Combining
MRS	Multiple Relay Selection
MSS	Mobile Satellite Service
NACK	Negative Acknowledgement
NLoS	Non-Line-of-Sight
ORS	Opportunistic Relay-Selection
PDF	Probability Distribution Function
PRS	Predictive Relay-Selection
Q-PSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RV	Random Variable
SDF	Selective Decode-and-Forward
SF	Store-and-Forward
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
SRS	Single Relay Selection
TDMA	Time Division Multiple Access

CHAPTER 1

INTRODUCTION

1.1 Background to Satellite Communications

Communication satellites can be defined as microwave stations (some having the capacity for onboard processing, switching, etc.) that permit two or more users with appropriate earth stations to deliver or exchange information in various forms. Satellites can be classified based on their orbit of rotation as either synchronous or non-synchronous. Synchronous satellites have orbits that make a complete rotation in 24 hours. Synchronous orbit satellites are of three types; the Geostationary Earth orbit (GEO) which revolves around the earth in the plane of the equator once in 24 hours thus maintaining precise synchronization with the earth's rotation; the geosynchronous orbit (GSO) and the highly elliptical synchronous orbit (HEO) which both involve satellites that appear to move relative to a fixed point on the earth. For GEO satellites, the range from user to satellite is an average of 36,000 km, which makes the design of the microwave link quite stringent in terms of providing adequate received signal power [1]. Also, that distance introduces a propagation delay of about one-quarter of a second for a single hop between a pair of users. The key advantage of GEO satellites however is its ability to provide coverage for an entire hemisphere at the same time. Non-synchronous (or generally referred to as Non-GEO) satellites have periods of revolution shorter than 24 hours and their orbits are below a mean altitude of 36,000 km. There are two types of Non-synchronous satellites; Low Earth Orbit (LEO) and Medium Earth Orbit (MEO). LEOs operate at an altitude of 500 – 2,000km while MEOs operate at 8,000 – 12,000km altitude above the ground surface. Non- synchronous satellites have the advantage of being closer to the earth than the GEO ones hence it allows much lower end-to-end latency in transferring data as well as better link budget conditions [1]. The major drawback for non-GEO satellites is that they need several satellites (as a constellation) to cover a region or the whole earth, so much that frequent handover procedures are needed to switch a connection from one satellite antenna beam to another, or even from a terrestrial gateway to another.

While the classification of satellites so far done had concentrated on the orbits of rotation (or space segment), another possible way of classifying satellites is by considering their applications on the ground or earth surface (ground segment). Based on ground applications, satellites can be classified into Fixed Satellite Service (FSS), Broadcasting Satellite Service (BSS) or Mobile Satellite Service (MSS). Fixed Satellite Service (FSS) and Broadcasting Satellite Service (BSS) involve commercial applications through earth stations at fixed locations on the ground providing services for television viewers, information network providers, enterprises, disaster workers and web surfers. Mobile Satellite Service (MSS) refers to ground users with ability to move from one place to another without necessarily causing a disruption in service delivery. MSS offers interactive voice and data services for ships, aircraft, and individuals on the land. MSS particularly designed for land use is generally referred to as Land Mobile Satellite Systems (LMSS).

1.2 Land Mobile Satellite Systems (LMSS) – Components and Characteristics

There has been a continuously increasing interest in Mobile Satellite Systems (MSS) in the last few years. Several sectors of the world like aeronautics, marine, military, rescue and disaster relief etc. all need mobile communication services. The terrestrial wireless communication infrastructures cannot serve these numerous communication needs in all areas (or terrains) of the world and at all times. The MSS is being continuously looked into as a means of supplementing the terrestrial system thus providing greater coverage, better service quality (QoS) and improving availability and reliability of communication systems. The Land Mobile Satellite Systems (LMSS) are a class of MSS that are particularly adapted for use within landed terrains. LMSS exhibit unique characteristics from terrestrial wireless systems with regard to the physical layer, interference scenarios, channel impairements, propagation delay, link characteristics, service coverage etc. They are particularly characterized by both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation conditions. This is mainly due to the presence of obstacles or return link budget restrictions caused by the low power and small antenna size available on their portable mobile terminals [2]. Hence, a combination of satellite and terrestrial networking is currently being employed for the LMSS. Two types of satellite-terrestrial networks are available –hybrid networks and integrated networks. Hybrid networks use terrestrial gap-fillers to retransmit locally the satellite signal when there is NLoS. It also employs the terrestrial cellular system as return link to simplify power management of the mobile terminals. Satellite coverage can also be extended by means of local wireless system that converts satellite signals to a local wireless one and vice versa at the base stations. On the other hand, integrated networks employ a terrestrial cellular network as an alternative system to connect the mobile users in both forward and return link, with respect to the satellite one. Frequency bands are assigned by ITU-R. A summary of the frequency bands and their current applications is given in Table 1.1.

Table 2.1 Frequency Bands for Satellite Communications [41]

Band	**Frequency Range**	**Total Bandwidth**	**General Application**
L	1 to 2 GHz	1 GHz	Mobile satellite services (MSS)
S	2 to 4 GHz	2 GHz	MSS, NASA, deep space research
C	4 to 8 GHz	4 GHz	Fixed satellite service (FSS)
X	8 to 12.5 GHz	4.5 GHz	FSS, Military, terrestrial earth exploration and meteorological satellites
Ku	12.5 to 18 GHz	5.5 GHz	FSS, broadcast satellite service (BSS)
K	18 to 26.5 GHz	8.5 GHz	BSS, FSS
Ka	26.5 to 40 GHz	13.5 GHz	FSS

While fixed services use high C and K frequency bands, LMSS are assigned the lower L and S bands. This is because L and S bands permit on-board antennas due to lower signal attenuation and reduced impact of atmospheric effects. Furthermore, the tall buildings and compact nature of the urban areas introduce scatterers thereby creating multipath phenomena that the LMSS can take advantege of. Mobile terminals used in LMSS can transmit signals in all directions and receive signals from all directions (they use Omni-directional antennas or phased-array directional antennas with fast tracking algorithms, as compared to fixed terminals that use directional antennas), hence, mobile terminal could interfere with each other and with other satellite networks. The minimum elevation angle from which a mobile terminal can see the satellite in a LMSS is also of paramount importance. In LMSS, there is the need to avoid a low value of minimum elevation angle. This will help minimize the occurrence of frequent shadowing and blockage events for the signal due to trees, buildings etc. By increasing elevation angle, an improvement is seen in the signal quality because shadowing and blockage effects are reduced significantly. However, the system costs also increases due to higher number of satellites in the constellation. To help adapt to channel variations as a result of user movements, LMSS uses an adaptive air interface with the best choice among several modulation and coding techniques. LMSS are now being developed to employ a feedback channel to inform the transmitter about the most suitable physical layer transmission parameters to guarantee a certain quality at the receiver. Finally, because of frequent handovers in LMSS, the resource assignment at the Medium Access Control (MAC) layer must provide adequate priorities for handover management [1], [2].

1.3 Applications of Land Mobile Satellite Systems (LMSS)

There are a number of current and future applications of the Land Mobile Satellite Systems. LMSS communication systems are designed to be able to provide to mobile users the same access characteristics as those of their terrestrial counterparts. Some of these application standards as discussed in [1] are summarized below:

a) Global System for Mobile Communication (GSM) via satellite: GSM is currently the most popular cellular communication standard in the world. Although it is a terrestrial system, extensions are now commercially available that permits a form of 'GSM' over satellite. An example is the GEO Mobile Radio (GMR). Furthermore, mobile terminals can be dual-mode thus allowing its usage either as the terrestrial GSM interface or the GEO satellite GSM when there is no terrestrial signal (this approach is referred to as the integrated network approach).

b) Satellite- Universal Mobile Telecommunications System (S-UMTS): UMTS is one of the 3G terrestrial cellular technologies. S-UMTS is not only intended to complement the terrestrial UMTS coverage, but it is also conceived to extend UMTS services to arrears where the terrestrial coverage would be either technically or economically unfeasible. S-UMTS uses frequency bands around 2 GHz that are close to those used by terrestrial 3G systems. S-UTMS supports user bit-rates up to 144kbit/s, an acceptable value for multimedia services to mobile users typically having small devices.

c) Digital Video Broadcasting- Satellite Version 2 Mobile Extension (DVB-S2): DVB-S2 is mostly employed for satellite broadcast services. However, DVB-S2 can also be employed for interactive point-to-point applications (e.g. internet access). This is achieved by using new operation modes that permits a dynamic adaptation of the modulation and coding levels depending on channel condition at receiver. This standard is being extended to mobile users on planes, trains, and landmasses by operating in Ku and Ka bands.

d) Satellite- Digital Multimedia Broadcasting (S-DMB): The S-DMB standard envisages a satellite-based broadcast component for 3G mobile networks. It permits the distribution of the

Multimedia Broadcast Multicast Service (MBMS) that can only be offered via GSM or 3G cellular networks.

e) Digital Video Broadcasting- Satellite Handheld (DVB-SH): This is a mobile broadcast standard based on a Time Division Multiplexing (TDM) or an Orthogonal Frequency Division Multiplexing (OFDM) air interface for the provision of audio and video broadcast services to small handheld terminals and to some vehicular devices. DVB-SH achieves large coverage by combining a satellite component and a Complementary Ground Component (CGC) system. Terrestrial repeaters are envisaged to increase the DVB-SH service availability in zones where it is impossible to have LoS conditions with the satellite (e.g. urban and indoor areas). DVB-SH is mainly interested in broadcast services, but also data push delivery and IP-based interactive services (via an external return link, e.g. UMTS) are supported. The user can access these services when travelling on ships, cars, trains, or while walking.

The DVB-SH is employed in this work for analyzing and characterizing the LMSS. Parameters for a typical DVB-SH system are used in simulating the system and obtaining the results later discussed in the work. The DVB-SH is chosen because of its versatile nature, large coverage and also its seamless satellite-terrestrial networking capabilities.

1.4 Examples of Land Mobile Satellite Systems (LMSS)

There are a number of LMSS providing communication services currently. Some of them like the Iridium and Globalstar operate in the LEO regions while others like the Inmarsat and Thuraya operate in the GEO region orbits. Some of these examples as given in [2] are briefly discussed.

a) Iridium LMSS: The iridium system is LEO-based, operates on the L frequency bands, employs Quadrature Phase Shift Keying (QPSK) at its physical layer and also the Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) multiple access for its propagation. It is designed to support real-time voice and low bit-rate data (web browsing, e-mail access) transmissions anywhere and anytime by using a constellation of sixty-six active LEO satellites with On Board Processing (OBP) capabilities and Inter Satellite Links (ISLs) among the satellites. It also uses the dual mode standard (satellite-GSM). The iridium system is the only satellite system to provide complete earth coverage which includes Polar Regions, aeronautical routes and oceanic regions.

b) Globalstar LMSS: The Globalstar system also employs the LEO orbits and operates on both the L and S frequency bands. It uses 48 bent-pipe LEO satellites with no Inter Satellite Links (ISLs). It uses Quadrature Phase Shift Keying (QPSK) in its physical layer, while its multiple access is combined FDMA/DS-CDMA with spreading factor $G = 128$ for both uplink and downlink. Globalstar adopts path diversity combining i.e. in order to mitigate shadowing and blockage it combines the signals to/from up to three visible satellites for a single call. It offers real-time voice, data and fax as well as web browsing and e-mail access. This satellite system can provide communication services in an area within ±700 latitudes in the zones where terrestrial gateways are present (it doesn't actually serve Polar Regions). There are currently 25 gateways in operation around the world with each gateway covering around 200km.

c) Inmarsat LMSS: This system was mainly established to serve the maritime community but has since been extended to deliver broadband communication services to enterprises and aeronautical users. It operates 12 GEO satellite constellations and with these it provides communication to the entire world. Its most innovative system is the Broadband Global Area Network (BGAN). BGAN operates on L frequency band, employs FDMA/TDMA multiple access, has bent-pipe satellite features, does not have Inter Satellite Links (ISLs) and operates a dual mode (satellite-GSM) standard. It supports applications like broadband internet access, VoIP, web browsing, e-mail access, live video, videoconferencing and real time voice to both fixed and mobile users.

d) Thuraya LMSS: The Thuraya system uses two GEO satellites and covers Europe, North and Central Africa, Middle East, Central Asia and the Indian sub-continent (over 110 countries) [2]. It uses GMR-1 air interface and operates in L frequency band. It employs the $\pi/4$ QPSK physical layer, operates on FDMA/TDMA multiple access, has On Board Processing (OBP) and beam switching features, does not use Inter Satellite Link (ISL), uses the dual mode (satellite-GSM) standard and supports applications including point-to-point file exchange, internet connectivity through small portable terminals, and real-time GSM-like voice.

e) Hispasat LMSS: This system uses six GEO satellites dispersed at different orbit positions. It employs the Ku frequency band, QPSK physical layer, Multiple Frequency –Time Division Multiple Access (MF-TDMA), On Board Processing (OBP) and beam switching features, it has no Inter Satellite Link (ISL) and uses the DVB-S/-RCS standards. Hispasat offers IP-based services such as access to internet and content distribution, tele-medicine and tele-education, voice over IP, video streaming and internet TV.

1.5 Challenges of Land Mobile Satellite Systems (LMSS)

The Land Mobile Satellite Systems (LMSS) technology is an evolving system. Though several satellite constellations have been successfully deployed and are fully operational providing services to several locations, several challenges are still identified which limits efficiency and service delivery of LMSS. Some of these challenges as highlighted and discussed in references [2] – [5] are summarized as;

a) Frequent handovers taking place between one satellite and another due to the fact that they are mobile. More so, users are also constantly changing in location, hence, mobility management must be taken into consideration.

b) Extending broadband for mobile communication via satellite. Most available mobile satellites are only applicable to voice and data communications, which requires low broadband usage. To include other services like multimedia and high capacity internet access, larger broadband is required.

c) Another challenge with the LMSS is in increasing its resource reuse factor. The resource reuse factor describes the extent to which a network can reuse its allotted frequencies in other to increase both capacity as well as its coverage area. The reuse factor is given as $1/K$ (or K according to some authors) where K is the number of cells which cannot use the same frequencies for transmission. Common values for the frequency reuse factor are 1/3, 1/4, 1/7, 1/9 and 1/12 (or 3, 4, 7, 9 and 12 depending on notation).

d) Some more generally identified challenges of the LMSS include how to reduce cost of providing the services, improving in quality and quantity of service provided and increasing the number of people being served by mobile satellite systems.

e) Size of mobile terminals. Devices that will be mobile must be small/portable, must run on low power so that the battery can last longer and as well and must be pretty inexpensive or affordable. Design and usage of such high capacity, small-sized mobile devices is currently underway. However, there is always room for improvement.

f) A major challenge with LMSS services is the possibility of providing an uninterrupted delivery to all mobile users and at all time, irrespective of location or channel condition. Certain environment types like the urban and suburban environments are characterized with high-rise buildings and compact structures that make multiple fading patterns a common occurrence. More so, mobile users due to their mobility are sometimes in places where line-of-sight (LoS) condition with the satellite is not obtainable. Therefore, there must be a means of establishing and maintaining a good network connection and a guarantee on quality of service.

In this research work, the last two challenges mentioned above (i.e. reducing size of mobile terminals and their required resource consumption as well as the challenge of providing consistent service for all users irrespective of the environment or fading conditions) are the major focus.

1.6 Solutions to the LMSS Challenges

There has been several research works carried out to help with mitigating the various challenges of the LMSS, and more work is currently being done. Some of the current research work focus on the following areas:

a) Providing seamless handover and mobility management between satellites in the constellation as well as between mobile terminals. New mobility models for LMSS are currently being investigated and are being recommended for immediate implementation [2], [6].

b) Providing increased broadband for the LMSS. To achieve this, satellite designers are currently focusing on engaging frequency bands that can deliver larger bandwidth and that are also not susceptible to attenuation due to rain [2]. Also, current research works are focusing on improving communication payloads, call admission control schemes, network flexibility, capacity and performance with relevant ideas on implementing them for the LMSS [7].

c) Advancement in technology is making the design and implementation of sleek, durable, high-capacity portable devices for the mobile users in LMSS possible. Although they initially come expensive, more recent research is focusing on making these portable devices available at cheaper cost [2], [7].

d) Achieving a greater reuse factor for the LMSS. One current solution for this has been to employ high directivity multi spot beam satellite antennas in transmitting signals [2]. A more recent approach is in employing multiple access systems like the Orthogonal Frequency Division

Multiple Access (OFDMA) which do not spread signals across the frequency band [8]. This makes room for a proper coordination of the resource allocation between different cells.

While the solutions so far proffered has resulted in major improvement in the LMSS service conditions and its overall service deliverables, the problem of poor quality of service due to fading effects in different environments have not been adequately mitigated. Due to the inconsistent fading patterns of the urban and suburban environments especially, poor service delivery is still being experienced for the LMSS. In this work therefore, a viable solution through cooperative diversity is being investigated. This is achievable by exploiting the broadcast nature of the satellite and then also employing the mobile relays on the ground at cooperative terminals. We seek to first identify the right cooperative diversity scheme applicable for the LMSS. Then, the problem of poor service quality due to fading effects can be adequately mitigated if the appropriate cooperative diversity scheme is employed. That solution is exactly what this research work seeks to find.

1.7 Research Motivation

For competitiveness with terrestrial networks, next generation Land Mobile Satellite Systems (LMSS) need to deploy the latest developments in communication theory like the MIMO techniques. This will help in addressing the problem of provisioning uninterrupted service delivery to all mobile users in places where NLoS condition is prevalent (e.g. urban and suburban areas where large, tall buildings are a common sight). The concept of Multiple-Input Multiple-Output (MIMO) or spatial diversity has been employed in terrestrial networks. Cooperative diversity is a version of MIMO that is applicable to the LMSS. In cooperative diversity, mobile relays employ their antennas to work together, forming a ‘virtual MIMO’. The cooperative diversity concept is thus a viable solution promising improved condition/quality of service (QoS) in LMSS especially in urban and suburban areas where the possibility of LoS cannot be guaranteed. A major motivation for this work is therefore to investigate the feasibility of bringing in cooperative diversity into the LMSS.

In achieving the goal of bringing cooperative diversity to LMSS, an appropriate and optimal cooperative diversity technique has to be investigated and its performance analyzed and compared with other established cooperative diversity schemes. Different diversity techniques have been proposed for terrestrial networks and they have been shown to improve the performance in terrestrial systems. However, they add some extra processing to the mobile terminals and lead to a power increase and hence a poorer Signal to Noise Ratio (SNR). The next motivation for this work therefore is to determine whether we can develop an optimal/better cooperative diversity technique for LMSS channels rather than adopting the conventional terrestrial ones. By carefully considering the LMSS characteristics vis-à-vis the terrestrial wireless characteristics, an optimal cooperative diversity scheme can be investigated and recommended if it shows an improved performance over the conventional cooperative diversity communication schemes.

In developing an optimal cooperative diversity scheme for the LMSS, a peculiar LMSS problem has to be put into consideration; the problem of long transmission delay between satellite and the mobile terminals situated on the ground. For several cooperative diversity techniques that require making a choice on the relay(s) to be selected and engages in cooperation, this is not a major problem for terrestrial networks. This is because the propagation delay in terrestrial networks is small and as such, the reported signal qualities by the relay terminals do not change significantly. However with the LMSS, the long transmission delay brings up a concept of outdated channel quality information (CQI). The outdated CQI concept arises from the fact that for the LMSS with mobile relay terminals used as cooperators, their reported CQI as at the time of estimation and their CQI at the time of transmission might have varied significantly. At transmission time therefore, the estimated CQI by each of the relays have become outdated or imperfect. Choosing the best relay(s) to cooperate based on the outdated CQI thus makes the relay selection process unreliable. The most important motivation for this work is therefore to find a way out of the outdated channel quality information challenge. This will help to optimally guarantee that the advantages that cooperative diversity can offer for the LMSS is maximized. In achieving this goal, we propose the use of prediction algorithms to cooperative diversity as a means of overcoming the outdated channel quality information challenge. To our knowledge, the introduction of predictions to cooperative diversity and particularly for the LMSS has not been done in literature.

The final motivation for this work is to determine the possibility of developing tractable analytical models to evaluate the performance of the proposed optimal cooperative diversity techniques for LMSS so developed in this research work.

1.8 Research Objectives

The main objectives and design goals for the research work are summarized as to:

a) Examine existing cooperative diversity schemes in wireless networks and their applicability to Land Mobile Satellite Systems, keeping in mind the LMSS characteristics and peculiarities.

b) Define, design and develop a cooperative diversity scheme that is most appropriate for the LMSS and that overcome the outdated channel quality information (CQI) problem.

c) Develop an analytical model for the optimal cooperative diversity scheme for LMSS that has been identified.

d) Investigate the performance of the developed cooperative diversity scheme for LMSS and validate results through simulations.

1.9 Contributions of the Research Work

Some major contributions to the field of wireless communication and particularly, the LMSS have been achieved in the course of undertaking this research work. Some of these contributions have been published or are currently under review for publication. These contributions are summarized below:

a) Incremental relay-selection (IRS) cooperative diversity was arrived at as the best cooperative diversity scheme for the LMSS amongst the currently existing cooperative schemes. The IRS cooperative scheme is discovered to be versatile as it is applicable to the store-and-forward (SF), amplify-and-forward (AF) and the decode-and-forward (DF) cooperative techniques. IRS cooperation gives the diversity advantage with a much reduced channel resource demand.

b) Introduction of a novel cooperative diversity scheme called predictive relay-selection (PRS) cooperative diversity for the LMSS. This diversity scheme is developed as a means of mitigating the challenge of choosing relays for cooperation based on outdated channel quality information (CQI). This challenge had been a major limitation to the application of relay-selection cooperative diversity schemes for the LMSS. With PRS cooperation therefore, selection of the relays for cooperation is being carried out based on the predicted CQI rather than the outdated CQI thus ensuring the advantages of cooperation are guaranteed.

c) Next, in carrying out the analysis of the novel PRS cooperative diversity scheme for LMSS, the two-state LMSS faded channel model is extended to include all the eight different possible combinations of the source-relay-destination (S-R-D) links. Considering that each of the links are independent and non-identically distributed (i.n.d), an accurate analysis of the performance can only be obtained when all the possible combinations of the links' states are captured. Analysis carried out with the probabilities of the eight different combinations of the S-R-D links, as developed in this work gives a far more accurate picture of the LMSS than what is currently obtained in the literature.

d) Finally, several prediction algorithms were considered and analyzed for the novel PRS cooperative diversity scheme. Based on the results obtained from both simulation and analysis of the prediction models, the prediction model with the best performance is recommended for the PRS cooperation for LMSS.

The first contribution not only reiterates the known fact that cooperative diversity is a means of gaining a better performance for wireless communications, but also shows that cooperative diversity is achievable for the LMSS despite its peculiar characteristics. The others contributions are our original contributions to the area of cooperative diversity for wireless communications, and especially the LMSS. These original contributions help in solving a major limitation of cooperative diversity (problem of outdated CQI) and has also opened up the cooperative diversity field for wider investigations and probable implementation.

1.10 Publications

The contributions of this work have resulted in writing of the following papers which have either been published or currently under review. Also, parts of their materials have been included in this dissertation.

1. Babatunde Awoyemi; Tom Walingo; Fambirai Takawira, “Relay Selection Cooperative Diversity in Land Mobile Satellite Systems,” *Proceedings of IEEE AFRICON,* 2013

In the paper, the feasibility of cooperative diversity concept was investigated for the Land Mobile Satellite Systems (LMSS). Using a two-state statistical LMSS satellite model, the cooperative diversity scheme employed sought to choose a best relay with highest received signal strength to cooperate with the destination terminal. This receiver-based cooperation was also carried out incrementally, that is, only when the direct communication was insufficient to guarantee good communication was cooperation employed. That helped to save resources even more as less spectrum bandwidth and relay power were utilized. The performance criteria considered were average output signal to noise ratio (SNR), outage probability, average bit error rate and average channel capacity for the cooperative satellite system. The results showed that for LMSS, cooperative communication performed better than direct communication alone, irrespective of the environment so considered.

2. Babatunde Awoyemi; Tom Walingo; Fambirai Takawira, "Cooperative Diversity in Land Mobile Satellite Systems Using Incremental Relay-Selection Scheme," *Proceedings of SATNAC,* 2013

The paper also investigated the receiver-based cooperative diversity model for Land Mobile Satellite Systems (LMSS) communication through incremental relay-selection (IRS) cooperative scheme. However, as an extension of the previous work, both single relay-selection (SRS) and multiple relay-selection (MRS) capabilities were investigated. Performances in terms of average output SNR and outage probability also showed that the cooperative communication gave a much better performance than direct communication, with MRS outperforming the SRS.

3. Babatunde Awoyemi; Tom Walingo; Fambirai Takawira, "Predictive Relay-Selection Cooperative Diversity in Land Mobile Satellite Systems," *IEEE Transactions on Vehicular Technology,* **"Under Review"**

In the Journal paper, the novel Predictive Relay-Selection (PRS) cooperative diversity model was developed for the LMSS. The new cooperative diversity model sought to optimize the LMSS communication through prediction protocols. The developed model incrementally selected a single best relay to cooperate, but taking into consideration the fact that the chosen best at estimation may not always be best at the time of communication. That fact is generally due to the time delay between when the best relay has been chosen and when it transmits its signal (problem of outdated Channel Quality Information). To solve this problem, the concept of channel prediction was introduced and employed whereby each relay determined a predicted value of its Channel Quality Information (CQI) based on its past measurements. The chosen best relay was therefore the one with the best predicted CQI value. Performance analyses of the outage probability and average bit error probability for the direct communication, cooperation with outdated CQI and cooperation with predictive CQI as carried out showed that the PRS cooperation gave a better performance than both direct communication and outdated CQI cooperation.

1.11 Organization of Dissertation

The rest of the dissertation is thus organized:

A basic description on cooperative diversity for wireless communications is carried out in chapter two. The chapter discusses different techniques of cooperative communication such as Store-and-Forward (SF), Amplify-and-Forward (AF), Decode-and-Forward (DF) and Coded Cooperation (CC). It also describes the various Relay-Selection (RS) schemes applicable to cooperative diversity such as Opportunistic Relay-Selection (ORS) and Incremental Relay-Selection (IRS). Also in the chapter, some challenges of cooperative communication are identified, several examples of cooperative communication in wireless networks are investigated and relevant ideas toward bringing the cooperative diversity concept into LMSS are discussed.

In chapter three, the feasibility of cooperative diversity in land mobile satellite systems is investigated. Incremental relay-selection (IRS) cooperative scheme is investigated for the LMSS channels using both single relay selection (SRS) and multiple relay selection (MRS) capabilities for SF and AF protocols. The results of the IRS cooperative scheme are presented and compared with the non-cooperation (direct communication) possibilities and other cooperative diversity schemes in the literature.

In chapter four, the Incremental relay-selection decode-and-forward (IRS-DF) scheme is investigated for the LMSS. The Moment Generating Function (MGF) approach is used to analyze the outage probability and numerical expressions are obtained. The results of the outage performance are presented and validated by simulation.

The outdated channel quality information (CQI) challenge has been a major setback in the investigation and implementation of cooperative diversity schemes for wireless systems. To combat this problem in the LMSS cooperative diversity, Chapter five introduces the novel predictive relay selection (PRS) cooperative diversity scheme. The PRS cooperative diversity scheme for LMSS as developed employs already established prediction models as a means of predicting the future channel quality information (CQI) of each mobile relay-satellite link. Several prediction algorithms are investigated for the new PRS cooperative diversity model. Furthermore, an analytical model of the performance metrics considered is developed. The performance metrics investigated include average signal to noise ratio (SNR), outage probability, average channel capacity and bit error probability. The analytical results are verified and validated by the results obtained from simulations.

Chapter six has the conclusion and relevant ideas for future considerations.

1.12 Summary

This chapter presented a general overview of satellite communication with particular emphasis on the Land Mobile Satellite Systems (LMSS). The problems with LMSS are identified and several solutions as are currently being investigated or implemented were highlighted. Two major problems of the LMSS which are the problem of fading effects on the transmitted signal especially in urban areas and the problem of outdated channel information due to mobility of the relays were identified as the basis for this research work. The goals of the work as well as the methodology employed in carrying out the research work were also highlighted. Finally, the contributions of this work to already established works on LMSS communications were briefly specified and the organization of this dissertation was presented.

CHAPTER 2

COOPERATIVE DIVERSITY IN WIRELESS COMMUNICATIONS

2.1 Introduction to Cooperative Diversity

Cooperative diversity is a recent diversity technique based on the concept that a group of mobile terminals can share their single antennas in order to generate a ‘virtual’ multiple antenna, thus obtaining similar effects that a MIMO system would give [9]. It has been devised as an alternative to spatial diversity for communications like the satellite systems where deploying multiple antennas is unrealistic [10]. The major idea here is that, because of the broadband nature of wireless medium, each transmitting terminal (user) sees an independent fading process. The signal sent from the source can therefore be received by the destination and a number of relay terminals within the destination’s interference range. By employing these relay terminals in sending the source’s original signal therefore, spatial diversity is generated since each user transmits data through different paths. Transmission can, in principle, be received and processed from a number of terminals and then jointly processed at the destination. In other words, instead of the source transmitting to the intended destination alone, two or more users can listen to the source’s transmissions and cooperatively communicate their received version of the sent information to the destination. Hence, these multiple terminals can combine resources such as power and bandwidth, to cooperatively transmit information signal from source or help receive information signal to the destination terminal. The concept of cooperative diversity though recent is gradually becoming a well-developed concept. Examples of the concept of cooperative diversity in the literature can be seen in references [9]-[15].

There are quite a number of ways of classifying cooperative diversity. A broad perspective of classifying cooperative diversity is to classify it as either receiver-based cooperative diversity or transmitter-based cooperative diversity. In receiver-based cooperative diversity, the cooperation involves the receiving terminals, i.e., the relay terminals close to the destination terminal are employed in ‘receiving’ the sent signal from the source. The relays are therefore generally closer to the destination than they are from the sender or source. In transmitter-based cooperative diversity, the cooperation involves the transmitting terminals, i.e., the relay terminals close to the source or sender are employed in ‘transmitting’ the source signal to the destination. For the LMSS under consideration in this research work, receiver-based cooperative diversity is being considered. This is because the relay terminals close to the destination terminal on the ground surface are the ones being employed in carrying out the cooperation. The cooperation simply involves the relays close to the destination terminal helping the destination get a better reception of the satellite's transmitted signal.

Receiver-based cooperative diversity has been implemented in several wireless communication systems such as Wireless Sensor Networks (WSN), Cellular Networks and Wireless ad-hoc Networks [9], [10]. Receiver-based cooperative diversity as applied to the mentioned wireless systems have shown improvement in performance in terms of Bit Error Rate (BER), Symbol Error Rate (SER), Packet Error Rate (PER) and outage probability performance, etc. Since Land Mobile Satellite Systems (LMSS) are also wireless communication systems, it becomes imperative to investigate and recommend for adoption an optimal receiver-based cooperative diversity for the LMSS.

For the goal of investigating and recommending an optimal receiver-based cooperative diversity for LMSS to be achieved, a careful review of existing cooperative diversity techniques and schemes is very important. With the characteristics and challenges of the LMSS already discussed, a review of the cooperative diversity techniques and schemes will help in determining which cooperative scheme will be most suitable or optimal for the LMSS. This chapter is therefore dedicated to achieving that purpose.

In this chapter, the various techniques applied in receiver-based cooperative diversity are first discussed. Then, relay-selection schemes which help cooperative diversity achieve a remarkable reduction in resource usage are considered and an appropriate scheme recommended. Next, some challenges that can be encountered in the process of investigating cooperative diversity in LMSS are mentioned. Following this, several examples of cooperative diversity system in wireless networks are reviewed with particular emphasis on how the different environment types are statistically modeled. The review includes both single-faded models and multiple-faded models since the LMSS are best modeled as a blend of several fading models. Finally, some important issues in the application of cooperative diversity to LMSS are generally discussed.

2.2 Techniques of Cooperative Diversity

An important aspect in the implementation of receiver-based cooperative diversity scheme is the type of processing the relays (cooperating nodes or terminals) undertake before retransmitting their received signal from the source to the destination. These different processing schemes result in the different cooperative diversity protocols or methods which are currently in the literature e.g. [16] – [24]. The most developed or/and applied cooperative diversity techniques are briefly summarized.

2.2.1 Store-and-Forward (SF):

In Store-and Forward (SF) cooperation, signals sent from the source are received and stored in the relay terminals ready to be transmitted to the destination. No processing of the signal is carried out by the relays. The scheme is easy to implement but it however has a low reliability compared to other cooperative schemes. The major advantage of this method is that the relay terminals keep a record of the entire transmitted signal from the source in its buffer (stores received signal) so that should there be a need for re-transmission (usually after a negative acknowledgment of the sent signal) it can resend to the destination terminal.

2.2.2 Amplify-and-Forward (AF):

In this method, the cooperative terminals or users receive a noisy version of the signal transmitted by the source and simply amplify the received signal and retransmit towards the destination terminal or user [16]. Several independent channels of transmission can therefore be made available. This scheme is simple to employ in that it does not need any encoding and decoding activities at the relay terminals but a simple retransmission with power amplification. More so, it has the advantage of realizing simple hardware devices since it requires minimum processing at the cooperator terminals. The AF cooperative diversity method is also the closest to achieving full diversity. However, because it transmits a noisy version of the signal, it implies that both signal and noise is transmitted, amplified and retransmitted by relay terminals thus bringing about a certain loss in performance.

2.2.3 Decode-and-Forward (DF):

In this method of cooperation, each cooperating terminal/user first demodulates and decodes signal coming from the source, then it recodes and re-modulates before retransmitting it towards the destination terminal [11]. This method helps to get rid of the noise from the signal received and also reduces the chances of amplifying noise. The DF cooperative diversity scheme is simple and adaptable to power condition, i.e., it can help with power allocation. In DF cooperation, the receiver needs the CQI between source and relay for maximum decoding of signal. The major challenge with this scheme is that possibility of spreading error which might have occurred in the process of decoding and recoding before onward transmission to destination terminal. A quick solution to this is to employ a Cyclic Redundancy Check (CRC) in the relay terminals whereby the relays check the received data before either deciding to forward or just to discard the received signal.

2.2.4 Coded Cooperation (CC): In this method, channel coding techniques are incorporated into the cooperation strategy. The signal to be transmitted is divided into clusters or portions transmitted through different independent fading channels to selected group of users or cooperators. Each user has a codeword which goes along with the transmission. The basic idea is that each user tries to transmit an incremental redundancy of its partner's data, apart from its own data [9]. By dividing each user's codewords into two segments, each user transmits a codeword containing its own data in the first segment. Then, each user receives and decodes its partner's first segment. If this is decoded correctly, each user can then compute the additional parity bits of the partner's data and transmit the new codeword containing the partner's data in the second segment. However, if the partner's information cannot be correctly decoded, the user reverts to the non-cooperative mode and it transmits its own data. The idea of coded cooperation is to use the same code rate and power for transmission as in a comparable non-cooperative system.

2.3 Relay Selection (RS) Cooperative Diversity

Relay-selection (RS) cooperation is a recent scheme of cooperative diversity which can be applied to either the amplify-and-forward (AF) or decode-and-forward (DF) techniques. The major idea behind relay-selection cooperation is to limit the number of relays that will be employed in cooperation so as to reduce the amount of channel resource consumed. In the RS cooperative scheme, channel measurements (or threshold tests) are carried out between cooperating terminals to ascertain channel quality. The link(s) with the best performance (usually the one(s) with the best channel quality information (CQI)) is/are selected for cooperation [17]. If a single best relay is selected, it is referred to as Single Relay Selection (SRS) scheme. If two or more 'best' relays are selected out of the available relays, it is called Multiple Relay Selection (MRS) scheme [20], [21]. Although performance of the system using multiple relays would theoretically be better than the performance obtained by using just one relay, the system using multiple relays consumes more resources (bandwidth and relay power) and is also more difficult to implement in real systems. Hence, selecting one (or few) relay(s) among several possible options is more practical. Different types of relay-selection cooperative diversity schemes have therefore emerged and are currently a major research focus. Examples of these are Opportunistic Relay Selection (ORS) and Incremental Relay Selection (IRS) schemes and are briefly discussed below:

2.3.1 Opportunistic Relay Selection (ORS)

In opportunistic relay-selection (ORS) cooperative scheme, the best relay is usually the relay with the best CQI. This best relay is determined opportunistically. To carry out the selection, a timer with value inversely proportional to the measured CQI is usually attached to all available relays such that the relay with his timer running out first is automatically selected as the best relay [22].

2.3.2 Incremental Relay Selection (IRS)

In incremental relay-selection (IRS) cooperative scheme, the relaying (cooperation) process is only limited to when it is necessary i.e. when direct transmission is insufficient [23]. IRS is therefore a means of saving channel requirements by restricting the amount of time when cooperative transmission (or reception) is carried out. This is usually implemented by exploiting a limited feedback from the destination terminal, e.g. by using a single bit indicating the success or failure of the direct transmission. If the source-destination transmission is not sufficiently high, the feedback requests that the relay resends its originally received signal.

In general, relay-selection cooperative diversity is simple to implement and has been proven to be capable of achieving the diversity advantage as the case where all relays are involved in the cooperation. Relay-selection cooperative schemes are therefore highly recommended for implementation in the LMSS. The incremental relay-selection (IRS) cooperative diversity is the chosen cooperative scheme investigated in this research work.

2.4 Challenges of Cooperative Diversity in Land Mobile Satellite Systems

In the application of the various schemes of cooperative diversity in wireless networks and particularly for the LMSS, several challenges have been identified which have given rise to current research works to help bring improvement in implementation. Some of these problems are identified as [10]:

a) The problem of identifying, deciding on and managing which partners are to cooperate with at any particular time within a multi-user network. For effectiveness and optimal efficiency, a distributed cooperative protocol in which users are able to independently decide with whom to cooperate is necessary. Also, the ability to have multiple partners to cooperate with at any given time is absolutely essential. The challenge then is developing a model that treats all users fairly, does not require significant additional system resources and can be implemented feasibly in conjunction with the system multiple access protocol.

b) Developing a means of controlling power during cooperative transmissions. Performance may be adequately improved by changing transmit power for each user based on the instantaneous uplink/downlink and inter-user channel conditions.

c) For coded cooperative diversity, a major challenge is in developing better coded cooperation methods specifically designed and implementable for the LMSS.

Solutions to the above-mentioned challenges of the receiver-based cooperative diversity are current research concerns. In this research work, the IRS cooperative scheme for LMSS is investigated and proposed to adequately combat the problem of identifying and managing partners to cooperate within a typical LMSS scenario. For a thorough analysis of the cooperative diversity network for LMSS, appropriate statistical model describing the faded signal must be utilized. A review of cooperative diversity schemes for different fading conditions is carried out in the next subsection.

2.5 Cooperative Diversity in Single-Faded Wireless Channels

Wireless channels are generally modeled using statistical distributions. To determine the performance of cooperative networks therefore, several works have investigated the different cooperative diversity techniques on the common fading distributions (Rician, Rayleigh, lognormal etc.) used in wireless communication. They have also described their varied applications, advantages and challenges. Some of these works are reviewed in this section.

2.5.1 Cooperative Diversity in Rician Fading Channels

The outage performance of dual-hop amplify-and-forward cooperative diversity system with maximum ratio combining (MRC) at receiver terminal in Rician fading environment was studied in [25]. The work shows a possibility of employing relays as cooperative networks in an environment where LoS might exist. By upper bounding the SNR at the receiver, probability density functions (PDF) and the moment generating functions (MGF) for the performance metrics were derived. Also by assuming that the nodes (terminals) were synchronized and the system employs half-duplex transmissions with an orthogonal transmit scheme where the source and relay transmit in non-overlapping time slots, numerical results so derived show that cooperative system with either direct or relay channels having LoS improves the performance in terms of outage probability. The best performance was observed when both destination and relays (cooperating terminals) have LoS channels. More so, outage performance improved as the Rician K-factor increased.

2.5.2 Cooperative Diversity in Rayleigh Fading Channels

The study of cooperative diversity using amplify-and-forward scheme over Rayleigh channel condition was conducted in [26] while in [27], incremental relay-selection scheme for Rayleigh fading channel was studied. Incremental relaying was proposed so as to restrict relaying process to only bad channel conditions only. By exploiting a limited feedback from the destination terminal to determine whether to retransmit through the relay or not and by using Maximum Ratio Combining (MRC) at the destination, the work showed that cooperative diversity using incremental relaying significantly improves the BER performance in comparison with direct transmission. It also showed that in the amplify-and-forward scheme, increasing the threshold SNR will always increase the error performance while for decode-and-forward scheme, increasing threshold SNR will not always improve the error rate because of the possibility of error propagation from the relay. Results also showed that the cooperative diversity scheme significantly increased throughput at medium and high SNR as well as high achievable rate as compared to that of direct transmission. Outage probability generally increased with increasing threshold SNR.

2.5.3 Cooperative Diversity in Lognormal Fading Channels

The work in [28] was based on the assumption that lognormal channel provides a more accurate channel model for indoor wireless environments as compared to Rayleigh, Rician or Nakagami channels which describes more appropriately outdoor radio propagation. The idea was that long-term and short-term fading effects tend to get mixed in indoor wireless channels and the lognormal statistics tend to dominate. By employing amplify-and-forward technique with TDMA-based cooperative protocols to correspond to SIMO, MISO and MIMO possibilities, upper bounds on pairwise error probability for each of the protocols were determined. The work considered single-relay scenarios where terminals operated in half-duplex mode and are equipped with single transmit-receive antennas. In the work, the source terminal communicated with the relay and destination terminals during the first time slot (broadcasting phase) and to both relay and destination terminal during the second time slot (relaying phase). The deductions from the work showed that the received signal at the destination is the superposition of the transmitted signals by the relay and the source terminals. Relative diversity orders were defined for lognormal channels where conventional definition of diversity order cannot be used. Diversity advantages for these orders were determined and based on a union bound on BER, a new rule (Optimum Power Allocation, OPA) was developed for performance improvement.

2.5.4 Cooperative Diversity in Nakagami-m Fading Channels

The performance of cooperative diversity of networks using amplify-and-forward technique and relaying over independent, non-identical, Nagakami-m fading channels was studied in [29]. Moment generating function (MGF) was used to determine the error rate and the outage probability. By using maximum ratio combining (MRC) at destination node, the study revealed that in Nagakami-m fading, Bit Error Rate (BER) is much tighter (it reduces) for higher SNR of transmitted signal as compared to that of other general cooperative links. Outage probability too was tighter, particularly at medium and high SNR. The number of cooperating relays has a strong impact on performance enhancement and the achieved diversity order.

2.6 Cooperative Diversity in Multiple-Faded Wireless Channels

In more recent works, e.g. [30] – [34], wireless fading channels are now most described as the resultant of a combination of two (or more) fading distributions, generally referred to as multiple-fading channels. In multiple-faded channels, the fading models are a combination of two or more single fading models. This helps to describe more appropriately and accurately the channel conditions for wireless networks. The cooperative system studied in [30] and [31] uses a multi-hop cooperative satellite-terrestrial network. The fading between satellite and destination was modeled as a shadowed Rician distribution, fading between satellite and relays was modeled as Rician distribution and fading between relays and destination was modeled as Rayleigh distribution. By using LMSS statistical experimental data of different fading conditions, the results for the multi-hop cooperative satellite-terrestrial communication showed diversity advantage. The work in [32] described a composite fading composing of multipath and shadowing effects simultaneously. The multipath fading was characterized by the Nagakami-m distribution while the shadowing was modeled by the lognormal distribution. The combined fading distributions led to a generalized-K fading channel model. These composite (multiple) fading channels are better descriptions for the land mobile satellite systems as they are more versatile and also give more accurate approximates of the channels than the single-fading models.

2.7 Bringing Cooperative Diversity to Land Mobile Satellite Systems – Issues and Applications

As seen in the last sub-section and many more similar references, much work have been done in investigating the application of the several diversity techniques/schemes to wireless communication channels. These studies/practical applications have revealed not just the feasibility but also the advantages in performance when cooperation is employed. These studies have also indicated possible drawbacks that could limit the implementation of these cooperative diversity models. Due to its numerous advantages (i.e., maximizing the use of the spatial domain), receiver-based cooperative diversity models are currently being investigated and extended for incorporation into satellite communications (as we have investigated in this work). In making the cooperative diversity investigations viable, appropriate channel and fading models describing satellite communications must be employed.

For the Land Mobile Satellites Systems (LMSS) under consideration in this research work, the introduction of user mobility and the use of lower frequency bands (L and S frequency bands) give rise to an entirely different channel modeling. In its channel and fading models, the following information about the LMSS must be adequately taken into consideration:

a) Propagation conditions of the LMSS are different, as well as link geometry which is constantly changing. This implies that NLoS communication with the satellite due to multipath and shadowing is a great possibility. As such, the statistical models to employ for the LMSS must adequately take care of the both the LoS and the NoS scenarios.

b) Since LMSS employs the L and S frequency bands instead of the Ku and Ka for fixed satellites, tropospheric phenomena is basically irrelevant. Hence, fading effects due to rain, fog, etc. that would normally have been taken into consideration for fixed satellite systems can simply be ignored for the LMSS.

c) To sustain a high degree of coverage even for indoor handheld users in urban areas where fast fading and multipath characteristics are obtainable, receiver-based cooperative diversity for the LMSS application can be complemented by a network of terrestrial repeaters [35], [36]. The mobile relay terminals close to the destination terminal can act as the complimentary terrestrial repeaters. This arrangement would form a hybrid satellite-terrestrial interface. The satellite and the terrestrial repeaters (or as in the LMSS case, the mobile relays) can then ‘share’ their antennas resembling a MIMO transmitter though the relays’ antennas are geographically dispersed.

d) An appropriate channel model for the LMSS is important since that will determine the viability of cooperative diversity application to the system. Although LMSS channels exhibit to some extent similarities with multipath in terrestrial mobile radio, the intensity of the same effect is not the same. This is because scatterers are present only at the receiver LMSS end of the link. Sometimes even, the situation might not hold when mobile satellite terminals are in open or suburban areas.

From the issues raised so far, it becomes imperative to use channel and fading models developed from actual measured LMSS data. There are a number of LMSS channel model measurements in this regard. For the purpose of this research work, a two-state Markov-chain based LMSS channel model is employed. This is discussed in chapter three where the IRS cooperative scheme was implemented.

2.8 Conclusion

In this chapter, a detailed review of current existing works on cooperative diversity has been thoroughly carried out. The several methods/techniques of cooperative diversity such as amplify-and-forward (AF), decode-and-forward (DF) and coded cooperation (CC) were discussed. Similarly, relay-selective schemes like the opportunistic relay-selection (ORS) and incremental relay-selection (IRS) were discussed and proposed as optimal cooperative scheme for the LMSS. Also, several examples of cooperative diversity in different fading conditions were cited and reviewed. Then, a review of the applicability of cooperative diversity in LMSS channel was analyzed while issues such as the importance of using appropriate fading models that describe LMSS were highlighted.

CHAPTER 3

INCREMENTAL RELAY-SELECTION COOPERATIVE DIVERSITY

3.1 Introduction

The study and application of cooperative diversity schemes in Land Mobile Satellite Systems (LMSS) is a means of gaining and maintaining high quality of service (QoS) irrespective of the channel conditions. This leverages on the fact that the satellite employs a broadcast nature of communication, hence, cooperation between the mobile relay terminals is possible since they all get the signal sent from the satellite. Satellite communication networks are however considerably different in architecture to other terrestrial wireless networks. To investigate an optimal receiver-based cooperative diversity scheme for LMSS therefore, a careful look into the LMSS architecture and service conditions is paramount. This will help in the selection of an appropriate cooperative diversity scheme that will be most suitable for this application.

The limitations of the LMSS include; the problem of mobility of satellite and mobile terminals, the problem of limitation in satellite space (size) and available power, the problem of long propagation delay and the problem of multiple fading conditions (blend of multipath and shadowing) especially in urban and suburban areas. Cooperative diversity schemes themselves do have some inherent limitations; they come at the expense of a reduction in the spectral efficiency (because the relays must transmit on orthogonal channels in order to avoid interfering with the source node and with each other as well) and an increase in power utilization by the relay terminals. This implies that in cooperative diversity networks, if N relaying nodes are available, (N + 1) channels are employed which incurs a loss in bandwidth. Similarly, if all N relays are to transmit to the destination at all times, they are all going to have their battery powers depleted so rapidly. To combat these problems therefore, the use of the Single Relay-Selection (SRS) or Multiple Relay-Selection (MRS) schemes are being considered for LMSS. In these schemes, the “best” relay node(s) only is/are selected to retransmit to the destination. Hence, there are just 2 (for SRS) or M+1 (for MRS, given that M relays are selected out of N available ones) channels required in this case. It has been investigated that the possibility of obtaining a full diversity order with the best-relay selection option is very high [33], [34]. This means that the diversity advantage as achievable by regular cooperative diversity network where all relays participate in cooperation is possible with relay-selection cooperation. A possibility of full diversity with best relay selection option would mean efficient resource utilization by the relay-selection scheme without necessarily sacrificing the signal quality. In incremental cooperation, cooperative communication is employed only at the times when the direct communication from satellite to destination is not good enough. By combining both relay-selection cooperation and incremental cooperation therefore, incremental relay-selection (IRS) cooperation is arrived at.

In this chapter therefore, the IRS cooperative diversity scheme is investigated for the S-band LMSS using parameters from a typical satellite link. Both the single relay-selection (SRS) and the multiple relay-selection (MRS) capabilities are investigated. The store-and-forward (SF) technique (which is also equivalent to the amplify-and-forward (AF) technique with an amplification factor of 1) is considered. First, the LMSS channel is properly defined by describing its network model and also the fading model considered. In the fading model, the effect of the multiple fading of the LMSS is captured by a Markov chain based two-state satellite mobile channel model. Next, to fully capture the LMSS characteristics in this research work, the link budget analysis of a DVB-SH is presented and the result obtained is applied in the simulations. Then, the performance metrics considered in the work are analyzed and finally, the results obtained for the IRS cooperative scheme are discussed.

3.2 System Model for the IRS Cooperative Diversity Scheme

The Land Mobile Satellite channel with Incremental Relay-Selection (IRS) cooperative diversity scheme requires an adequate system model which properly describes its architecture. To get an appropriate and a meaningful network flow (or algorithm), a choice of the cooperative technique under consideration has to be made. For the chapter, the store-and-forward (SF)/amplify-and-forward (AF) techniques are being considered. A clearer description of the network is presented in the next sub-section.

3.2.1 Network Model

The cooperative satellite channel consists of one satellite (S) which is the source, one destination (D) and $R_1 - R_N$ cooperative relays out of which one best relay R_B (for SRS) or R_M best relays (for MRS) are selected to cooperate out of N available relays (see Fig. 3.1.). IRS cooperative diversity scheme is employed. The destination terminal first checks it received signal and compares with pre-set threshold value of channel quality information (CQI). The CQI is used in calculating the SNR. If the received signal at destination equals or exceeds the threshold SNR value, the relays are not employed at all. Only when the received signal at destination falls below the threshold SNR value is cooperation employed.

Two time slots are employed in transmission, with a positive acknowledgement (ACK) or negative acknowledgement (NACK) feedback after every slot. In the first slot, the satellite broadcasts its signals to both the destination and relays terminals. The destination terminal checks the received SNR to see if it is greater than or equal to the threshold SNR. If it is, the direct transmission mode is employed. The ACK feedback from destination to the source and relays indicate success of transmission. The relays are not employed in that time slot. Thereafter, the satellite sends its next signal in the second time slot. However, if the signal received at the destination is below the threshold SNR, the feedback from destination to source is a NACK. On receiving the NACK feedback, the satellite sends no signal in the second time slot. The relays also get the NACK message from the destination terminal. Each relay then determines its CQI (and uses this to calculate its SNR). The calculated SNR is sent to the destination by each relay. The destination determines the best relay (for SRS) or best relays (for MRS) with the highest SNR values and chooses them for cooperation. Next, the destination terminal broadcasts a single bit CBR (Chosen Best Relay) signal containing the identity of the selected best relay(s) and indicating they have been selected for cooperation. The other relays receive the CBR but ignore it since it does not contain their identity. The relay(s) with the highest predicted channel quality (i.e. selected best relay(s), R_B /R_M) receive the CBR signal and then enters into a transmitting mode, forwarding their already stored signal to the destination. For the SF scheme, no amplification of the satellite signal is carried out at the relays while for the AF scheme, an amplified version of the received signal is sent from the relay(s) to the destination. Signal from the relays and the destination terminal are combined at the destination through Maximum Ratio Combining (MRC).

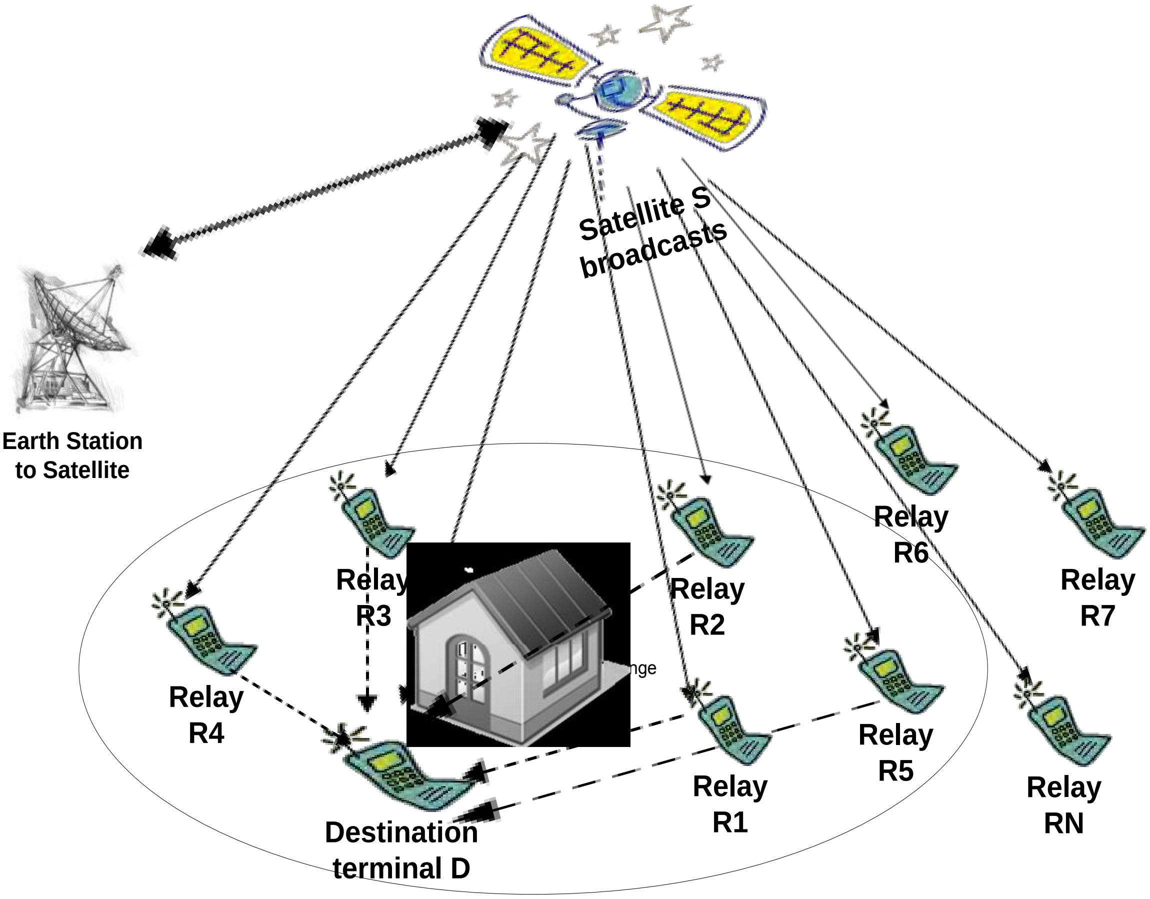

Fig. 3.1. Receiver-based Cooperative Diversity with Incremental Relay Selection (IRS) in LMSS

The total frame of transmission, divided into mini frames for both the direct communication and the cooperative communication are given in Fig. 3.2. and Fig. 3.3. respectively

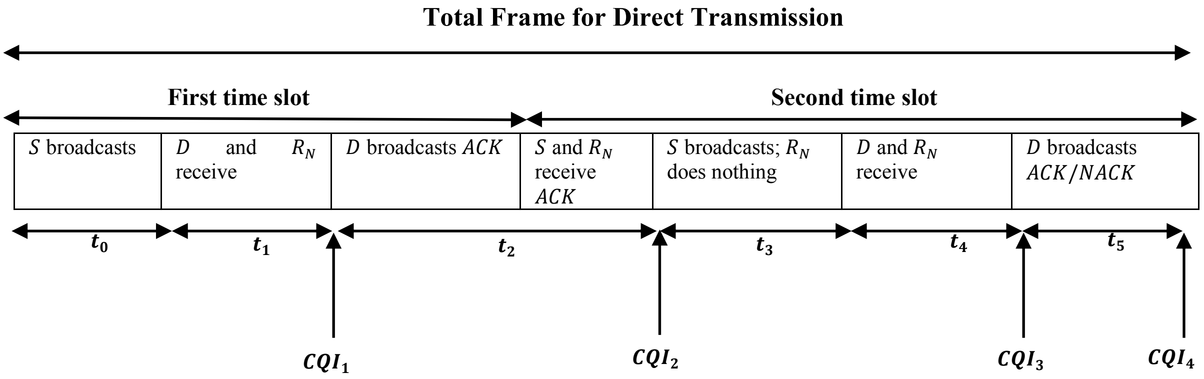

Fig.3.2. Total Time Frame for Direct Communication

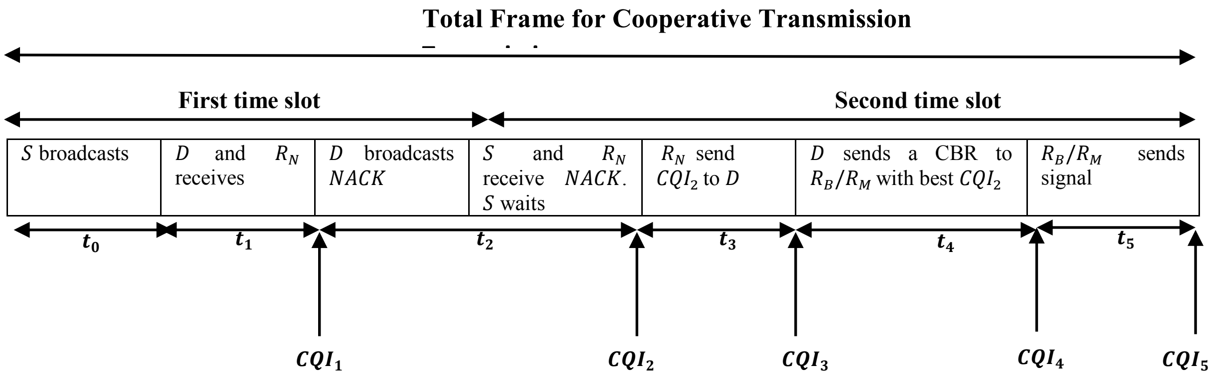

Fig. 3.3. Total Time Frame for Cooperative Communication

The network model for the IRS cooperative diversity scheme as described above can be simply summarized in the algorithm below.

Incremental Relay-Selection (IRS) Cooperative Diversity Algorithm

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S – Satellite; R_N – Available Relays; R_B – Selected Best Relay (for SRS); R_M – Selected Best Relays (for MRS); D – Destination; CBR – Chosen Best Relay; MRC – Maximum Ratio Combining; γ_{sd} – Satellite-Destination SNR; γ_{th} – threshold SNR;

```
Start
$S$ broadcasts
$D$ and $R_N$ receive signal (and keeps its times series in a buffer)
  If ( $\gamma_{sd} > \gamma_{th}$ ) then
  (use direct transmission)
          $D$ sends $ACK$ to $S$ and $R_N$
          ($R_N$ does nothing in second time slot)
          $S$ sends next signal
  else
  (use cooperative transmission)
          $D$ sends $NACK$ to $S$ and $R_N$
          ($S$ does nothing in second time slot)
          Each $R_N$ determines its $CQI$ (and calculates its $SNR$)
          Each $R_N$ sends it $SNR$ to $D$
          $D$ chooses best relay $R_B$ or $R_M$ with highest $SNR$ values (for SRS or MRS)
```

```
        $D$ sends a $CBR$ signal to $R_B\ orR_M$ informing it to send signals
        $R_B\ orR_M$ send(s) signals
        Signals from $D$ and $R_B\ orR_M$ are combined at $D$ through $MRC$
    End If
End
```

3.2.2 Fading Model

Statistical models are generally used in describing the LMSS channels [37] – [41]. These statistical models provide a good trade-off between complexity of implementation and accuracy in the representation of channel conditions and various impairment characteristics. They are able to provide time series of the variations of the complex envelop of the received signal.

a) **Single-state versus multi-state fading models for LMSS:** Channel models for wireless communication systems are generally divided into two categories; single-state models and multi-state models. Single state models are employed in describing the stationary channels since they assume that the envelope or power of the received signal follows a unique probability distribution. Multi-state models have multiple states, each state corresponding to different types of probability density distribution or the same types of distribution with different parameters. They are therefore useful in describing mobile systems such as the Land Mobile Satellite Systems. The channel models for a typical LMSS such as the Digital Video Broadcasting – Satellite Handheld (DVB-SH) systems using L – or S – bands are described in [39] and [40]. These channel models are best described as narrowband or frequency non-selective (flat) fading models. Narrowband fading assumes that the channel coherence bandwidth is larger than the system bandwidth hence, the delay spread is not taken into consideration. The received signal is usually a combination of both slow and fast fading. The fast fading is as a result of multipath effects and brings about shifts in Doppler frequencies when the receivers move. The slow fading is usually caused by shadowing and blockage of the direct signal over a large area. As a result of this combination of fading, single statistical distributions such as Rayleigh or Rician fading are not very adequate in describing the narrowband LMSS channel conditions. The state-oriented (or multiple state) models are better suited for the purpose, as they allow for the definition of a set of states with each state assigned probabilities for different distribution types and parameters for each degree of multipath and shadowing conditions of the network.

b) **Examples of multi-state models for the LMSS:** There are a number of multi-state models that describe the LMSS networks. These models use Markov chain or semi-Markov chain in describing the different possible states and their characteristics. Some examples of these Markov-chain based LMSS models can be found in references [39] – [43] and [48] – [50]. The work in [39] describes a two-state model with the transition from one state to another based on the Markov chain The Loo's model for satellite systems, which is a combination of Rayleigh and lognormal distributions was employed for the two states, but with different values of the parameters (mean, standard deviation and multipath power). The work in [40] describes a versatile three-state model for LMSS while still using Loo's fading distributions with different parameters for the three states. In [43], a two-state model was developed combining two well-established models (Loo's and Corazza's models for LMSS). The two-state LMSS Markov chain model employed in this work is obtained from actual measured data on Land Mobile Satellites as investigated in [43]. This model consists of a 'good state' represented as g and a 'bad state' represented as b. The good state defines the periods in communication when the channel is not affected by heavy shadowing. During these periods, average signal SNR is high and communication is barely interrupted. The probability that link is in a good state is given as p_g. During the 'bad' state, the communication channel is strongly affected by heavy shadowing, the link quality (average SNR) is poor and communication is most likely to be interrupted. The probability that link is in a bad state is given as p_b. The switching back and forth between the states is carried out by a Markov chain model. The state probability matrix $\boldsymbol{W}$ is the collection of the probabilities of each state in either the good or the bad state. The state transition matrix $\boldsymbol{P}$ is the probability of a state moving to another state. Changes in the channel from one state to the other can thus be determined once their state probability $\boldsymbol{W}$ and the state transition $\boldsymbol{P}$ are determined. Fig. 3.4. shows the two-state Markov chain model.

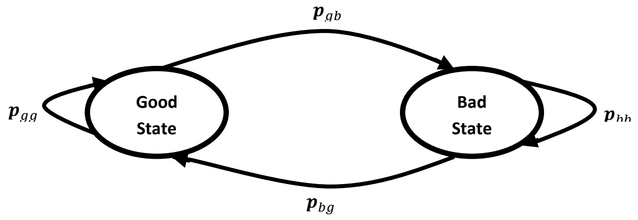

Fig. 3.4. Two-State Markov Model

where p_{gg} is the probability of the channel switching from good state to good state, p_{gb} is the probability of the channel switching from a good state to a bad state, p_{bb} is the probability of the channel switching from bad state to bad state, and p_{bg} is the probability of the channel switching from a bad state to a good state. The relationships between the state transition probabilities are given as;

$$p_{gb} = 1 - p_{gg} \tag{3.1}$$

and

$$p_{bg} = 1 - p_{bb} \tag{3.2}$$

The state probability matrix $\boldsymbol{W}$ and the state transition matrix $\boldsymbol{P}$ for the different environment types is given in the Table 3.1 and applied in the LMSS channel fading simulations. The Corazza's model (a combination of Rician and lognormal distributions) is employed in describing the good state while the bad state is described by a Loo's model (a combination of Rayleigh and lognormal distributions). An extract of the models' parameters for different elevation angles in three types of channel environments - open space (representing light shadowing), rural (representing moderate shadowing) and urban (representing heavy shadowing) are presented in Table 3.2 (for the good state) and Table 3.3 (for the bad state). These parameters are used in simulating the faded signal. This in turn helps in generating the simulation results presented that are presented.

Table 3.1 State Probability W and state transition matrix P for LMSS channel fading [43]

Environment Type	State Probability Matrix (W)		State Transition Matrix (P)	
	p_g	p_b	p_{gg}	p_{gb}
			p_{bg}	p_{bb}
Open Space	0.892	0.108	0.956	0.044
			0.891	0.109
Rural Area	0.624	0.376	0.832	0.168
			0.747	0.253
Urban Area	0.297	0.703	0.382	0.618
			0.179	0.821

Table 3.2. Good State Model Parameters [43]

Environment	Elevation $(^0)$	Good State model parameters		
		b_0	μ	d_0
Open Space	40	0.0020	0.0102	0.0002
	60	0.0035	-0.0115	0.0010
Rural Area	40	0.0151	-0.0312	0.0075
	60	0.0090	-0.0839	0.0083
Urban Area	40	0.0056	-0.0403	0.0058
	60	0.0039	-0.0525	0.0194

where b_0 is the average power of the multipath scattering, μ is the mean of the direct component, d_0 is the variance of the direct component. The mathematical expression of the model (Corazza's model) is given in chapter four and five where the analyses are carried out.

Table 3.3. Bad State Model Parameters [43]

Environment	Elevation $(^0)$	Bad State model parameters		
		K	m_3	σ_3
Open Space	40	1.3089	-0.1532	0.0368
	60	3.1623	-0.0652	0.0518
Rural Area	40	0.8943	-0.4326	0.2072
	60	2.8733	-0.8456	0.2878
Urban Area	40	0.8638	-1.7960	0.4835
	60	2.1276	-1.3585	0.5411

where $\boldsymbol{K}$ is the Rician factor, $\boldsymbol{m_3}$ is the mean of the direct component and $\boldsymbol{\sigma_3}$ is the standard deviation of the direct component. The mathematical expression of the model (Loo's model) is given in chapter four and five where the analyses are carried out.

3.3 Link Budget Analysis for LMSS

In other to fully capture the LMSS characteristics in this research work, the link budget analysis of a DVB-SH is presented and the result obtained is applied in simulating the LMSS. A link budget accounts for all of the gains and losses from the transmitter, through the medium (satellite, amplifiers, free space, waveguide, fiber, etc.) to the receiver in a typical satellite communication system. It also accounts for the attenuation of the transmitted signal due to propagation, the kind of fading experienced, as well as the antenna gains, feed line and miscellaneous losses. The satellite used in this work is a EUTELSAT & SES-ASTRA satellite (S-band payload, GEO, W2A satellite for DVB-SH). Detailed information on the satellite can be obtained from references [2] and [39]. Table 3.4 given below is however a summary of the information and parameters of the satellite. The table contains information on the carrier frequency of the satellite (2.2GHz), the $EIRP$, the average distance R of receivers (destination and relays) from satellite and the free space loss (FSL).

Table 3.4 DVB-SH Link Budget example [39]

		DVB-SH-B 5MHz channel			
		Handheld category 3	Handheld category 2b	Portable category 2a	Vehicular category 1
TDM occupied bandwidth (B)	MHz	4.888	4.888	4.888	4.888
Uplink $C/(N+I)$	dB	20.0	20.0	20.0	20.0
Satellite Transmission					
Transmission frequency	GHz	2.2	2.2	2.2	2.2
EIRP effective/beam	dBW	63.0	63.0	63.0	63.0
Satellite to receiver terminal propagation					
Propagation distance (R)	Km	36,000	36,000	36,000	36,000
Free Space Loss (FSL)	dB	191.0	191.0	191.0	191.0
Atmospheric Attenuation	dB	0.5	0.5	0.5	0.5
Total Attenuation (Losses)	dB	191.5	191.5	191.5	191.5
Terminal Receiver Reception					
Terminal G/T	dB/K	32.1	29.1	24.9	21.0
Polarization losses	dB	3.0	3.0	3.0	3.0

The SNR value γ is obtained from the link budget analysis formula given as;

$$\gamma = \{EIRP + G/T - FSL - K - B - Fading\}\,(dB) \qquad (3.3)$$

where γ is the received signal-to-noise ratio (SNR), $EIRP$ is the Equivalent Isotropic Radiated Power, G/T is the Terminal Receiver Gain per Temperature (in Kelvin), FSL is the Free Space Loss, K is the Boltzmann's Constant, B is the Bandwidth and $Fading$ is the combined effect of the shadowing and multipath fading characteristics as defined in the fading model. Since the destination terminal and the relay terminals are within a close interference range, an approximate distance of 36,000Km have been assumed and used in calculating the free space loss (FSL). Extracts from Table 3.4 used in calculating the link budget is as follows;

Bandwidth, $B = 4.888 MHz = 10\log(4.888 \times 10^{6}) = 66.9 dB$

$EIRP$ effective/beam = $63.0 dBW$

Free Space Loss, $FSL = 191.0 dB$

Terminal G/T (for Portable category 2a) = $-24.9 dB/K$

Boltzmann's Constant $K = 1.38 \times 10^{-23} J/K = 10\log(1.38 \times 10^{-23}) = -228.6 dB$

Substituting the values into the link budget formula gives the following submission;

$$\gamma = \{63.0 - 24.9 - 191.0 - (-228.6) - 66.9 - Fading\}(dB)$$

$$\gamma = \{8.8 - Fading\}(dB) \tag{3.4}$$

From the LMSS link budget given above, the SNR, γ obtained is dependent on the amount of fading experienced in the system. The two-state fading model employed in this work gives the constantly changing values of the fading distribution. This is due to the combined statistical distributions employed in generating the faded signal. This then helps in generating the SNR of the IRS cooperative diversity scheme for the LMSS.

3.4 Performance Evaluation Metrics

The performance analysis of the IRS scheme, both by choosing single best relay (SRS) as well as multiple best relays (MRS) is given in this section. The performance metrics considered are average output SNR, outage probability, bit error rate (BER) and average channel capacity. These performance metrics are derived below.

3.4.1 Output Signal to Noise Ratio (SNR)

The output SNR γ_{MRC}, (in dB) is defined as the total instantaneous SNR received at the destination terminal with time (i.e., after Maximum Ratio Combining (MRC)). For the direct communication, the value is obtained by averaging the destination terminal's SNR with time. In case of cooperation, the value is obtained by averaging the combined signals from both the direct link and the cooperative link(s). both direct and cooperative link SNRs are usually combined at destination using Maximum Ratio Combining (MRC). Mathematically, the average output SNR γ_{MRC} is given as;

$$\gamma_{MRC} = \begin{cases} \bar{\gamma}_{sd} & for\ direct \\ \bar{\gamma}_{sd} + \bar{\gamma}_{R_B} & for\ SRS\ cooperation \\ \bar{\gamma}_{sd} + \sum_{i=1}^{M} \bar{\gamma}_i & for\ MRS\ coopertion \end{cases} \tag{3.5}$$

where $\bar{\gamma}_{sd}$ is the source-destination average SNR, $\bar{\gamma}_{R_B}$ is the best relay average SNR as forwarded to the destination, $\bar{\gamma}_i$ is the average SNR for the ith selected relay ($i = 1,2,3,\dots,M$) and γ_{MRC} is the combined SNR at destination for both direct and cooperative links after MRC (M is the number of best relays selected).

3.4.2 Outage Probability

The outage probability P_0 is the probability that the total SNR received at the destination terminal, γ_{MRC} will fall below the predetermined threshold SNR, γ_{th}. The outage probability P_0 is given by;

$$P_0 = Pr[\gamma_{MRC} < \gamma_{th}] \tag{3.6}$$

The threshold SNR is given by $\gamma_{th} = 2^{2R} - 1$ where R is the data rate of the transmission [25].

Let $f_{\gamma_{MRC}}(\gamma)$ be the probability distribution function (PDF) of the total received signal SNR γ_{MRC} and $F_{\gamma_{MRC}}(\gamma)$ its cumulative distribution function (CDF), the outage probability can also be defined as the CDF of γ_{MRC} over the threshold value γ_{th} [24]. This becomes;

$$P_0 = \int_0^{\gamma_{th}} f_{\gamma_{MRC}}(\gamma)d\gamma = F_{\gamma_{MRC}}(\gamma_{th}) \tag{3.7}$$

3.4.3 Average Bit Error Rate

The average Bit Error Rate (BER) of a communication system is the amount of bits that have errors compared to the total number of bits received by the receiver. Average BER is a very strong indicator of how often data units have to be retransmitted due to error in its transmission. It is a function of the bit energy per noise density (E_b/N_0) which is obtained from the signal-to-noise ratio (SNR). The average BER for a QPSK signal (which is usually employed for the LMSS communication) is given as [44];

$$BER(t) = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}(t)}\right) \tag{3.8}$$

The function $erfc$ is called the complimentary error function and it describes the cumulative probability curve of a Gaussian distribution. The bit energy per noise density (E_b/N_0) is related to the total signal-to-noise ratio SNR (γ_{MRC}) as;

$$\frac{E_b}{N_0} = \gamma_{MRC} \times \frac{B}{R_b} \tag{3.9}$$

where B is the bandwidth and R_b is the bit rate.

3.4.4 Average Channel Capacity

The average channel capacity C_{avg} is defined as the maximum amount of data an appropriate channel can accommodate under some given constraints. It gives an idea of the maximum achievable transmission rate under which the errors are recoverable. For the satellite communication using both direct and cooperative communication modes, the average channel capacity C_{avg} is given as [27];

$$C_{avg} = \Pr(dir) \times C_{dir} + \Pr(coop) \times C_{coop} \tag{3.10}$$

where $Pr(dir)$ is the probability that the direct communication mode is employed, C_{dir} is the average channel capacity during direct communication, $\Pr(coop)$ is the probability that the cooperative mode is employed and C_{coop} is the average channel capacity during cooperative communication. Hence,

$$C_{avg} = p_g \times C_{dir} + \left(1 - p_g\right) \times C_{coop} \tag{3.11}$$

where $p_g$is the probability of the system in good state.

C_{dir} and C_{coop} are calculated from the Shannon's equation and they are given by;

$$C_{dir} = B\int_0^{\infty} \log_2(1 + \gamma_{sd}) f_{\gamma_{sd}}(\gamma_{sd}) d\gamma_{sd} \tag{3.12}$$

$$C_{coop} = \frac{B}{2}\int_0^{\infty} \log_2(1 + \gamma_{MRC}) f_{\gamma_{MRC}}(\gamma_{MRC}) d\gamma_{MRC} \tag{3.13}$$

where B is the bandwidth, γ_{sd} is the SNR value at destination terminal and $f_{\gamma_{sd}}(\gamma_{sd})$ is its PDF when the direct communication mode is employed, γ_{MRC} is the combined SNR at destination and $f_{\gamma_{MRC}}(\gamma_{MRC})$ its PDF when the cooperative communication mode is employed.

3.5 Results and Discussion

The results of the SNR values obtained from the link budget analysis for the $\mathrm{DVB-SH}$ communication was used in generating the SNR values of the IRS cooperative diversity. In generating the faded signal, the values for the good and bad state as well as the state transition and state probability matrixes for the urban and rural environment types as given in Tables 3.1 to Table 3.3 were employed. A total of 10 relays $(N = 10)$ were assumed to be available in the destination terminal's interference range while the threshold SNR value was varied at regular interval between 0 and 30dB. For SRS, $M = 1$ while for MRS, results for $M = 2$ and 3 were considered.

The outage probability P_0 for the direct communication and two IRS cooperative schemes (single state fading and the LMSS two-state fading model) is shown in Fig. 3.5. The threshold SNR value of 7dB was assumed. The result shows that for a given threshold SNR, the outage probability generally decreasing with an increasing output SNR. The results were benchmarked to those in [27] which considered a single state Rayleigh fading model for both its direct and IRS cooperative communications. The two-state fading model for LMSS which incorporates Rayleigh, Rician and lognormal fading distributions performed better than the single-state Rayleigh fading model. This result indicates that the two-state model gives a better representation of the LMSS channel conditions than the single-state distributions. Also, the IRS cooperative scheme performed better than the direct transmission as the outage experienced during cooperative communication is significantly less than the outage experienced for direct communication. This is expected as the cooperative system gives an average SNR value greater than the direct system at almost all instances. It is therefore easy to conclude that the IRS cooperation helps the LMSS achieve the diversity advantage.

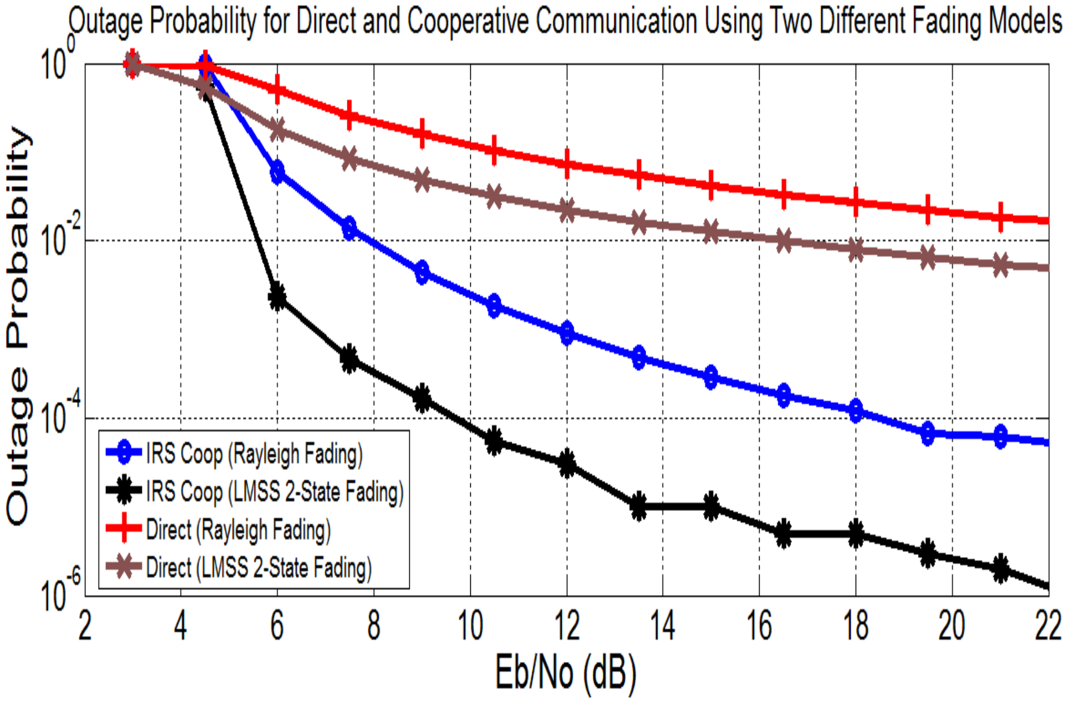

Fig. 3.5. Outage Probability comparison for the direct and the IRS cooperation diversity scheme

The outage probability P_0 performance versus threshold SNR for both the direct communication and cooperation communication for two different environment types (urban and rural) is shown in Fig. 3.6. In the result, the outage probability generally increases as the threshold SNR increases. The result clearly shows the advantage of cooperative communication over non-cooperation (direct transmission). For the urban environment in direct cooperative communication, the outage probability is approximately zero when threshold SNR is below 6dB. Between 6 and 10dB, the outage probability increases significantly until it saturates. Above 10dB, the outage probability is approximately unity. For the urban environment in cooperative communication, the outage probability is approximately zero when threshold SNR is below 10dB. Between 10 and 16dB, the outage probability increases significantly until it saturates. Above 16dB, the outage probability is approximately unity. Similar extreme values are observed for the rural environment as well. However, in-between the extreme values, the outage probability perform better in the rural environment than in the urban environment for both direct and cooperative communication. For instance, at 13dB threshold, the outage probability for the rural environment is approximately 0.2 while the outage probability for the urban environment is approximately 0.8. The reason for the better performance of the rural environment over the urban is because of the better line-of-sight communication experienced in the rural, as compared to the urban.

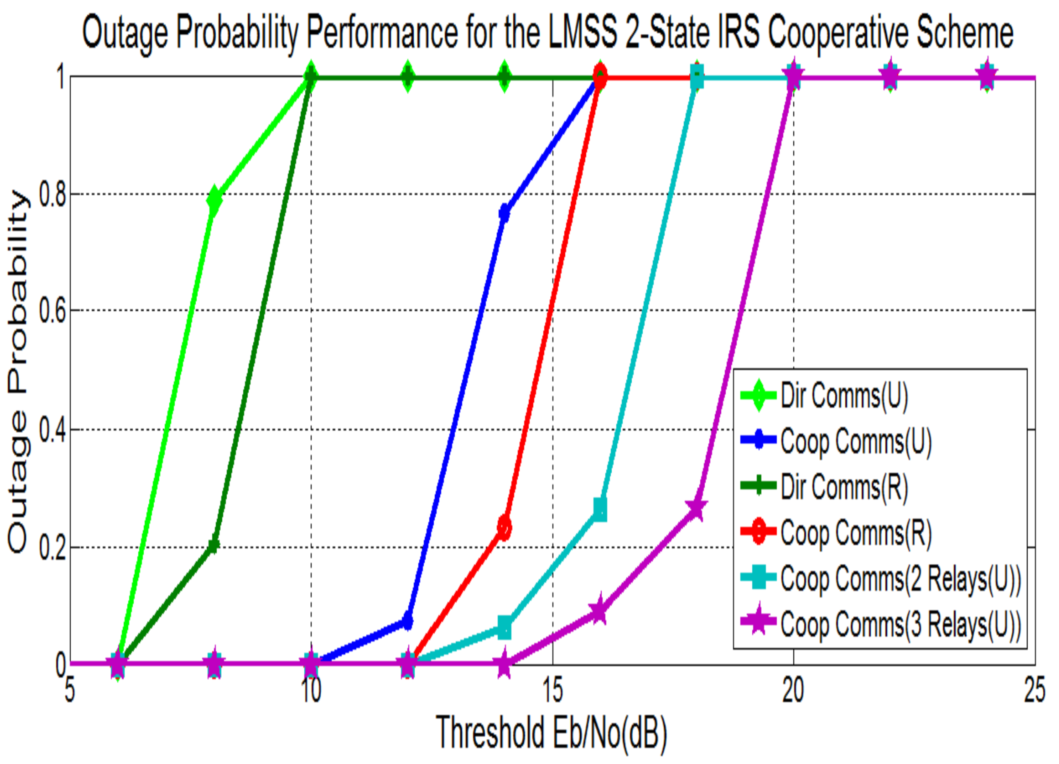

Fig. 3.6. Outage Probability compared for direct and cooperative communication in rural (R) and urban (U) environments

The result in Fig. 3.6 also shows the outage probability comparison for single relay selection (SRS) and multiple relay selection (MRS) schemes. As seen in the result, the outage probability performed better as more and more relays were employed in transmission for a given value of threshold SNR. Hence, if the threshold SNR value for a particular communication is high, a better outage performance can be obtained by employing more relays. The reason for the better performance is because, for higher threshold demands, more relays send their received signal, thus making less room for an outage as the total signal received at the destination becomes higher.

The comparison in terms of average bit error rate (BER) for the direct and the cooperative communication techniques is shown in Fig. 3.7 using both the Rayleigh fading (single-state model) and the two-state LMSS model. The result shows that the BER generally reduces with an increasing average SNR. The results were also benchmarked to those in [27] which considered a single state Rayleigh fading model for both its direct and IRS cooperative communications. Both the IRS cooperative communications (single state and 2-state models) outperformed the direct communication as their average BER reduce with increasing SNR for a given transmission. More so, the two-state model performs better than the single-state model. The reason for this is that the average SNR value of the cooperative communication link is higher than the direct link hence the average BER of the cooperative communication is lower than that of the direct. Thus, the IRS cooperative communication also outperforms the direct communication system in terms of average BER as well.

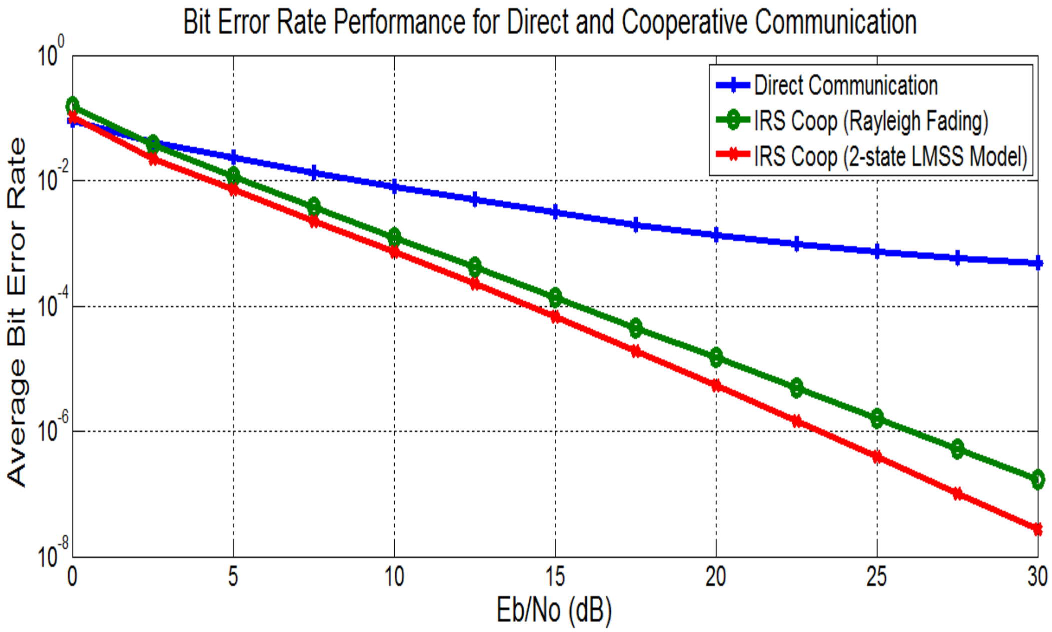

Fig. 3.7. Bit Error Rate (BER) versus SNR for direct and cooperative communications

A comparison of the average channel capacity per bandwidth for the direct and the cooperative communication is shown in Fig. 3.8. The result shows that the average capacity generally increases with an increasing average SNR. It is also obvious that the cooperative communication, either for rural or urban environment, gives a better channel capacity performance than the direct communication. This implies that the cooperative communication channel is able to deliver a higher average capacity as compared to when only the direct communication channel is employed. This is because the cooperative link employs both the direct and the relay link in sending its signal, thus it can accommodate a larger capacity than can be delivered by the direct communication.

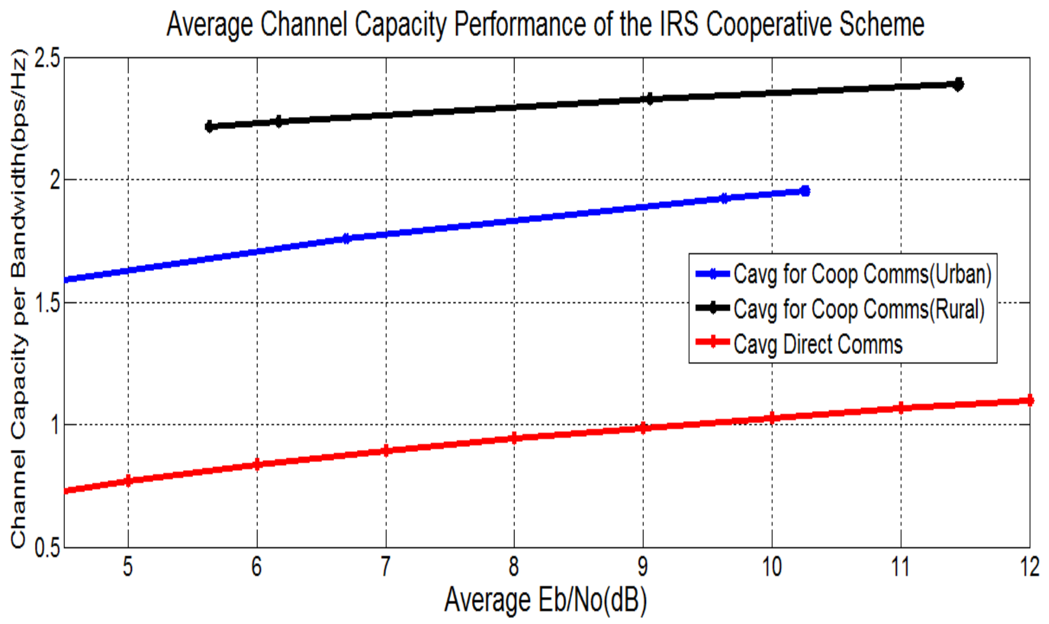

Fig. 3.8. Average Channel Capacity performance for the IRS cooperative communication in rural and urban environments

From the performance results presented above (outage probability, bit error rate and average channel capacity), it can be safely concluded that just as in other wireless communications, cooperative diversity for the LMSS (as investigated in this chapter using the IRS cooperative scheme) also gives a much better performance than using direct communication alone.

3.6 Conclusion

In this chapter, the cooperative diversity concept was implemented on Land Mobile Satellite Systems by using data from an existing LMSS model which employs a two (2) – state Markov chain based statistical approach. The incremental relay-selection (IRS) cooperative diversity concept was employed in the investigation as it promised greater conservation in the use of satellite and relay resources. Performance results for direct, single-relay selection (SRS) and multiple-relay selection (MRS) were compared in terms of outage probability, average bit error rate (BER) and average channel capacity. Furthermore, results obtained for the two-state LMSS cooperative model were compared with similar results from a single-state cooperative model using just the Rayleigh fading. In all, the cooperative schemes for both single state and two-state showed better performance than the direct communication. Furthermore, the two-state model gave a better performance than the single-state model. As expected, the MRS performed better than the SRS thus confirming the diversity advantage of the investigated scheme.

CHAPTER 4

INCREMENTAL RELAY SELECTION COOPERATIVE DIVERSITY USING DECODE-AND-FORWARD

4.1 Introduction

In receiver-based cooperative diversity systems, nearby mobile relays close to the destination terminal are employed in sending signal from source to the destination. This usually brings about a better quality of service (QoS) as the received signal at destination is generally improved. Land Mobile Satellite Systems (LMSS) have peculiar channel conditions due to the combined shadowing and multipath effect that the links experience, leading to poor signal quality at the receiver. To help provide a consistently high quality of service (QoS) especially in urban and suburban areas therefore, receiver-based cooperative diversity is a viable option for the LMSS. In the previous chapter, the incremental relay-selection (IRS) scheme was studied using the store-and-forward (SF) cooperative technique (which is also applicable to the amplify-and-forward (AF) technique). In this chapter, the work is being extended to the decode-and-forward (DF) cooperative technique. The new scheme is called incremental relay-selection decode-and-forward (IRS-DF) cooperative diversity for the LMSS.

There are currently few works on the performance of decode-and-forward cooperative scheme for satellite systems in the literature. References [45] – [47] are some examples of these recent works on decode-and-forward cooperation investigated particularly for satellite systems using satellite fading models. In [45], the authors analyzed and simulated the symbol error probability for a decode-and-forward cooperative scheme in satellite mobile channel using various fading models. Authors in [46] and [47] also derived expressions for the symbol error probability (SEP) of decode-and-forward cooperation in satellite-terrestrial networks using different types of multiple (or composite) fading models. Having argued favourably in the last two chapters that the incremental relay-selection (IRS) cooperation is optimal for the LMSS (because of its reduced channel demands), an investigation into the performance of the decode-and-forward technique is carried out in this chapter using the two-state LMSS model. An analytical model in deriving expressions for the various performance metrics is also considered in this chapter. Two approaches to analyzing performance of cooperative diversity metrics as available in the literature are the Probability Distribution Function (PDF)/Cumulative Distribution Function (CDF) approach and the Moment Generating Function (MGF) approach and [45], [47]. The MGF approach is considered in this chapter.

In the chapter, the channel model of the IRS-DF cooperative scheme for the LMSS is first developed. Next, an analytical model for the IRS-DF cooperative scheme using the multiple fading distributions of the two-state LMSS is also developed. Then, the derivation of close-band approximation of the outage probability is carried out for the IRS-DF cooperative scheme using the Moment Generating Function (MGF) approach. Finally, the results of the outage probability for the IRS-DF cooperation are presented and they show a better performance in the LMSS when IRS-DF cooperative diversity is used as compared to using direct communication alone.

4.2 System Model for the IRS-DF Cooperative Diversity Scheme

The LMSS system model with incremental relay-selection decode-and-forward (IRS-DF) cooperative diversity scheme is similar to the IRS system model described in section 3.2. The model is typically the same except for the inclusion of a decode-and-forward mini-slot in the cooperative transmission time slot. The network model is briefly summarized as follows;

The network model during direct transmission follows exactly the explanations already given in section 3.2 (Fig. 3.2.). However, when cooperation is required for the IRS-DF cooperative scheme, the relays get the NACK message from the destination after first time slot. With the NACK feedback, the satellite waits at the second time slot. Each relay terminal determines its received SNR (it calculates this using its CQI) from the satellite and sends this to the destination. At the destination, the relays with their reported channel SNR values high enough to allow for successful decoding of original signal are grouped together to form a decoding set R_M (the decoding set is defined as the set of relays that can decode the satellite signal correctly). The destination terminal then broadcasts a single bit CBR (Chosen Best Relay) signal to all relays containing the detailed identities of the relays in the decoding set R_M indicating they has been selected for cooperation. The relays not selected get the CBR and simply ignores it since their identities are not included. Next, relays in the decoding set R_M re-modulate their received signal to the destination. The destination then combines the relays' signal with its original signal through maximum ratio combining (MRC).The total frame for cooperative transmission, divided into mini frames for the IRS-DF cooperation is shown in Fig. 4.1.

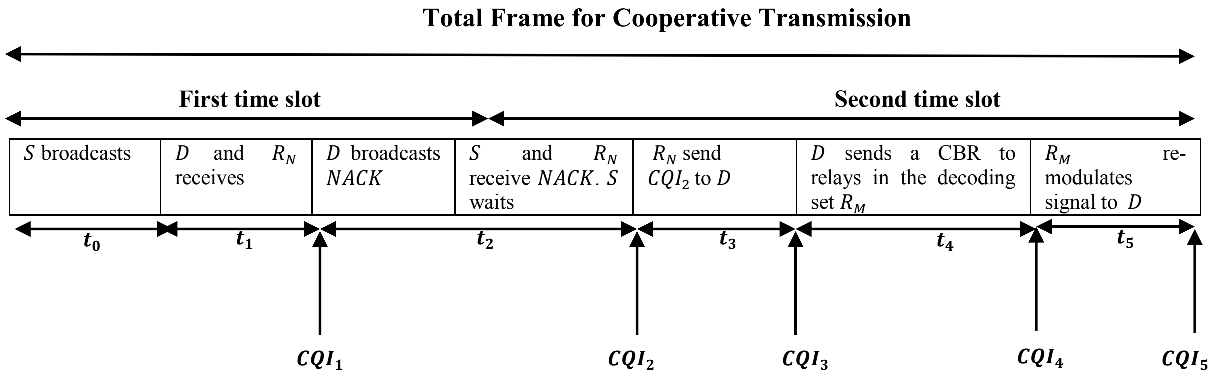

Fig. 4.1. Total Time Frame for Cooperative Communication with IRS-DF

The network model for the IRS-DF cooperative diversity scheme as described above can be simply summarized in the algorithm below.

Incremental Relay-Selection Decode-and-Forward (IRS-DF) Cooperative Diversity Algorithm

---

S – Satellite; R_N – Available Relays; R_M – Relays in the decoding set; D – Destination; CBR – Chosen Best Relay; MRC – Maximum Ratio Combining; γ_{sd} – Satellite-Destination SNR; γ_{th} – threshold SNR;

```
Start
S broadcasts
D and R_N receive signal (and keeps its times series in a buffer)
  If ( $\gamma_{sd} > \gamma_{th}$ )  then
  (use direct transmission)
          D sends ACK to S and R_N
          (R_N does nothing in second time slot)
          S sends next signal
  else
  (use cooperative transmission)
          D sends NACK to S and R_N
          (S does nothing in second time slot)
          Each R_N determines its CQI (and calculates its SNR)
          Each R_N sends it SNR to D
```

```
            $D$ chooses best relays $R_M$ within the decoding set
            $D$ sends a $CBR$ signal to $R_M$ informing it to send signals
            $R_M$ send(s) signals
            Signals from $D$ and $R_M$ are combined at $D$ through $MRC$
    End If
End
```

The received signal at the destination and the relay terminals after the satellite broadcasts at the first time slot is given by [47];

$$r_{sd} = \sqrt{P_s} h_{sd} x_s + n_d \tag{4.1}$$

$$r_{sr_i} = \sqrt{P_s} h_{sr_i} x_s + n_{r_i} \tag{4.2}$$

where P_s is the average transmit power of the satellite, r_{sd} is the received signal at the destination, r_{sr_i} the received signal at the i^{th} relay, x_s the source transmitted signal, h_{sd} is the channel coefficient between source and destination, h_{sr_i} the channel coefficient between source and the i^{th} relay, n_d and n_{r_i} are the noise components (AWGN) at the destination and the i^{th} relay respectively.

In the second slot, cooperation may be needed if signal at destination is below threshold signal. For cooperative transmission, the received signal at destination due to the relays in the second time slot is given as;

$$r_{r_i d} = \begin{cases} \sqrt{P_{r_i}} h_{r_i d} x_s + n_d, & \text{when } r_i \epsilon R_M \\ 0, & \text{otherwise} \end{cases} \tag{4.3}$$

where P_{r_i} is the average transmit power of the relay r_i, $h_{r_i d}$ is the channel coefficient between i^{th} relay and the destination, n_d is the relay-destination noise component and x_s is the decoded signal at the relay and is assumed to be error free (since in IRS-DF scheme, only relays with their received SNR high enough to decode accurately the satellite signal are selected).

To help derive closed form approximations for the IRS-DF scheme for LMSS, the various distributions for the satellite-destination, satellite-relays and relay-destination links have to be considered. The satellite-destination (S-D) link is represented by a Loo's model (which is a combination of Rayleigh and lognormal distributions) [43], [49]. The probability distribution function (PDF) of the received power channel coefficient $|h_{sd}|^2$ using Loo's model is given by [49];

$$f_{|h_{sd}|^2}(r) = \frac{r}{\sigma_1^2\sqrt{2\pi d_0}}\int_0^\infty \frac{1}{z} exp\left[-\frac{(\ln z-\mu)^2}{2d_0}-\frac{(r^2+z^2)}{2\sigma_1^2}\right].I_0\left(\frac{rz}{\sigma_1^2}\right)dz \qquad (4.4)$$

where σ_1^2 is the average power of the multipath scattering, μ is the mean of the direct component, d_0 is the variance of the direct component $\ln z$, and $I_0(.)$ is the zeroth order modified Bessel function of the first kind.

During cooperation, the selected relays in the decoding set usually have a high signal strength received from satellite and thus a greater Rician factor. The satellite-relay (S-R) link is therefore described by the Corazza's model (which is a combination of Rician and lognormal distributions) [43], [50]. The probability distribution function (PDF) of the received power channel coefficient $|h_{sr}|^2$ using the Corazza's model is given by [50];

$$f_{|h_{sr}|^2}(r) = \frac{r}{\sqrt{2\pi}\sigma_0^2\sigma_3}.\int_0^\infty \frac{1}{y^3} exp\left(-\frac{(r/y)^2+\rho^2}{2\sigma_0^2}-\frac{(\ln y-m_3)^2}{2\sigma_3^2}\right).I_0\left(\frac{r\rho}{y\sigma_0^2}\right)dy \qquad (4.5)$$

where σ_0^2 is the average power of the multipath scattering, ρ is the amplitude of the direct component, m_3 is the mean of the direct component, σ_3 is the standard deviation of the direct component and $I_0(.)$ is the zeroth order modified Bessel function of the first kind. The Rician factor K is given as $K=\rho^2/(2\sigma_0^2)$.

The relay-destination (R-D) link is usually a multipath link and is simply described by Rayleigh fading channel. The PDF of the received power channel coefficient $\left|h_{r_i d}\right|^2$ is given as [51];

$$f_{\left|h_{r_i d}\right|^2}(r) = \frac{r}{\sigma_2^2} exp\left(-r^2\Big/2\sigma_2^2\right) \qquad (4.6)$$

where r is the received signal envelop and σ_2^2 is the average power for the multipath scattering.

4.3 Performance Analysis

The performance of the IRS-DF cooperative scheme in terms of outage probability is analyzed in this section using the moment generating function (MGF) approach. The outage probability is defined as the probability of the total received SNR at destination falling below the preset threshold

SNR γ_{th} for the required communication QoS. The outage probability P_o of the IRS-DF cooperative scheme for LMSS using MGF is given as [47];

$$P_o = \mathcal{L}^{-1}\left(\frac{\mathcal{M}_{\gamma_{MRC}}(s)}{s}\right)\bigg|_{\gamma_{th}} \tag{4.7}$$

where $\mathcal{L}^{-1}$ is the inverse Laplace transform and $\mathcal{M}_{\gamma_{MRC}}(s)$ is the moment generating function (MGF) of the total instantaneous SNR at destination after maximum ratio combining (MRC) of the direct and the cooperative links. To obtain P_o, the MGF of γ_{MRC} has to be obtained first. The following analysis is carried out to derive the MGF for γ_{MRC}.

The instantaneous received SNR for each of the links is first obtained from the channel coefficients. For the S-D link, the instantaneous received SNR γ_{sd} is given as;

$$\gamma_{sd} = |h_{sd}|^2 \times \bar{\gamma}_{sd} \tag{4.8}$$

where $\bar{\gamma}_{sd} = {}^{P_s}\!/_{N_0}$ is the average transmitted SNR of satellite-destination link. For the S-R and R-D links, the following relationships hold;

$$\gamma_{sr} = |h_{sr}|^2 \times \bar{\gamma}_{sr} \tag{4.9}$$

where $\bar{\gamma}_{sr} = {}^{P_s}\!/_{N_0}$ is the average transmitted SNR of satellite-relay link.

$$\gamma_{r_i d} = \left|h_{r_i d}\right|^2 \times \bar{\gamma}_{r_i d} \tag{4.10}$$

where $\bar{\gamma}_{r_i d} = {}^{P_{r_i}}\!/_{N_0}$ is the average transmitted SNR of i^{th} relay-destination link.

The PDF of the instantaneous received SNR γ_{sd} for the S-D link is given as;

$$f_{\gamma_{sd}}(\gamma) = \frac{1}{\bar{\gamma}_{sd}} \times f_{|h_{sd}|^2}\left(\frac{\gamma}{\bar{\gamma}_{sd}}\right) \tag{4.11}$$

Substituting $f_{|h_{sd}|^2}(\gamma)$ into (4.11), $f_{\gamma_{sd}}(\gamma)$ becomes;

$$f_{\gamma_{sd}}(\gamma) = \frac{\gamma}{\bar{\gamma}_{sd}\sigma_1^2\sqrt{2\pi d_0}}\int_0^{\infty}\frac{1}{z}exp\frac{1}{\bar{\gamma}_{sd}}\left[-\frac{(\ln z-\mu)^2}{2d_0}-\frac{(\gamma^2+z^2)}{2\sigma_1^2}\right].I_0\left(\frac{\gamma z}{\bar{\gamma}_{sd}\sigma_1^2}\right)dz \tag{4.12}$$

Similarly, the PDF of the instantaneous received SNR γ_{sr} for the S-R link becomes;

$$f_{\gamma_{sr}}(\gamma) = \frac{1}{\bar{\gamma}_{sr}} \times f_{|h_{sr}|^2}\left(\frac{\gamma}{\bar{\gamma}_{sr}}\right) \tag{4.13}$$

$$f_{\gamma_{sr}}(\gamma) = \frac{\gamma}{\bar{\gamma}_{sr}\sqrt{2\pi}\sigma_0^2\sigma_3} . \int_0^{\infty} \frac{1}{y^3} exp \frac{1}{\bar{\gamma}_{sr}}\left(-\frac{(\gamma/y)^2+\rho^2}{2\sigma_0^2} - \frac{(\ln y - m_3)^2}{2\sigma_3^2}\right) . I_0\left(\frac{\gamma\rho}{\bar{\gamma}_{sr} y \sigma_0^2}\right) dy \tag{4.14}$$

And the PDF of the instantaneous received SNR $\gamma_{r_i d}$ for the R-D link becomes;

$$f_{\gamma_{r_i d}}(\gamma) = \frac{1}{\bar{\gamma}_{r_i d}} \times f_{\left|h_{r_i d}\right|^2}\left(\frac{\gamma}{\bar{\gamma}_{r_i d}}\right) \tag{4.15}$$

$$f_{\gamma_{r_i d}}(\gamma) = \frac{1}{\bar{\gamma}_{r_i d}} \exp\left(-\frac{\gamma}{2b_0\bar{\gamma}_{r_i d}}\right) \tag{4.16}$$

where $2b_0$ is the average channel power gain of the Rayleigh fading.

The total instantaneous received SNR at destination after maximum ratio combining (MRC) γ_{MRC} is given as;

$$\gamma_{MRC} \ = \gamma_{sd} \ + \sum_{i=1}^{R_M} \gamma_{r_i d} \tag{4.17}$$

The moment generating function (MGF) is generally defined as;

$$\mathcal{M}_X(s) = \ \mathbb{E}[e^{-sx}] = \int_0^{\infty} e^{-sx} f_X(x) dx \tag{4.18}$$

where $\mathbb{E}[.]$ is the mathematical expectation operation and $f_X(x)$ is the PDF of x.

For the S-D (direct) link, the MGF $\mathcal{M}_{\gamma_{sd}}(s)$ is given as;

$$\mathcal{M}_{\gamma_{sd}}(s) = \ \mathbb{E}[e^{-s\gamma}] = \int_0^{\infty} e^{-s\gamma} f_{\gamma_{sd}}(\gamma) d\gamma \tag{4.19}$$

Substituting $f_{\gamma_{sd}}(\gamma)$ into the MGF equation, $\mathcal{M}_{\gamma_{sd}}(s)$ becomes;

$$\begin{aligned}\mathcal{M}_{\gamma_{sd}}(s) = \frac{\gamma}{\bar{\gamma}_{sd}\sigma_1^2\sqrt{2\pi d_0}} \int_0^{\infty} e^{-s\gamma} \int_0^{\infty} \frac{1}{z} exp \frac{1}{\bar{\gamma}_{sd}} \Bigg[-\frac{(\ln z - \mu)^2}{2d_0} \\ - \frac{(\gamma^2+z^2)}{2\sigma_1^2}\Bigg] . I_0\left(\frac{\gamma z}{\bar{\gamma}_{sd}\sigma_1^2}\right) dz\, d\gamma\end{aligned} \tag{4.20}$$

For the S-R-D cooperative link, the MGF has to be obtained. However, this MGF has been analyzed in [47] and the results obtained are employed in this work. Given that α_i is the instantaneous received SNR of the relayed link i at the destination which takes into account both the S-R and the R-D links, the MGF of α_i was given in [47] as;

$$\mathcal{M}_{\alpha_i}(s) = P_{sr_i} + \left(1 - P_{sr_i}\right)\left(1 + 2b_0\bar{\gamma}_{r_id}s\right)^{-1} \tag{4.22}$$

where P_{sr_i} is the probability that the selected relay r_i decodes incorrectly, $\bar{\gamma}_{r_id}$ is the average relay-destination SNR and $2b_0$ is the average channel power gain of the Rayleigh faded relay-destination link.

The MGF of γ_{MRC} is therefore obtained by multiplying the MGFs. This becomes;

$$\mathcal{M}_{\gamma_{MRC}}(s) = \mathcal{M}_{\gamma_{sd}}(s)\prod_{i=1}^{R_M}\mathcal{M}_{\alpha_i}(s) \tag{4.23}$$

The outage probability is obtained by substituting equation (4.23) into equation (4.7).

4.4 Results and Discussion

The simulation and analytical results of the IRS-DF cooperative diversity in comparison with the direct communication model are presented in this section. Using the parameters given in chapter 3 (section 3.2.) and by varying threshold SNR between the range 0-30dB, the performance plots of the outage probability P_0 for the cooperative satellite system are shown. A total of 10 relays are assumed to be available within the destination terminal's interference range out of which the decoding relays set is chosen.

The outage probability P_0 for the direct communication and IRS-DF cooperative schemes is shown in Fig. 4.2. The threshold SNR value of 7dB was assumed. The result shows that for a given threshold SNR, the outage probability generally decreases with an increasing output SNR. The results were benchmarked to those in [27] which considered a single state Rayleigh fading model for both its direct and IRS-DF cooperative communications. The two-state fading model for LMSS which incorporates Rayleigh, Rician and lognormal fading distributions performed better than the single-state Rayleigh fading model. This result shows that for the IRS-DF cooperative scheme, the two-state Markov model is a better representation of the fading conditions of the LMSS than the single Rayleigh fading model.

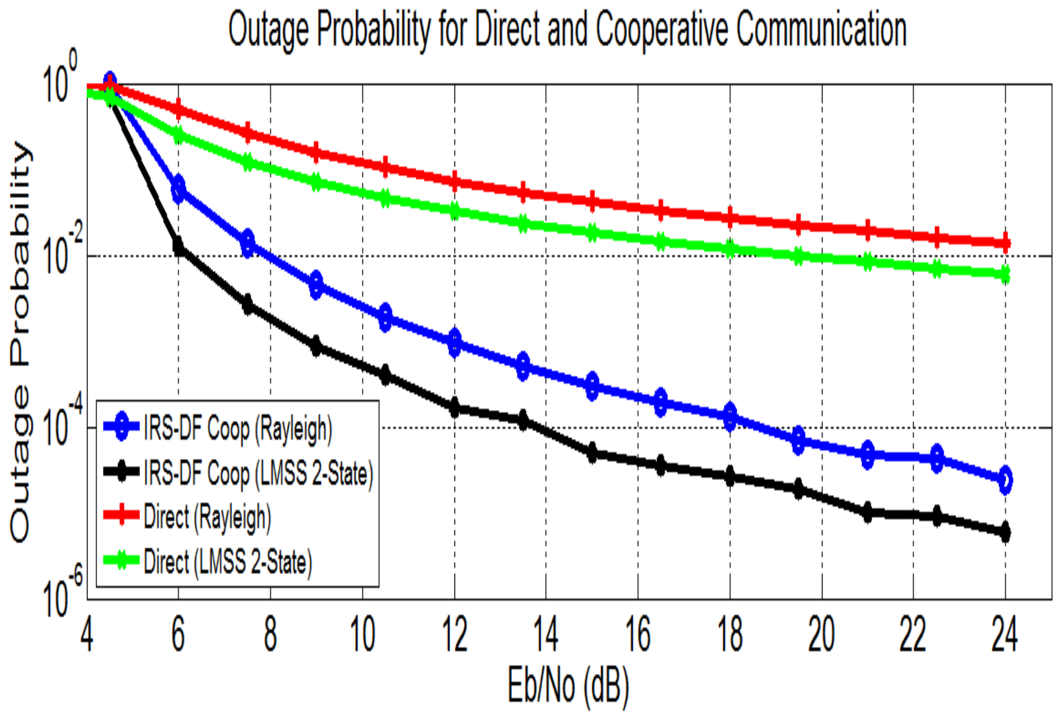

Fig.4.2. Outage Probability comparison for the direct and IRS-DF Cooperative Diversity scheme

The outage probability comparison of the IRS-DF cooperative diversity scheme with the direct communication (non-cooperation) is shown in Fig. 4.3. for the urban environment and Fig. 4.4. for the rural environment. The results show that outage probability generally increases with an increasing threshold SNR value. For the urban environment, outage probability for the direct communication is approximately zero at threshold SNRs below 5dB. It remains approximately zero for the cooperative communication until about 13dB. The outage probability steadily increases to unity for thresholds 5 - 10dB for the direct communication and 13 – 20 dB for the cooperative communication. After these range of values, the outage probability saturates. The analytical results are well matched by simulations thereby validating the analysis.

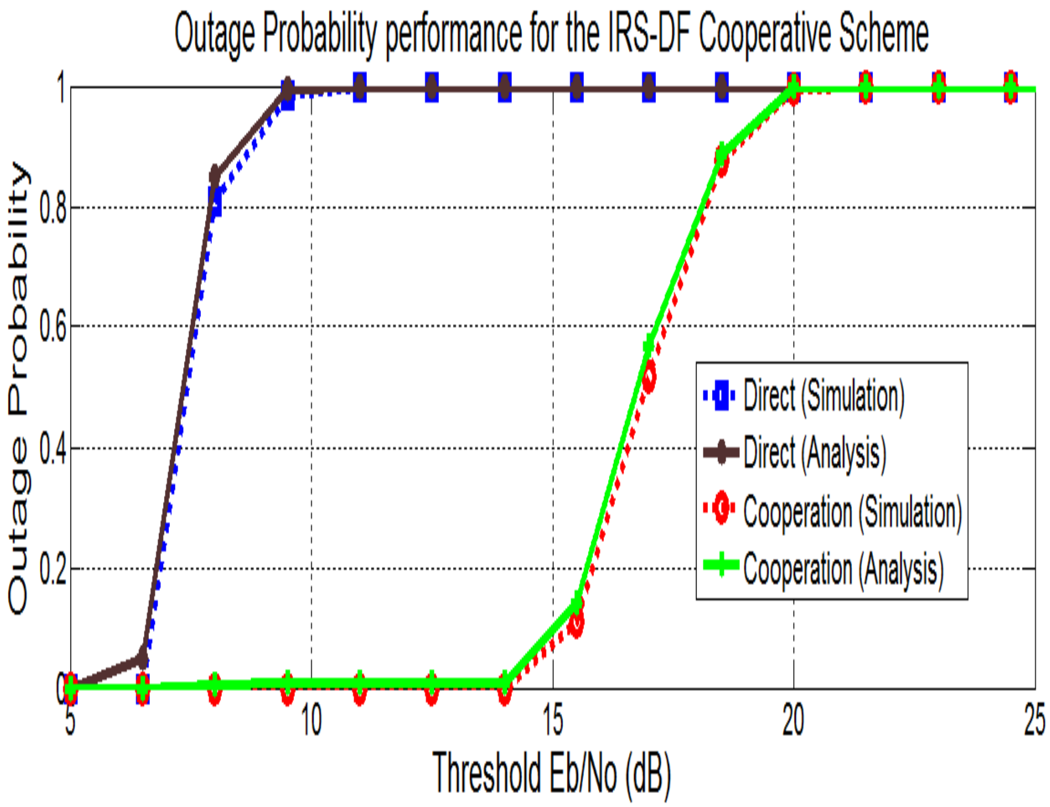

Fig. 4.3. Analytical and Simulation results of the IRS-DF cooperative diversity for the urban environment

For the rural environment, outage probability for the direct communication is approximately zero at threshold SNRs below 6dB. It remains approximately zero for the cooperative communication until about 13dB. The outage probability steadily increases to unity for thresholds 5 - 13dB for the direct communication and 13 – 30 dB for the cooperative communication. After these range of values, the outage probability also saturates. The reason for the better performance of the rural environment over the urban is because of the better line-of-sight communication experienced in the rural, as compared to the urban environment.

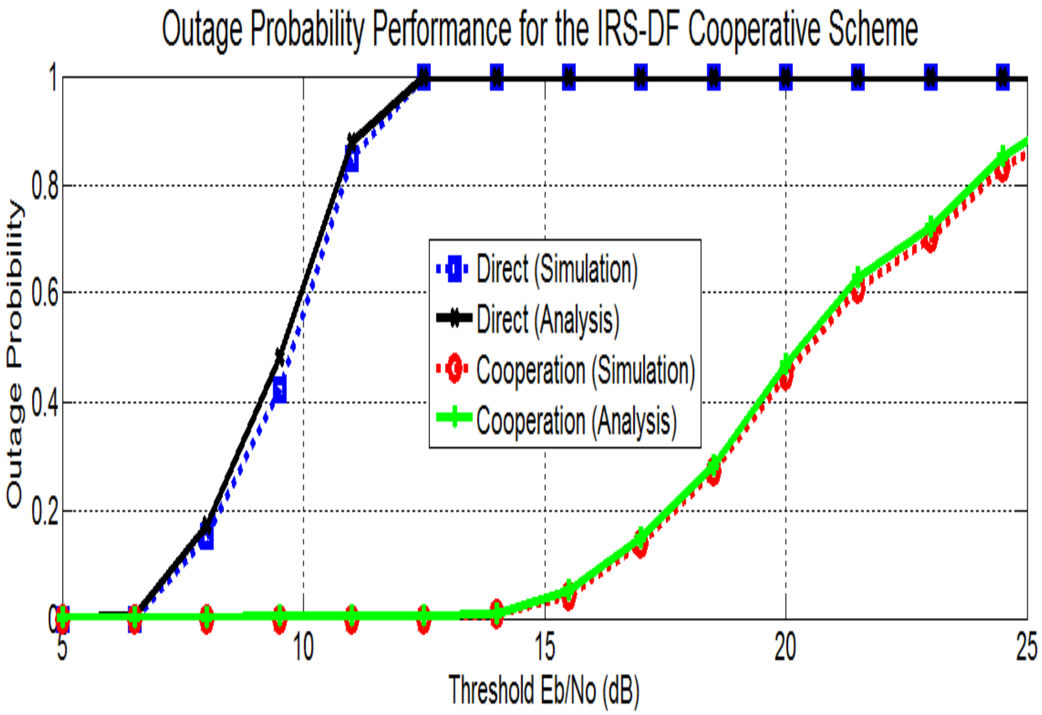

Fig. 4.4. Analytical and Simulation results of the IRS-DF cooperative diversity for the rural environment

The results for the IRS-DF given above show that irrespective of the environment type considered, a significant improvement in the outage probability is observed for the LMSS when IRS-DF cooperative diversity is employed, as compared to non-cooperative communication.

4.5 Conclusion

In this chapter, the incremental relay-selection decode-and-forward (IRS-DF) cooperative diversity concept was implemented on Land Mobile Satellite Systems by using data from an existing LMSS model which employs a two – state Markov chain based statistical approach. The IRS-DF model developed used the combined power of both relay-selection and also incremental cooperation to bring about an optimum performance for decode-and-forward cooperation. Moment Generating Function (MGF) approach was used in deriving the outage probability performance of the IRS-DF cooperative scheme. Both simulation and numerically analyzed results were presented. A comparison between direct communication and the IRS-DF cooperative communication was also carried out. The results from simulations were well matched by the results obtained from analysis and showed clearly that the IRS-DF cooperative communication gives better performance than direct communication for Land Mobile Satellite Systems.

CHAPTER 5

PREDICTIVE RELAY-SELECTION COOPERATIVE DIVERSITY

5.1 Introduction

There are a number of cooperative diversity schemes in the literature and they are being proven to provide better quality of service (QoS) for wireless communication systems. In the previous chapters, the incremental relay-selection (IRS) scheme was investigated for LMSS using the store-and-forward (SF)/amplify-and-Forward (AF) and the decode-and-forward (DF) cooperative techniques. The choice of IRS cooperative scheme was made because of its simplicity in application as well as a considerable reduction in spectrum and relay power consumption. The IRS cooperation only chooses one or few of the available relays (usually the best ones) for cooperation and also reduces cooperation to only the times when it is necessary.

Although the IRS schemes as investigated so far had shown a significant improvement in the performance of the LMSS, these investigations (and similar ones in the literature) had been carried out on an assumption – that the channel quality information (CQI) upon which the relay selection was made is perfect. However, in LMSS communications with mobile relay terminals, the channel CQI varies with time (or is rather outdated or imperfect). The outdated or imperfect CQIs as delivered by the relay terminals are caused by the long propagation delay and the continuously changing multistate fading statistics of the LMSS. This generally have a negative implication on the relay-selection process. In this chapter, the IRS cooperative diversity scheme is therefore extended to address this major challenge of the LMSS communication – the problem of outdated CQI. A novel version of the IRS cooperative scheme called predictive relay-selection (PRS) cooperation is proposed and investigated as a viable solution to this major challenge. In this novel model developed, predictive algorithms are employed in determining the future CQIs of the relays and selection is made on these predicted CQIs.

The most important contributions of this research work are therefore carried out in this chapter. The contributions in this chapter include:

a) Investigating the problem of outdated CQI for the LMSS,
b) Developing a novel Predictive Relay-Selection (PRS) cooperative diversity model for the LMSS as a solution to the outdated CQI challenge,
c) Applying various prediction algorithms for the PRS cooperative diversity model,

d) Carrying out the performance analysis of the novel, PRS cooperative diversity model and,
e) Recommending the best predictive model for application in the novel PRS cooperative diversity scheme.

In this chapter, the problem of outdated channel quality information (CQI) is first discussed and relevant literature on its effects is reviewed. Next, the applicability of predictive models to solving the outdated CQI challenge of LMSS is analyzed. Thereafter, the system model of the novel predictive relay-selection (PRS) cooperative diversity is developed. Next, the prediction models applied in the PRS cooperative diversity for LMSS as employed in this research work are analyzed. Following this, the performance analysis of the novel PRS cooperative diversity scheme is carried out using the PDF/CDF approach. Finally, the analytical and simulation results of the PRS cooperative scheme are presented and discussed.

5.2 Problem of Outdated Channel Quality Information (CQI)

Although most relay-selection cooperative diversity investigations have shown in clear terms the advantages in performance that can be derived from the various relay-selection cooperative schemes as they have shown high diversity orders, better outage probabilities, increased channel capacity, etc., the major challenge with these works is that they had all based their investigations on an assumption – that the channel quality information (CQI) upon which the relay selection was made is perfect. However, in systems where the relay terminals are mobile (such as the mobile relays of the LMSS), the channel gains vary with time. Hence, there is a time delay between when the relays estimate their CQI and when the chosen relay(s) actually send their information (due to time delay during feedback between relay and destination terminals). This implies therefore that the CQI at the time of transmission by the selected relay(s) is rather outdated. In other words, the CQI at the time of transmission by the chosen relay(s) might not be exactly the same as the one they estimated upon which they were chosen for cooperation.

Investigations into the effect of outdated CQI on the performance of relay-selection cooperative diversity have been on-going. References [52] – [57] are just a few of the many works found in the literature on outdated CQI as it affects relay-selection cooperation in wireless communications. The authors in [52] and [53] investigated the viability and gains of using Decode-and-Forward cooperative diversity in a wireless terrestrial network (e.g. WiMAX) using opportunistic relay selection scheme with outdated CQI. The investigation showed that the opportunistic relaying cooperation experiences a performance loss as well as a diversity loss when the CQI is not exact and when the number of relays available for cooperation is low. The work in [54] focused on relay selection in amplify-and-forward cooperative diversity with outdated CQI. The results demonstrate that if the correlation coefficient of the CQI at estimation and its value at transmission is not unity, there is a significant performance loss in the cooperative protocol. The work in [54] also showed that the diversity order of all single 'best' relay selection schemes which would have achieved full diversity in the presence of a perfect CQI reduces to unity in the presence of outdated CQI. This shows that selecting best relays based on outdated CQI may not be able to effectively overcome the problem of diversity loss in relay-selection cooperative systems, especially for mobile satellite networks. The works in the above-mentioned references (and other similar ones) all seem to have come to the same conclusion – that diversity orders of all relay-selection schemes swiftly reduce to unity in the face of outdated CQI, once the correlation coefficient between the CQI at estimation and CQI at transmission is not unity. Hence, the presumed better performance gained by employing relay-selection cooperative diversity fizzle out once the CQI is outdated. To guarantee a better performance through relay-selection cooperation therefore, the problem of outdated channel information must be adequately combated.

5.3 Applicability of Prediction Models to Cooperative Diversity in LMSS

As a solution to the outdated CQI problem identified above, the knowledge of the future channel condition (or CQI) becomes imperative in deciding which relay(s) are to be selected for cooperation. This work therefore introduces and investigates the practicability of CQI prediction to LMSS relay-selection cooperation. Several prediction algorithms for various fading models have been described in the literature some of which are applicable to narrowband and wideband systems. Depending on the application, the prediction range could vary from a fraction of a millisecond to many milliseconds ahead. These prediction models as employed have helped in improving performance of adaptive modulation and coding, adaptive power control, transmitter antenna diversity, antenna beam-forming, channel equalization etc. [58] - [60]. In [58] for instance, it was demonstrated that reliable fading prediction makes adaptive transmission feasible in diverse wireless communication systems like the wireless sensor networks (WSN). The work in [58] classified the several fading prediction schemes in literature into three groups – Auto-regressive (AR) model-based techniques, Sum-of-Sinusoid (SOS) model-based techniques and band-limited process model-based basic expansion techniques. The basic expansion techniques had not been investigated for realistic or measured channels hence it is ignored in this work. As a follow up to that work, we have classified the various prediction algorithms as applicable to satellite channel modeling as – Linear prediction using the Auto-Regressive (AR) models, Sum-of-Sinusoids (SOS) based prediction models and Pattern-Matching Prediction models.

Linear Prediction (LP) models are Auto-Regressive (AR) based prediction methods using low order AR models to capture most of the fading dynamics. Linear predictions models are easy to use, have low complexity and are capable of making predictions over a long range [60]. The authors in [60] also argued that the SOS prediction models are generally more complex in implementation and are also not as reliable as the linear prediction models. The SOS prediction models are therefore ignored in this work. Pattern-matching prediction have been used for channel quality prediction in Adaptive Modulation and Coding [61], for wireless mobile ad hoc networks (MANET) SNR prediction [62], for predicting SNR in mesh networks [63] and in predicting mobility of nodes in mobile ad hoc networks [64]. These well-established prediction algorithms (linear prediction and pattern-matching prediction models) are therefore employed in this work for the LMSS communication.

5.4 System Model for the PRS Cooperative Diversity Scheme

The LMSS system model with predictive relay-selection cooperative diversity scheme is also similar to the IRS system model described in section 3.2. The model is typically the same except for the inclusion of a predictive part in the cooperative transmission time slot. The network model and corresponding network algorithm are briefly summarized.

5.4.1 Network Model

The network model during direct transmission follows exactly the explanations already given in section 3.2 (Fig. 3.2.). However, when cooperation is required for PRS cooperative scheme, the relays get the NACK message from the destination after first time slot and each relay calculates its predicted CQI and sends this to the destination. The destination determines the relays with the highest predicted CQI and chooses it as the best relay. Then, the destination broadcasts a Chosen Best Relay (CBR) signal to all relays with the identity of the selected best relay indicating it has been selected for cooperation. Other relays that receive the CBR but have not been selected simply ignore. The relay with the highest predicted channel quality (i.e. selected best relay, R_B) also receives the CBR signal containing its identity and indicating it has been selected for cooperation. R_B then enters into a transmitting mode, forwarding its already stored signal to the destination. The best relay's signal is afterwards combined with the destination's originally received signal through maximum ratio combining (MRC).

The total frame for cooperative transmission, divided into mini frames for the PRS cooperation is shown in Fig. 5.1.

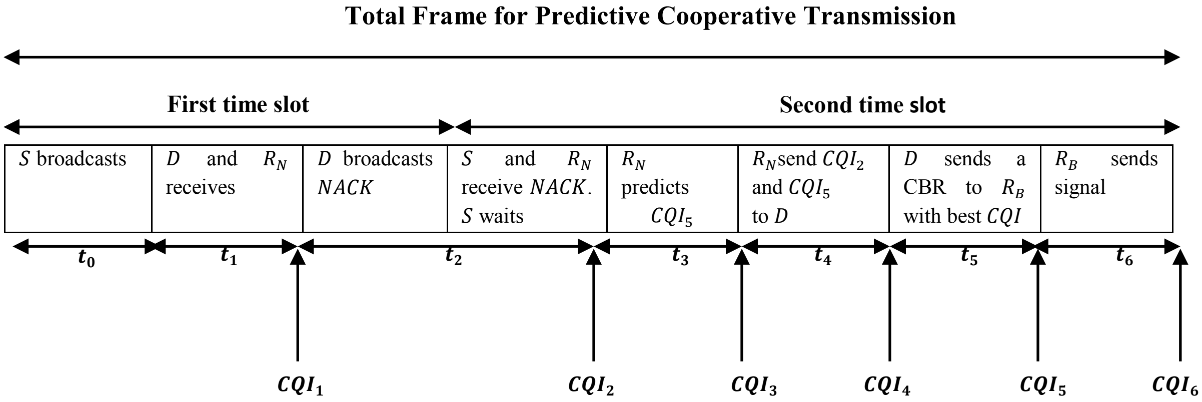

Fig. 5.1. Total Time Frame for Predictive Cooperative Communication

From the total time frame for the cooperative communication, the problem of outdated CQI is evident. It can be noticed in the time delay between when the relays send their estimated CQI (after time t_2) and when the selected best relay is contacted to retransmit (after time t_5). While the relays send their estimated CQI value at time t_2, they will only be contacted to send after time t_5. In mobile relays, this time delay may be big enough to cause a major difference between what is reported as CQI_2 and what is eventually transmitted as CQI_5. Hence, by selecting the best relay based on CQI_2 alone, the diversity advantage might not be achieved. To solve the outdated CQI problem, the concept of prediction CQI is being introduced. The goal is to be able to compute a likely value for CQI_5- the relays' CQI at the time the chosen relay will be transmitting its signal. The relay selected is one with the best predicted CQI_5 value. To achieve this goal, the linear and pattern-matching prediction models are considered in the following sections.

5.4.2 Network Algorithm

The transmission of signals from source to destination can either be direct transmission or cooperative transmission depending on whether or not the received signal reaches the threshold SNR value. The system algorithm is given below;

Predictive Relay-Selection (PRS) Cooperative Diversity Algorithm

S – Satellite; R_N – Available Relays; R_B – Selected Best Relay; D – Destination; CBR – Chosen Best Relay; MRC – Maximum Ratio Combining; γ_{sd} – Satellite-Destination SNR; γ_{th} – threshold SNR; $CQI_{predicted}$ – Predicted CQI value.

```
Start
$S$ broadcasts
$D$ and $R_N$ receive signal (and keeps its times series in a buffer)
  If ( $\gamma_{sd} > \gamma_{th}$ ) then
  (use direct transmission)
        $D$ sends $ACK$ to $S$ and $R_N$
        ($R_N$ does nothing in second time slot)
        $S$ sends next signal
  else
  (use cooperative transmission)
        $D$ sends $NACK$ to $S$ and $R_N$
        ($S$ does nothing in second time slot)
        Each $R_N$ evaluates its $CQI_{predicted}$ (using the prediction algorithm)
        Each $R_N$ sends it $CQI_{predicted}$ to $D$
        $D$ chooses best relay $R_B$ with highest $CQI_{predicted}$
        $D$ sends a $CBR$ signal to $R_B$ informing it to send signals
        $R_B$ sends signals
        Signals from $D$ and $R_B$ are combined at $D$ through $MRC$
  End If
End
```

In the next two sub-sections the prediction models employed in this work are briefly considered.

5.5 Linear Prediction Models

The Linear Prediction (LP) models are Auto-Regressive (AR) based prediction methods. They use low order AR models to capture most of the fading dynamics. An example of the LP algorithm is the Minimum Mean Square Error (MMSE) Long Range prediction (LRP) discussed in [60]. Linear models are easy to use and have low complexity, but they may sometimes be prone to error in the prediction of a channel fading process. A linear prediction model forecasts the amplitude of a signal at time m, i.e. $x(m)$, using a linearly weighted combination of M past samples $[x(m-1), x(m-2), \dots, x(m-M)]$ as [65];

$$\hat{x}(m) = \sum_{k=1}^{M} a_k x(m-k) \tag{5.1}$$

where the integer variable m is the discrete time index, $\hat{x}(m)$ is the prediction of $x(m)$, a_k is the predictor coefficient, M is the AR-model order (or number of past samples used in predicting the next sample). The LP is expected to have excellent performance provided that the prediction coefficients can be correctly identified and tracked. The AR prediction coefficients a_k can be computed by several algorithms, e.g. the Levinson-Durbin Recursive algorithm employed in [65]. The LP algorithms; Minimum Mean Square Error (MMSE) and Weighted Least Square Error (WLSE) are used in this work because they have been argued to have the lowest prediction error $e(m)$ [65]. The prediction error is defined as the difference between the actual sample value $x(m)$ and its predicted value $\hat{x}(m)$. The prediction error is given by;

$$e(m) = x(m) - \hat{x}(m) \tag{5.2}$$

$$e(m) = x(m) - \sum_{k=1}^{M} a_k x(m-k) \tag{5.3}$$

5.5.1 Minimum Mean Square Error Linear Prediction (MMSE-LP) Algorithm

This is one of the best ways to determine predictor coefficients. It is obtained by minimizing the mean square error criterion defined as;

$$E[e^2(m)] = E\left[\left(x(m) - \sum_{k=1}^{P} a_k x(m-k)\right)^2\right] \tag{5.4}$$

The least mean square error solution gives the $\boldsymbol{Weiner - Hopf\ equation}$ given by;

$$Ra^{(D)} = r \tag{5.5}$$

where,

$$a^{(D)} = \left[a^{(D)}(1), a^{(D)}(2), \dots, a^{(D)}(M)\right]^T$$

$$r = [R_{xx}(1), R_{xx}(2), R_{xx}(3), \dots, R_{xx}(M)]^T$$

$$R = \begin{bmatrix} R_{xx}(0) & R_{xx}(-1) & R_{xx}(-2) & & R_{xx}(1-M) \\ R_{xx}(1) & R_{xx}(0) & R_{xx}(-1) & \cdots & R_{xx}(2-M) \\ R_{xx}(2) & R_{xx}(1) & R_{xx}(0) & & R_{xx}(3-M) \\ \vdots & & & \ddots & \vdots \\ R_{xx}(M-1) & R_{xx}(M-2) & R_{xx}(M-3) & \cdots & R_{xx}(0) \end{bmatrix}$$

$a^{(D)}$ is the predictor coefficient, r is the autocorrelation vector and R is the autocorrelation function matrix of the input vector $[x(m-1), x(m-2), \dots, x(m-M)]$.

The autocorrelation function R can be found by its expectation function given in by

$$R_{xx}(k) = \frac{1}{M-k}\sum_{k=1}^{M} x(m)x(m-k); \quad for\ k = 1,2,\dots,M \tag{5.6}$$

To solve the above $Weiner - Hopf$ equation for $a^{(D)}$, the Levinson-Durbin Recursive algorithm which makes use of the $Toeplitz$ structure of the matrix R is employed. The algorithm uses the prediction filter coefficient of order $k-1$ to compute the coefficients of the filter of order k for $k = 1\ to\ M$.

The algorithm for MMSE linear prediction is as follows;

Algorithm for Linear Prediction MMSE approach [65]

The algorithm is initialized by setting $\hat{a}_0 = 1,\ P_0 = R_{xx}(0),\ \Delta_0 = R_{xx}(1)$.

For $m = 1\ to\ M$ (where M is the order of prediction)

1. Calculate mth order reflection coefficient given by

$$\Gamma_m = -\frac{\Delta_{m-1}}{P_{m-1}}$$

where P_m is the mth order filter

2. Calculate the coefficients $\hat{a}_{m,k}$ for the mth order prediction-error filter, given by

$$\hat{a}_{m,k} = \hat{a}_{m-1,k} + \Gamma_m \hat{a}^*_{m-1,m-k,} \quad k = 0,1,\dots,m$$

where,

$$\hat{a}_{M,k} = \begin{cases} 1 & k = 0 \\ -a_{M,k} & k = 1,2,\dots,M \end{cases}$$

$\hat{a}^*_{m-1,m-k,}$ is the conjugate of $\hat{a}_{m-1,m-k}$

3. Calculate the Root Mean Square (RMS) error for the mth order filter as

$$P_m = P_{m-1}(1 - |\Gamma_m|^2)$$

4. Calculate Δ_m, given by

$$\Delta_m = r_m^{BT} a_{m-1}$$

where,

$r_m^{BT} = [R_{xx}(m) \quad R_{xx}(m-1) \quad \ldots \; R_{xx}(1)]$ and $R_{xx}(m)$ denotes the autocorrelation function of the sequence $x(m)$ for a lag k.

5.5.2 Weighted Least Square Error Linear Prediction (WLSE-LP) Algorithm

While the MMSE based linear prediction is carried out by minimizing the error in the predicted and actual values of the Root Mean Square error analysis, the WLSE algorithm bases its prediction on minimizing the weighted sum of the error taken for a given set of weights. In this algorithm, new sets of filter coefficients are found at each time $t = m$ and using those coefficients, the value of the coefficient for the next instance of time $t = m + 1$ is predicted. Hence, the coefficients are adaptively changing in order to meet the minimum MLSE criterion. The major advantage of the WLSE algorithm in comparison with the MMSE algorithm is that the autocorrelation function of the input process is not required for the WLSE algorithm. The formula for the WLSE algorithm is given as;

$$\hat{x}(m) = \frac{1}{2}\sum_{i=1}^{M} \alpha_i [a_M^T u(i) - x(i)]^2 \tag{5.7}$$

where $\hat{x}(m)$ is the best linear unbiased estimator, α_i are the weights, a_M^T is the transpose of the coefficient vector and $u(i)$ is the input to the filter at time $t = i$ i.e. $u(i) = [x(m-1)\, x(m-2) \ldots \; x(m-M)]^T$ and $x(m) = a_M^T(m-1)u(m)$. M is the prediction order.

The algorithm for WLSE linear prediction is as follows;

Algorithm for Linear Prediction WLSE approach [65]

The algorithm is started with $a_M = [1,0,0,\ldots,0]^T$ and $P(1) = I$, the $M \times M$ identity matrix. Hence, the next samples of the input process are adaptively estimated.

M is the order of prediction; P is the complex square matrix with every principal minor > 0; α is the forgetting factor chosen to be 0.99

For $m = 2\ to\ \infty$ (prediction starts at time 2 and can extend to any range)

1. Calculate the current predicted output $\hat{x}(m) = a_M^T(m-1)u(m)$

2. Update the coefficient vector

$$a_M(m) = a_M(m-1) + \frac{P(m-1)u(m)}{\alpha + u^T(m)P(m-1)u(m)}[x(m) - \hat{x}(m)]$$

3. Update the P matrix

$$P(m) = \frac{1}{\alpha}\left\{P(m-1) - \frac{P(m-1)u(m)u^T(m)P(m-1)}{\alpha + u^T(m)P(m-1)u(m)}\right\}$$

5.6 Pattern-Matching Prediction Model

The applicability of pattern-matching prediction algorithm in long-term channel quality prediction was investigated in [61] where pattern-based link quality prediction was carried out for Adaptive Coding and Modulation (ACM) in wireless networks. In [62]-[64], the authors developed a pattern-matching based prediction algorithm based on the cross-correlation of present signal estimates with samples of its past measurements. This pattern matching algorithm was referred to as XcoPred (meaning Cross-Correlation Prediction) in [62] and [63]. This prediction algorithm was used in [62] for wireless mobile ad hoc networks (MANET) SNR prediction while it was used in [63] for predicting SNR in mesh networks. In [64], the pattern matching prediction algorithm was used in predicting mobility of nodes in mobile ad hoc networks. The advantage of pattern-matching prediction over other methods of prediction algorithms (like linear prediction which may usually be based on oversimplified assumptions) is that it does not make specific assumptions about the noise, fading or interference process. It rather makes patterns of channel signal of the present from the past and simply assumes that such patterns are repetitive. It therefore predicts the future channel by comparing present and past channels in determining the 'best match' from which the future value(s) of the signals are predicted [61].

The pattern-matching prediction algorithm is given below;

Pattern-Matching Prediction Algorithm

For each available cooperative relay terminal;

1. Take CQI measurements at time interval T_s to form a time series $c_o, c_1, c_2, \dots, c_n, \dots$

where c_n is the CQI estimate at time $(n \times T_s)$

2. Filter the signal samples to eliminate inherent noise. A low pass filter is used to generate the filtered signal given as

   $$s_n = \alpha c_n + (1-\alpha)s_{n-1}$$

   where s_n is the filtered (smoothed) CQI estimate at time $(n \times T_s), \alpha$ is the forgetting factor chosen to be 0.99. Thus, $s_n = s_0, s_1, s_2, \dots, s_n$ for $n = 0,1,2,\dots,n$.This value is then taken as the training data and is stored in a buffer by each receiver (or relay terminal). $s_n = s_0, s_1, s_2, \dots, s_n$ is therefore equivalent to the input signals $[x(m-1), x(m-2), \dots, x(m-M)]$ of the linear prediction algorithms.

3. At query time, collect the query order q and the prediction order p.

4. Form a query or current lag by taking the last q measurements in the training data, i.e.,

   $$query = \{s_{n-q+1}, s_{n-q+2}, \dots, s_n\}$$

5. Form the lags or windows using the remaining part of the training data. Each lag must have the same size as the query order. Hence;

   $$lag\ 1 = \{s_{n-2q+1}, s_{n-2q+2}, \dots, s_{n-q}\}$$
   $$lag\ 2 = \{s_{n-3q+1}, s_{n-3q+2}, \dots, s_{n-2q}\}$$
   $$lag\ 3 = \{s_{n-4q+1}, s_{n-4q+2}, \dots, s_{n-3q}\}$$

   Take all possible lags from the available training data in the buffer up to a lag m to form a series of lags $i; i = 1,2,3,\dots,m$. Lag m is given as

   $$lag\ m = \{s_{n-(m+1)q+1}, s_{n-(m+1)q+2}, \dots, s_{n-mq}\}$$

   m is so chosen as a tradeoff between accuracy of the prediction algorithm and the use of available memory of each relay terminal.

6. Find the normalized cross correlation ρ_i of the current lag with each lag $i; i = 1,2,3,\dots,m$

   The normalized cross-correlation ρ_i formula, given two series $x(i) and\ y(i) where\ i = 1,2,3,\dots,m$ is given as

   $$\rho_i = \frac{\sum_{i=1}^{m}[(x(i)-\bar{x})(y(i)-\bar{y})]}{\sqrt{\sum_{i=1}^{m}(x(i)-\bar{x})^2}\sqrt{\sum_{i=1}^{m}(y(i)-\bar{y})^2}}$$

7. Determined the lag with the highest normalized cross-correlation, $\max(\rho_i)$. This lag with the highest cross correlation is called the match lag.

8. Divide p by q to determine the set (x, y) of the prediction, where x is quotient of the division (and is also the number of lags ahead of the match lag needed to determine the prediction value(s)) and y is the remainder of the division (and is the number of steps in the prediction lag that gives the predicted value(s), the last lag of x being the prediction lag).

9. Return the value(s) in the prediction lag as the predicted CQI value(s).

5.7 Performance Analysis of the PRS Cooperative Scheme

The performance analysis of the PRS cooperative diversity scheme is carried out in this section. The performance metrics considered are outage probability and average bit error rate (BER) as they have been argued to be the most important performance metrics for wireless communication system [66]. These performance metrics are derived in the next two sub-sections.

5.8 Outage Probability

The outage probability has been defined as the probability of the total received signal SNR at destination γ_{MRC} falling below the threshold SNR γ_{th} required for communication. The outage probability of a cooperative diversity network is generally defined as the cumulative distribution density (CDF) of the total received signal γ_{MRC} and is given as [67];

$$P_0 = \int_0^{\gamma_{th}} f_{\gamma_{MRC}}(\gamma) d\gamma = F_{\gamma_{MRC}}(\gamma_{th}) \tag{5.8}$$

where $f_{\gamma_{MRC}}(\gamma)$ is the PDF of the total received signal SNR and $F_{\gamma_{MRC}}(\gamma_{th})$ its CDF.

To obtain γ_{MRC}, the SNR values of both direct and cooperative links have to be considered. Let γ_{sd} be the SNR of the satellite-destination (S-D) link and γ_{srd} the SNR of the selected satellite-relay-destination (S-R-D) link, the instantaneous output SNR for the selected best S-R-D link is given by the formula;

$$\gamma_{srd} = \frac{\gamma_{sr}\gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1} \tag{5.9}$$

where γ_{sr} is the SNR for the satellite-relay (S-R) link and γ_{rd} is the SNR for the selected relay-destination (R-D) link. To find the PDF of the total SNR at destination, the SNR for the cooperative link, i.e. γ_{srd} must be written in a mathematically more tractable form. It has been shown that $\gamma_{srd} \leq \min(\gamma_{sr}, \gamma_{rd})$ where, $\min(x, y)$ is the minimum of x and y [27]. $\min(\gamma_{sr}, \gamma_{rd})$ is thus a tight upper-bound for γ_{srd} and is mathematically more tractable and accurate as well.

The total output SNR at destination after both direct and cooperative links have been combined through MRC is therefore given as;

$$\gamma_{MRC} = \gamma_{sd} + \min(\gamma_{sr}, \gamma_{rd}) \tag{5.10}$$

As one of the main contributions of this research work, the two-state LMS channel is modeled for the different possible combinations of the S-R-D links. The eight scenarios and their different probabilities are given in Table 5.1. The outage probability for the two-state LMS cooperative diversity system is therefore given as;

$$P_o = \sum_{j=1}^{8} [P\{\gamma_{MRC} \leq \gamma_{th}\} P(A_j)] \tag{5.11}$$

where $P(A_j)$ is the probability of scenario A_j occurring and $j = 1,2,..,8$.

Table 5.1 Different Possible Combinations of the S-R-D link

Cooperative link (SRD)	State; G is good, B is Bad	Probability of total (SRD) link being G	State; G is good, B is Bad	Probability of total (SRD) link being B
S-D	G	A_1	G	A_5
R-D	G		G	
S-D	B	A_2	B	A_6
R-D	G		G	
S-D	G	A_3	G	A_7
R-D	B		B	
S-D	B	A_4	B	A_8
R-D	B		B	

5.8.1 Amplify-and-Forward (AF)

The outage probability for the IRS cooperative diversity for LMSS using the Amplify-and-Forward (AF) scheme is defined as;

$$P_o = \sum_{j=1}^{8} \left[P\{\gamma_{sd} \leq \gamma_{th}\} \, P\{\gamma_{sd} + \min(\gamma_{sr}, \gamma_{rd}) \leq \gamma_{th} | \gamma_{sd} < \gamma_{th}\} P(A_j) \right] \tag{5.12}$$

$$P_o = \sum_{j=1}^{8} [P\{\gamma_{sd} + \gamma_{srd} \leq \gamma_{th}\} \, P(A_j)] \tag{5.13}$$

This reduces to;

$$P_o = \sum_{j=1}^{8} [P\{\gamma_{MRC} \leq \gamma_{th}\} \, P(A_j)] \tag{5.14}$$

The PDF of γ_{MRC}, $f_{\gamma_{MRC}}(\gamma)$ is given as;

$$f_{\gamma_{MRC}}(\gamma) = \int_{-\infty}^{\infty} f_{\gamma_{sd}}(\gamma_1) f_{\gamma_{srd}}(\gamma_2) d\gamma_2 \tag{5.15}$$

where $f_{\gamma_{sd}}(\gamma_1)$ is the PDF of the SNR for the S-D link and $f_{\gamma_{srd}}(\gamma_2)$ is the PDF of $\min(\gamma_{sr}, \gamma_{rd})$. The CDF of the SNR for the link, $F_{\gamma_{MRC}}(\gamma)$ is given as;

$$F_{\gamma_{MRC}}(\gamma) = \int_{0}^{\infty} \int_{0}^{\gamma_{th} - \gamma_{srd}} f_{\gamma_{sd}}(\gamma_1) \, f_{\gamma_{srd}}(\gamma_2) d\gamma_1 d\gamma_2 \tag{5.16}$$

Hence, the outage probability P_o becomes;

$$P_o = \sum_{j=1}^{8} [\int_{0}^{\infty} \int_{0}^{\gamma_{th} - \gamma_{srd}} f_{\gamma_{sd}}(\gamma_1) \, f_{\gamma_{srd}}(\gamma_2) d\gamma_1 d\gamma_2 \times P(A_j)] \tag{5.17}$$

The various PDFs and CDFs of the links are calculated next. For the source-destination (S-D) link, the Loo's model (Rayleigh-Lognormal distributions) is employed. The PDF of the S-D link, $f_{\gamma_{sd}}(\gamma_1)$, is given by [49];

$$f_{\gamma_{sd}}(\gamma_1) = \frac{r}{\sigma_1 \sqrt{2\pi d_0}} \int_{0}^{\infty} \frac{1}{z} exp\left[-\frac{(\ln z - \mu)^2}{2d_0} - \frac{(r^2 + z^2)}{2\sigma_1} \right] . I_0\left(\frac{rz}{\sigma_1}\right) dz \tag{5.18}$$

and its CDF is given as;

$$F_{\gamma_{sd}}(\gamma_1) = 1 - \int_0^\infty Q_1\left(\frac{y}{\sqrt{\sigma_1}}, \frac{R}{\sqrt{\sigma_1}}\right)\frac{1}{y\sqrt{2\pi d_0}}\exp\left(-\frac{(\ln \mathrm{y} - \mu)^2}{2d_0}\right)dy \tag{5.19}$$

where σ_1 is the average power of the multipath scattering, μ is the mean of the direct component, d_0 is the variance of the direct component $\ln z$, and $I_0(.)$ is the zeroth order modified Bessel function of the first kind, R is the threshold signal amplitude and $Q_1(a,b) = \int_b^\infty z.\exp\left(-\frac{z^2+a^2}{2}\right).I_0(az)dz$ represents the first-step Marcum function.

For the source-relay-destination (S-R-D) link, the PDF of $\min(\gamma_{sr}, \gamma_{rd})$, i.e., $f_{\gamma_{srd}}(\gamma_2)$ has to be obtained. The link SNR between S-R, γ_{sr} is represented as a Corazza's model (Rician-Lognormal distributions) and the link SNR between R-D, γ_{rd} is represented as Rayleigh distribution. Hence, the PDF of S-R is given as [50];

$$f_{\gamma_{sr}}(\gamma_2) = \frac{r}{\sqrt{2\pi}\sigma_2^2\sigma_3}.\int_0^\infty \frac{1}{y^3} exp\left(-\frac{(r/y)^2+\rho^2}{2\sigma_2^2} - \frac{(\ln y - m_3)^2}{2\sigma_3^2}\right).I_0\left(\frac{r\rho}{y\sigma_2^2}\right)dy \tag{5.20}$$

and its CDF is given as;

$$\begin{aligned} F_{\gamma_{sr}}(\gamma_2) = \frac{2(K+1)}{\sigma_3\sqrt{2\pi}}.\exp(-K)\int_0^R r\int_0^\infty \frac{1}{y^3}\exp\Bigg(&-\frac{(K+1)r^2}{y^2} \\ &- \frac{(ln\, y - m_3)^2}{2\sigma_3^2}\Bigg).I_0\left(\frac{2r\sqrt{K(K+1)}}{y}\right)dydr \end{aligned} \tag{5.21}$$

where σ_0^2 is the average power of the multipath scattering, ρ is the amplitude of the direct component, m_3 is the mean of the direct component and σ_3 is the standard deviation of the direct component and $I_0(.)$ is the zeroth order modified Bessel function of the first kind. The Rician factor K is given as $K = \rho^2/(2\sigma_2^2)$ and the received signal power is normalized i.e. $\rho^2 + 2\sigma_2^2 = 1$.

The PDF of the relay-destination (R-D) link is the Raleigh distribution given as [51];

$$f_{\gamma_{rd}}(\gamma_2) = \frac{r}{\sigma_3^2} exp\left({}^{-r^2}\!\Big/_{2\sigma_3^2}\right) \tag{5.22}$$

and its CDF is given as;

$$F_{\gamma_{rd}}(\gamma_2) = 1 - exp\left(\left. -r^2 \middle/ 2\sigma_3^2 \right.\right) \tag{5.23}$$

where r is the received signal envelop and σ_3^2 is the average power for the multipath scattering. To obtain $f_{\gamma_{srd}}(\gamma_2)$, the law of probability for independent distributions is employed. Let $F_{\gamma_{srd}}(\gamma_2)$ be the CDF of $f_{\gamma_{srd}}(\gamma_2)$. Following statistical analysis for independent distributions, $F_{\gamma_{srd}}(\gamma_2)$ is given as [67];

$$F_{\gamma_{srd}}(\gamma_2) = F_{\gamma_{sr}}(\gamma_2) + F_{\gamma_{rd}}(\gamma_2) - F_{\gamma_{sr}}(\gamma_2)F_{\gamma_{rd}}(\gamma_2) \tag{5.24}$$

$f_{\gamma_{srd}}(\gamma_2)$ is obtained by taking the derivative of its CDF. This gives;

$$f_{\gamma_{srd}}(\gamma_2) = \left(1 - f_{\gamma_{sr}}(\gamma_2)\right)\left(1 - F_{\gamma_{rd}}(\gamma_2)\right) + \left(1 - F_{\gamma_{sr}}(\gamma_2)\right)\left(1 - f_{\gamma_{rd}}(\gamma_2)\right) \tag{5.25}$$

5.8.2 Decode-and-Forward (DF)

The outage probability for the IRS cooperative diversity for LMSS using the Decode-and-Forward (DF) is given as;

$$P_o = \sum_{j=1}^{8} [(P\{\gamma_{sr} \leq \gamma_{th}\}P\{\gamma_{sd} \leq \gamma_{th}\} + P\{\gamma_{sr} > \gamma_{th}\}P\{\gamma_{sr} + \gamma_{rd} \leq \gamma_{th}\}) \times P(A_j)] \tag{5.26}$$

The following statistical analysis is employed to obtain $Pr\{\gamma_{sr} + \gamma_{rd} \leq \gamma_{th}\}$ given that $f_{\gamma_{sr}}(\gamma_1)$ is the PDF of the S-R link and $f_{\gamma_{rd}}(\gamma_2)$ the PDF of the R-D link.

We define X as the sum of the S-R and R-D link, i.e., $X = \gamma_{sr} + \gamma_{rd}$. Then, the CDF of X, $F_X(x)$ is by definition given as;

$$F_X(x) = P\{X \leq \gamma_{th}\} = P\{\gamma_{sr} + \gamma_{rd} \leq \gamma_{th}\} \tag{5.27}$$

Assuming γ_{sr} and γ_{rd}, are independent, then by the definition of conditional probability and statistical independence,

$$F_X(x) = \int_{-\infty}^{\infty} P\{\gamma_{sr} + \gamma_{rd} \leq \gamma_{th} | \gamma_{sr} = \gamma_1\} f_{\gamma_{sr}}(\gamma_1) d\gamma_1 \tag{5.28}$$

Letting $\gamma_{sr} = \gamma_1$,

$$F_X(x) = \int_{-\infty}^{\infty} P\{\gamma_1 + \gamma_{rd} \leq \gamma_{th}\} f_{\gamma_{sr}}(\gamma_1) d\gamma_1 \tag{5.29}$$

By the definition of CDF,

$$P\{\gamma_1 + \gamma_{rd} \leq \gamma_{th}\} = F_{\gamma_{rd}}(\gamma_{th} - \gamma_1)$$

So that;

$$F_X(x) = \int_{-\infty}^{\infty} F_{\gamma_{rd}}(\gamma_{th} - \gamma_1)\, f_{\gamma_{sr}}(\gamma_1) d\gamma_1 \tag{5.30}$$

Also by the relationship between PDF and CDF;

$$f_X(x) = \frac{dF_X(x)}{dx}$$

By substitution, we have;

$$f_X(x) = \frac{d}{dx}\left[\int_{-\infty}^{\infty} F_{\gamma_{rd}}(\gamma_{th} - \gamma_1)\, f_{\gamma_{sr}}(\gamma_1) d\gamma_1\right] \tag{5.31}$$

By Leibnitz's rule for differentiating integrals,

$$f_X(x) = \int_{-\infty}^{\infty} \frac{dF_{\gamma_{rd}}(\gamma_{th} - \gamma_1)}{dx} f_{\gamma_{sr}}(\gamma_1) d\gamma_1 \tag{5.32}$$

By the relationship between a PDF and its CDF;

$$f_{\gamma_{rd}}(\gamma_2) = \frac{dF_{\gamma_{rd}}(\gamma_2)}{d\gamma_2} \times \left(\frac{d\gamma_2}{dx} = 1\right) = \frac{dF_{\gamma_{rd}}(\gamma_2)}{dx}$$

Finally;

$$f_X(x) = \int_{-\infty}^{\infty} f_{\gamma_{rd}}(\gamma_{th} - \gamma_1) f_{\gamma_{sr}}(\gamma_1) d\gamma_1 \tag{5.33}$$

5.9 Bit Error Probability

The average unconditional error probability $P(e)$ of the combined signal at destination (after MRC) for the incremental-relaying (IRS) cooperation (which is also applicable to the PRS cooperation) using either the AF or the DF schemes is given by [27];

$$P(e) = \sum_{j=1}^{8} \left[P(\gamma_{sd} \leq \gamma_{th}) \times P_{coop}(e) + (1 - P(\gamma_{sd} \leq \gamma_{th}) \times P_{dir}(e) P(A_j) \right] \tag{5.34}$$

where γ_{sd} is the instantaneous SNR between S and D, γ_{th} is the threshold SNR, $P_{coop}(e)$ is the average probability that an error occurs in the combined S-R-D link, $P_{dir}(e)$ is the average probability that an error occurs at the direct (S-D) link given that the destination already decided that the relay should not forward source signal, $P(\gamma_{sd} \leq \gamma_{th})$ is the CDF of the S-D link. The conditional error probability $P_{dir}(e|\gamma)$ for the S-D link is defined as;

$$P_{dir}(e|\gamma) = a \times erfc\left(\sqrt{b\gamma_{sd}}\right) \tag{5.35}$$

where (a, b) are constants depending on the type of modulation (for the LMSS in consideration, the modulation scheme employed is the QPSK and its constant values are $a = 0.5, b = 1$), $erfc(x)$ is the complimentary error function defined as;

$$erfc(x) = \left({}^{2}\!/_{\sqrt{\pi}} \right) \int_{x}^{\infty} \exp(-x^2)\, dx \tag{5.36}$$

The average error probability for the S-D link, $P_{dir}(e)$ is therefore given as;

$$P_{dir}(e) = \int_{0}^{\infty} P_{dir}(e|\gamma) f_{\gamma_{sd}}(\gamma|\gamma_{sd} > \gamma_{th}) d\gamma \tag{5.37}$$

where $P_{dir}(e|\gamma)$ is the conditional error probability and $f_{\gamma_{sd}}(\gamma|\gamma_{sd} > \gamma_{th})$is the conditional PDF of γ_{sd} given that γ_{sd} is greater than γ_{th}. The conditional PDF $f_{\gamma_{sd}}(\gamma|\gamma_{sd} > \gamma_{th})$ is easily obtained from the PDF $f_{\gamma_{sd}}(\gamma)$.

5.9.1 Amplify and Forward (AF)

The error probability for the IRS cooperative diversity for LMSS using the Amplify-and-Forward (AF) technique is given as;

$$P(e) = \sum_{j=1}^{8} \left[P(\gamma_{sd} \leq \gamma_{th}) \times P_{coop\_AF}(e) + (1 - P(\gamma_{sd} \leq \gamma_{th}) \times P_{dir}(e) P(A_j) \right] \tag{5.38}$$

where $P_{coop\_AF}(e)$ is the average probability that an error occurs in the combined S-R-D link when AF cooperation is employed. The average error probability $P_{coop\_AF}(e)$ is given as;

$$P_{coop\_AF}(e) \; = a \int_{0}^{\infty} f_{\gamma_{MRC}}(\gamma|\gamma_{sd} \leq \gamma_{th}) erfc(\sqrt{b\gamma}) d\gamma \tag{5.39}$$

where $f_{\gamma_{MRC}}(\gamma|\gamma_{sd} \leq \gamma_{th})$ is the conditional PDF for $f_{\gamma_{MRC}}(\gamma)$ conditioned on $\gamma_{sd} \leq \gamma_{th}$. The conditional PDF $f_{\gamma_{MRC}}(\gamma|\gamma_{sd} \leq \gamma_{th})$ is easily obtained from the PDF $f_{\gamma_{MRC}}(\gamma)$ and the error probability $P(e)$ is obtained after the necessary substitutions carried out.

5.9.2 Decode and Forward (DF)

The error probability for the IRS cooperative diversity for LMSS using the Decode-and-Forward (DF) technique is given as;

$$P(e) = \sum_{j=1}^{8} \left[P(\gamma_{sd} \leq \gamma_{th}) \times P_{coop\_DF}(e) + (1 - P(\gamma_{sd} \leq \gamma_{th}) \times P_{dir}(e) P(A_j) \right] \tag{5.40}$$

where $P_{coop\_DF}(e)$ is the average probability that an error occurs in the combined S-R-D link when DF cooperation is employed. The error probability for the cooperative link using decode-and-forward can be written as;

$$P_{coop\_DF}(e) \; = P_{sr}(e) P_{x}(e) + \left(1 - P_{sr}(e) P_{y}(e)\right) \tag{5.41}$$

where $P_{sr}(e)$ is the probability of error at the relay, $P_{x}(e)$ is the probability of error at destination given that the relay decoded unsuccessfully and $P_{y}(e)$ is the probability of error at destination given that the relay decoded successfully. The probability of error at the relay $P_{sr}(e)$ is given as;

$$P_{sr}(e) = a \left(1 - \sqrt{\frac{b\bar{\gamma}_{sr}}{1 + b\bar{\gamma}_{sr}}} \right) \tag{5.42}$$

If there is a decision error at the relay, the relay forwards an erroneous signal to the destination. The error probability due to error propagation $P_{x}(e)$ has been bounded with the worst value $P_{x}(e) < 0.5$ [27].

In the case of spatial diversity being achieved (i.e., the relay decodes correctly), there is still a probability of an error occurring at the destination and that probability is given by $P_{y}(e)$. The probability $P_{y}(e)$ is given as;

$$P_y(e) = \int_0^{\infty} f_X(x|\gamma_{sd} \leq \gamma_{th}) erfc(\sqrt{bx}) dx \qquad (5.43)$$

where $f_X(x|\gamma_{sd} \leq \gamma_{th})$ is the conditional PDF for $f_X(x)$ conditioned on $\gamma_{sd} \leq \gamma_{th}$. The conditional PDF $f_X(x|\gamma_{sd} \leq \gamma_{th})$ is easily obtained from $f_X(x)$.

5.10 Results and Discussion

The results of the Predictive Relay Selection (PRS) cooperative diversity in comparison with the direct communication and outdated cooperation communication models are presented in this section. Using the parameters given for the LMSS fading model in chapter 3 and by varying the SNR thresholds, the plots of the performance in terms of outage probability P_0 and bit error probability for the cooperative diversity schemes are presented. For the simulation, ten (10) relays were assumed to be available within the destination terminal's interference range out of which a single best was selected. The parameters for the two-state transition and probability matrixes as well as parameters for urban and rural areas at elevation angle 60^0 as given in [43] were used in generating the faded signal. The extensive performance results presented in this work features the three prediction algorithms considered compared with the outdated and non-cooperation (direct) communication for the rural and urban environment types. All these were investigated with regards to the average output SNR, outage probability and the average bit error probability. The developed analytical model was also validated by simulation. While several results were obtained, for brevity, only the most significant results are presented in this chapter.

The result of output SNRs averaged over time for direct communication, cooperative communication with oudated CQI and the cooperative communication with predictive CQI using the MMSE linear prediction algorithm is shown in Fig. 5.2. The result shows that the average output SNR for the direct communication is an approximately constant value over time duration. For the cooperative communications (either outdated or predicted), the average output SNR first increases with time until it reaches an approximately constant peak value. It can be seen that for both rural and urban environment types, both cooperative communication outperforms the direct communication giving larger values of average output SNR. This is because the cooperative systems employ an extra relay in generating its average SNR whenever the original SNR of the satellite-destination link falls below the threshold SNR value. Also, the predictive cooperative diversity protocol gives a greater average output SNR than the outdated cooperative diversity protocol because of the better choice of its best relay selected for cooperation. The better performance of the predictive scheme can be very significant for most communication systems, and especially the LMSS. Similar results and explanation hold for the WLSE Linear Prediction model and the Pattern-Matching Prediction model as shown in Fig. 5.3. and Fig. 5.4. respectively. A comparison of the output SNR for the three prediction schemes is presented in Fig. 5.5. for both rural and urban environments and it shows that the WLSE prediction performs the best. Results presented in Fig. 5.3 to Fig. 5.5. are all from the Amplify-and-Forward (AF) Cooperative scheme. The comparison of the output SNR for the three predictive cooperative schemes using Decode-and-Forward (DF) is shown in Fig. 5.6. Similarly, the WLSE prediction outperforms both the MMSE linear prediction and the pattern-matching prediction schemes for both the rural and the urban environment types.

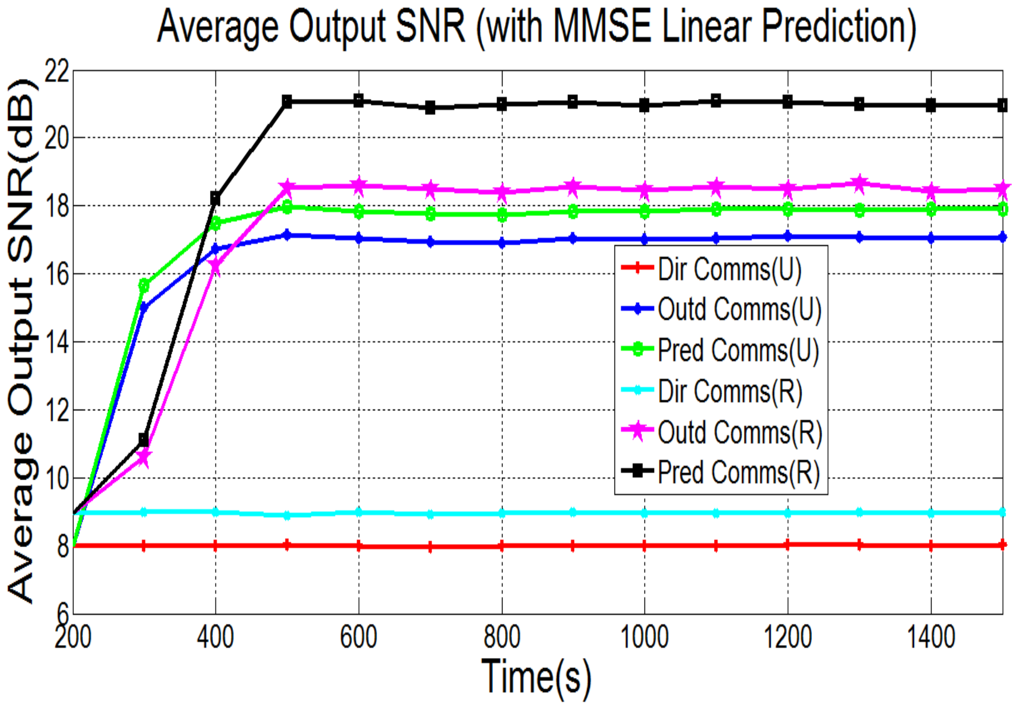

Fig.5.2. Output SNR for the Direct (Dir), Outdated Cooperative (Outd) and MMSE Predictive Cooperative (Pred) Communication. (R) is rural, (U) is urban

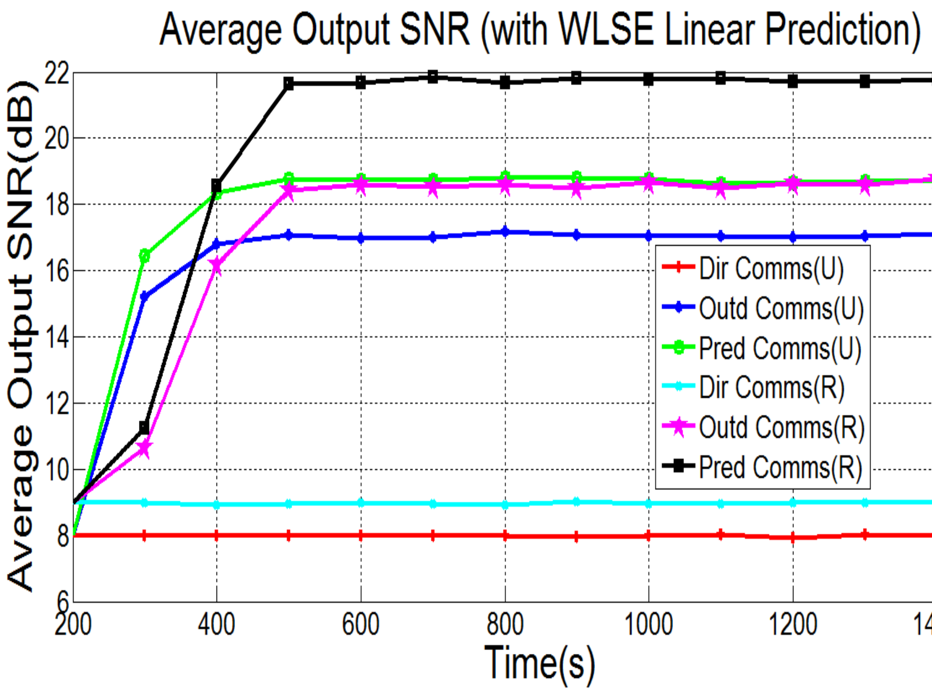

Fig.5.3. Output SNR for the Direct (Dir), Outdated Cooperative (Outd) and WLSE Predictive Cooperative (Pred) Communication. (R) is rural, (U) is urban

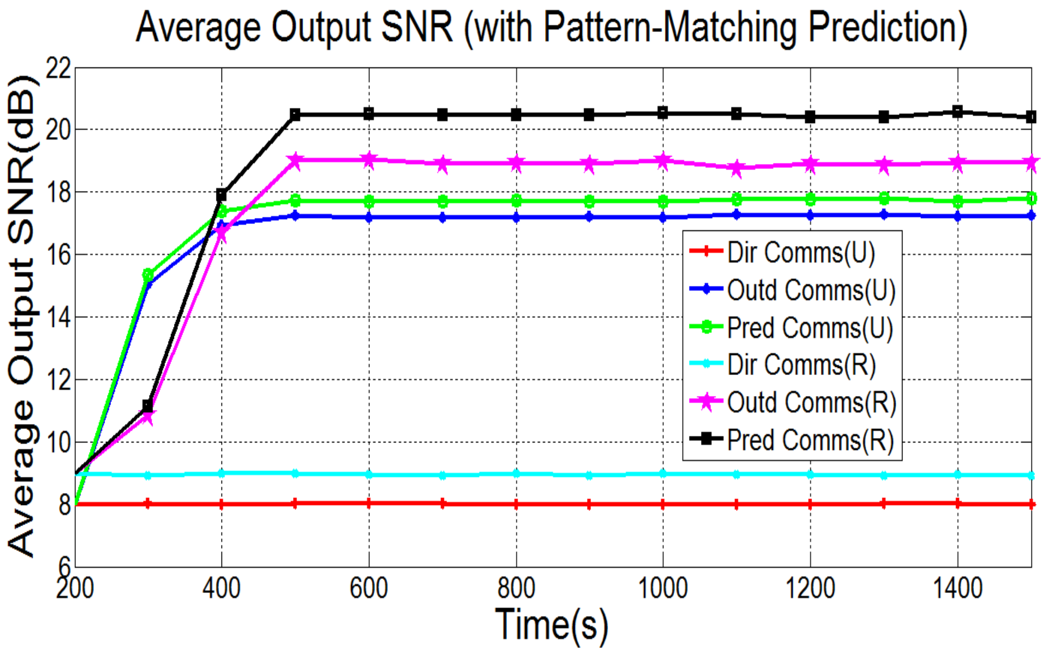

Fig.5.4. Output SNR for the Direct (Dir), Outdated Cooperative (Outd) and Pattern-Matching Predictive Cooperative (Pred) Communication. (R) is rural, (U) is urban

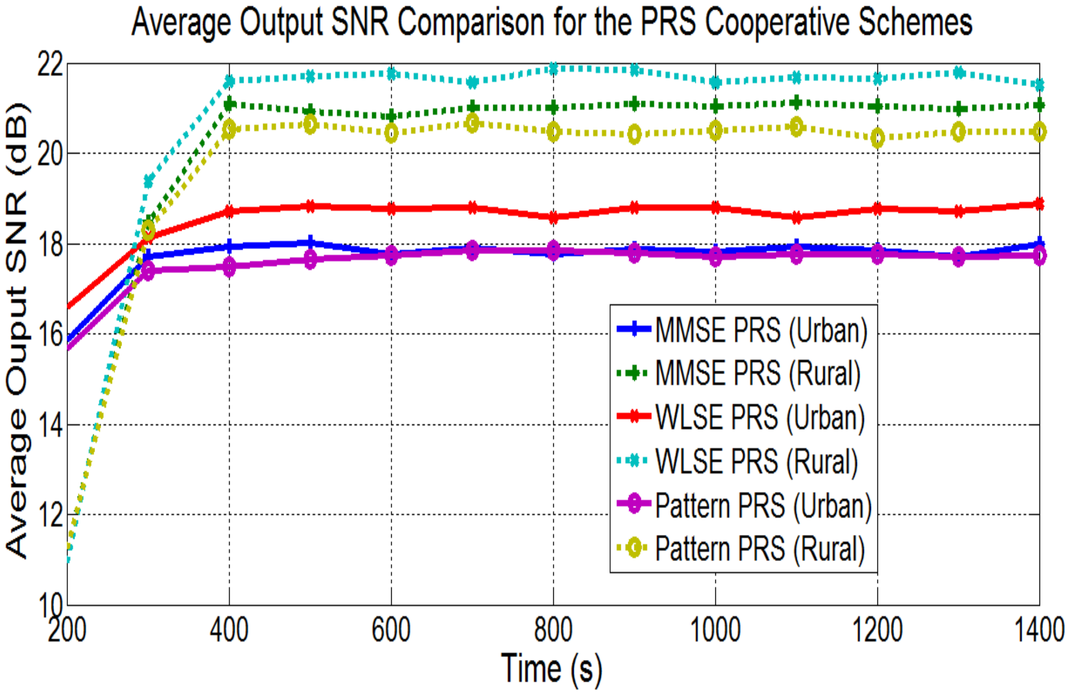

Fig.5.5. Comparison of the PRS Cooperative Schemes for the Urban and Rural environment types (Amplify-and-Forward)

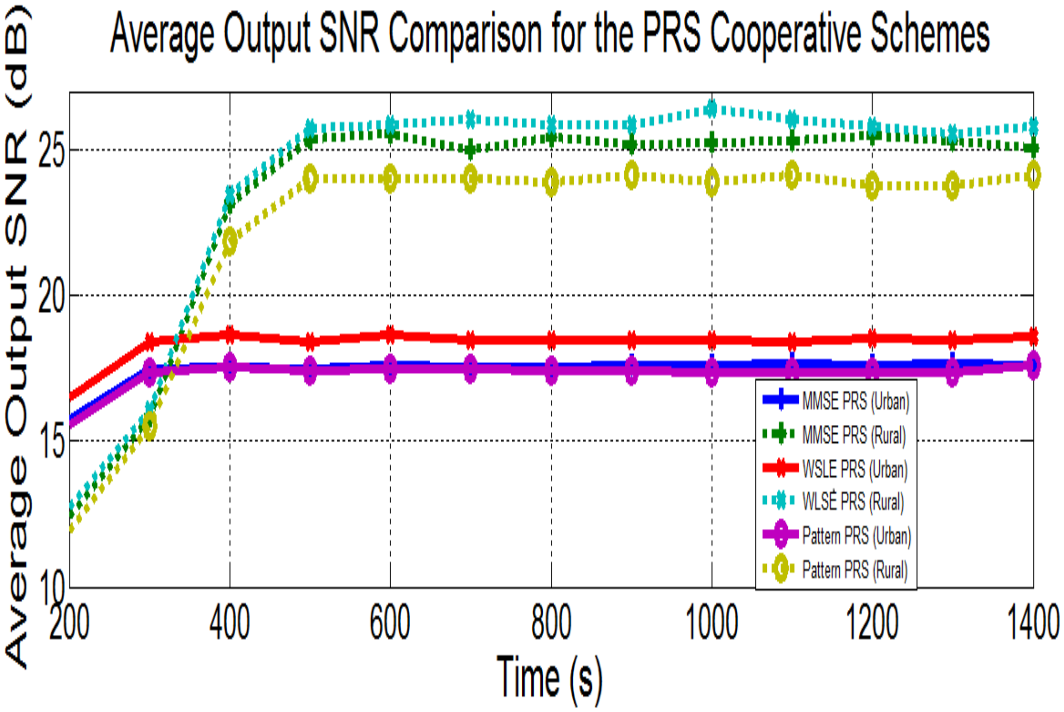

Fig.5.6. Comparison of the PRS Cooperative Schemes for the Urban and Rural environment types (Decode-and-Forward)

The results of the outage probability (P_0) versus threshold SNR of the three predictive relay-selection (PRS) cooperative communications are shown in Fig. 5.7. and Fig. 5.8. for Amplify-and-Forward (AF) and Decode-and-Forward (DF) schemes respectively. The results show that the outage probability generally increases with an increasing threshold SNR. The results also indicate that the developed analytical model is well matched and validated by the simulation. At thresholds below 14dB, the outage probability is very low (approximately zero). At thresholds between 16dB and 21dB, the outage probability gradually increases until it reaches unity and saturates. The reason is that at a higher threshold SNR demand for a given communication QoS, the likelihood of an outage is usually more prominent. The WLSE linear prediction model outperforms the other prediction models for both the AF and the DF schemes.

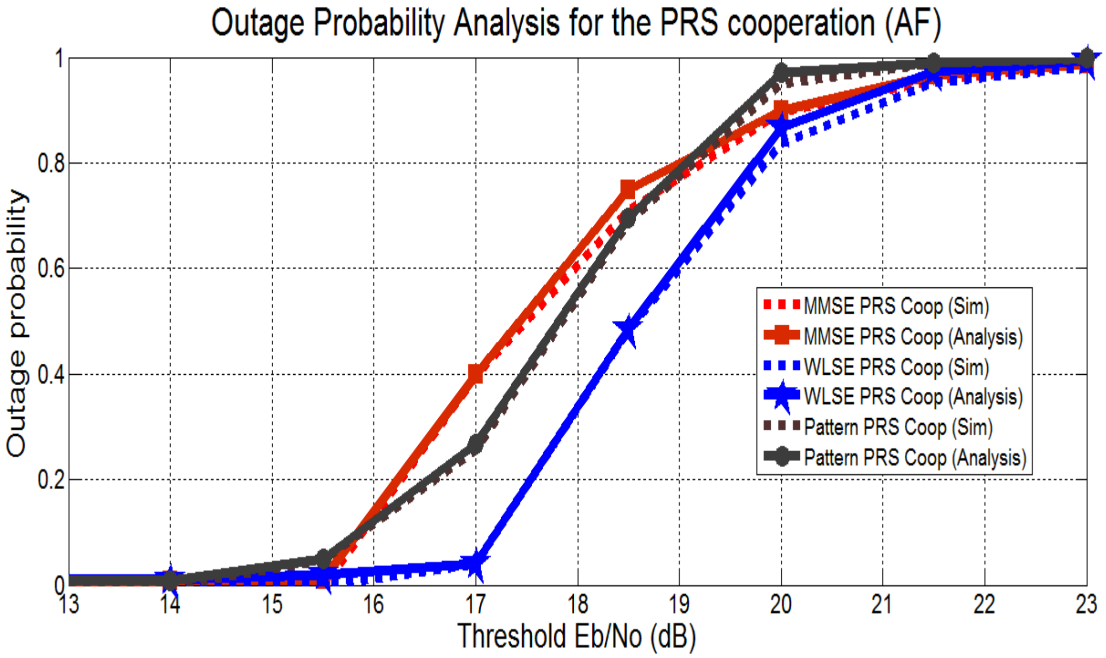

Fig.5.7. Simulation vs Analysis of the outage probability for the PRS cooperative models using Amplify-and-Forward

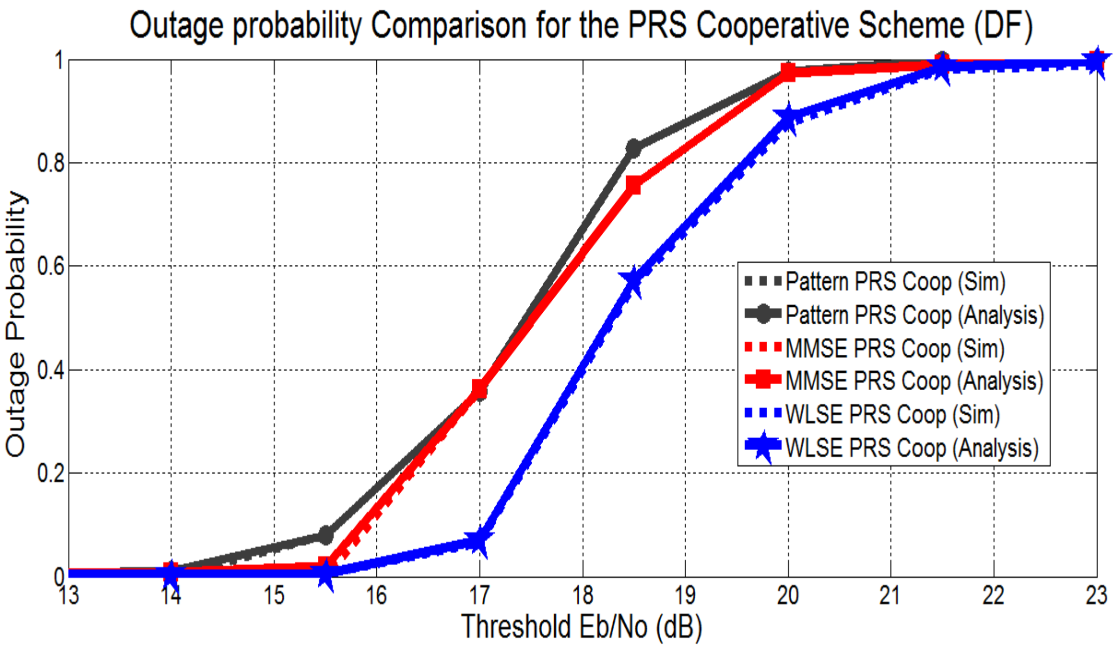

Fig.5.8. Simulation vs Analysis of the outage probability for the PRS cooperative models using Decode-and-Forward

The results of the average bit error probability versus average SNR (E_b/N_o in dB) of the three predictive relay-selection (PRS) cooperative communications are shown in Fig. 5.9. and Fig. 5.10. for Amplify-and-Forward (AF) and Decode-and-Forward (DF) techniques respectively. The results show that the bit error probability generally reduces with an increasing average SNR value. The developed analytical model is also well matched and validated by the simulation. From the results, it could be deduced that the WLSE linear prediction model also outperforms the other prediction models for both the AF and the DF cooperative techniques.

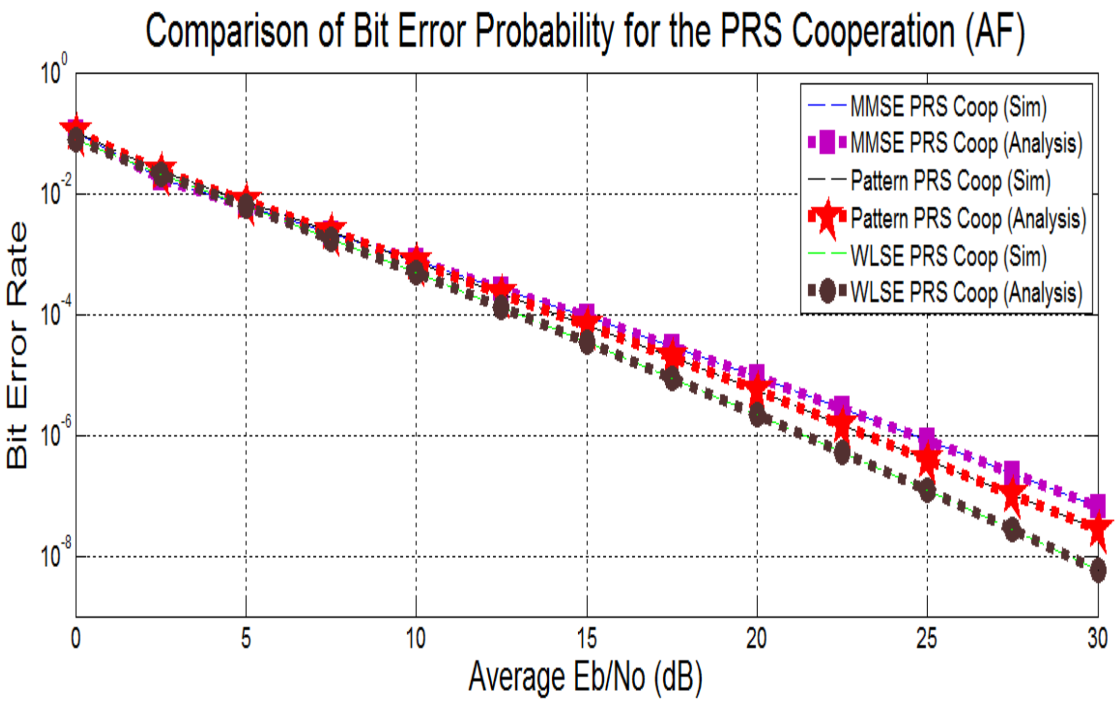

Fig.5.9. Simulation vs Analysis of the bit error probability for the PRS cooperative models using Amplify-and-Forward (AF)

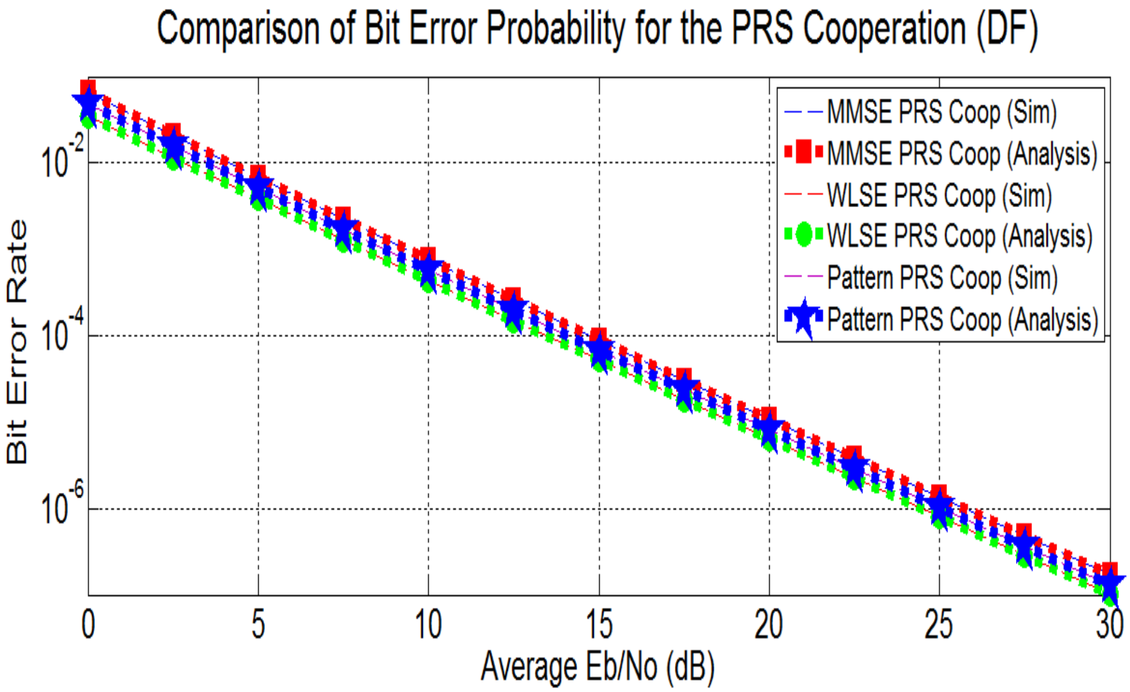

Fig.5.10. Simulation vs Analysis of the bit error probability for the PRS cooperative models using Decode-and-Forward (DF)

From the outage probability and the bit error probability results, it can be concluded that the WLSE predictive cooperation is the best predictive model for LMSS cooperative diversity.

The outage probability comparison for the cooperative communication and direct communication (non-cooperation) is shown in Fig. 5.11. to Fig. 5.13. Both predictive cooperation and outdated cooperation are considered for all three predictive algorithms studied. The results generally show that outage probability increases with an increasing threshold SNR. From the results, it is observed that the outage experienced during cooperative communication is significantly less than the outage experienced for direct communication (for instance, at a threshold 10dB, while the direct communication outage probability is above 0.9, the cooperative communication outage probability was still 0). This is expected as the cooperative system gives an average SNR value greater than the direct system at every instance. Furthermore, all PRS cooperative diversity protocols outperformed the relay-selection cooperation with outdated CQI. This result is significant in that it confirms that the relay-selection cooperation using outdated CQI cannot always guarantee the intended quality of service and that the PRS cooperation gives a higher diversity advantage.

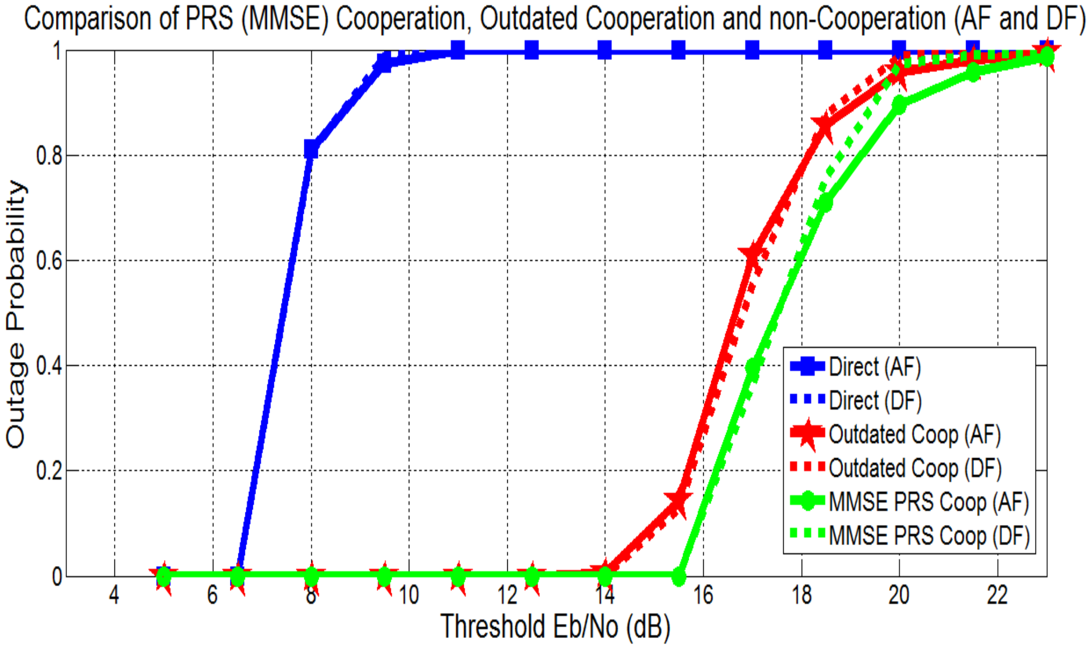

Fig.5.11. Outage probability comparison of the PRS (MMSE) cooperation with outdated cooperation and direct communication

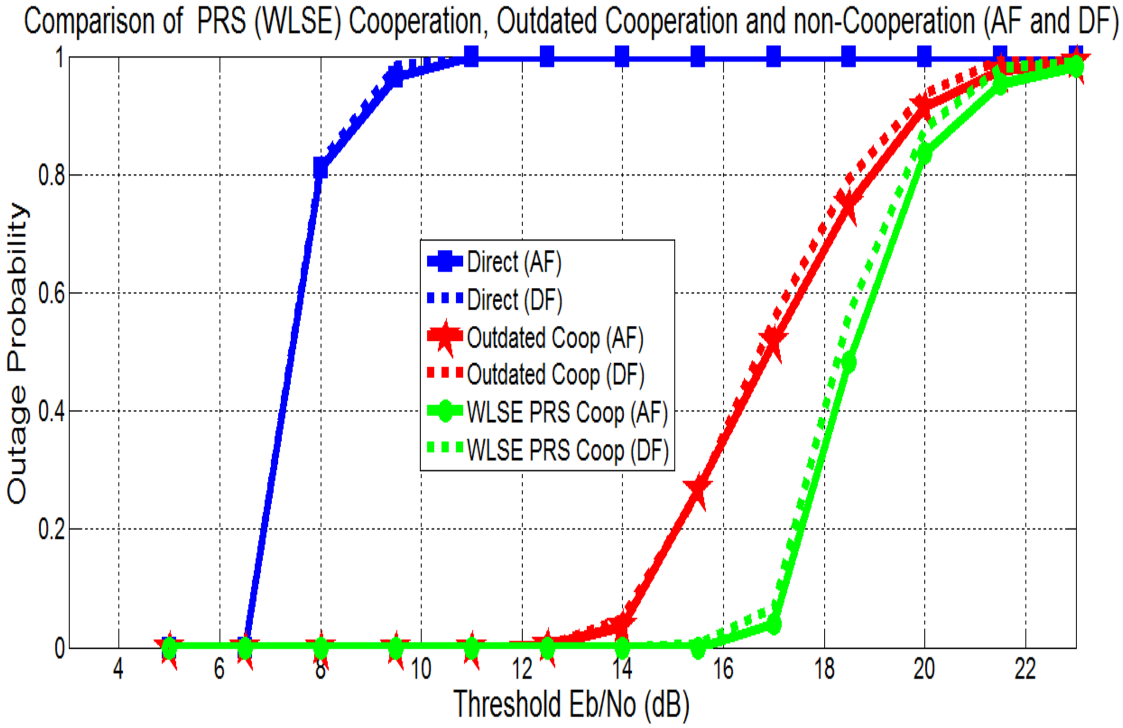

Fig.5.12. Outage Probability comparison of the PRS (WLSE) cooperation with outdated cooperation and direct communication

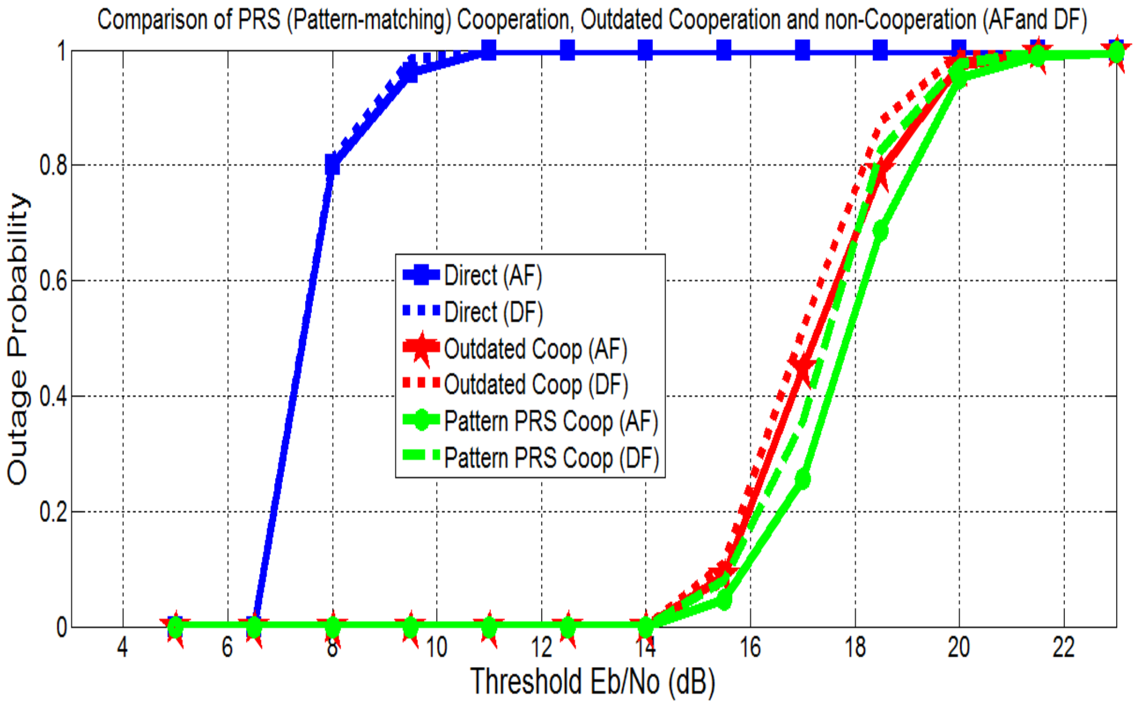

Fig. 5.13. Outage probability comparison of the PRS (Pattern-matching) cooperation with outdated cooperation and direct communication

The bit error rate (BER) plots of the PRS cooperation, outdated cooperation and direct communication are compared in Fig. 5.14. to Fig. 5.16. for both the AF and DF cooperative schemes. The results show that the bit error rate (BER) generally decreases with an increasing average SNR value. Similar to the results for the outage probability, the three PRS cooperative schemes outperformed both the direct communication as well as the cooperation with outdated CQI.

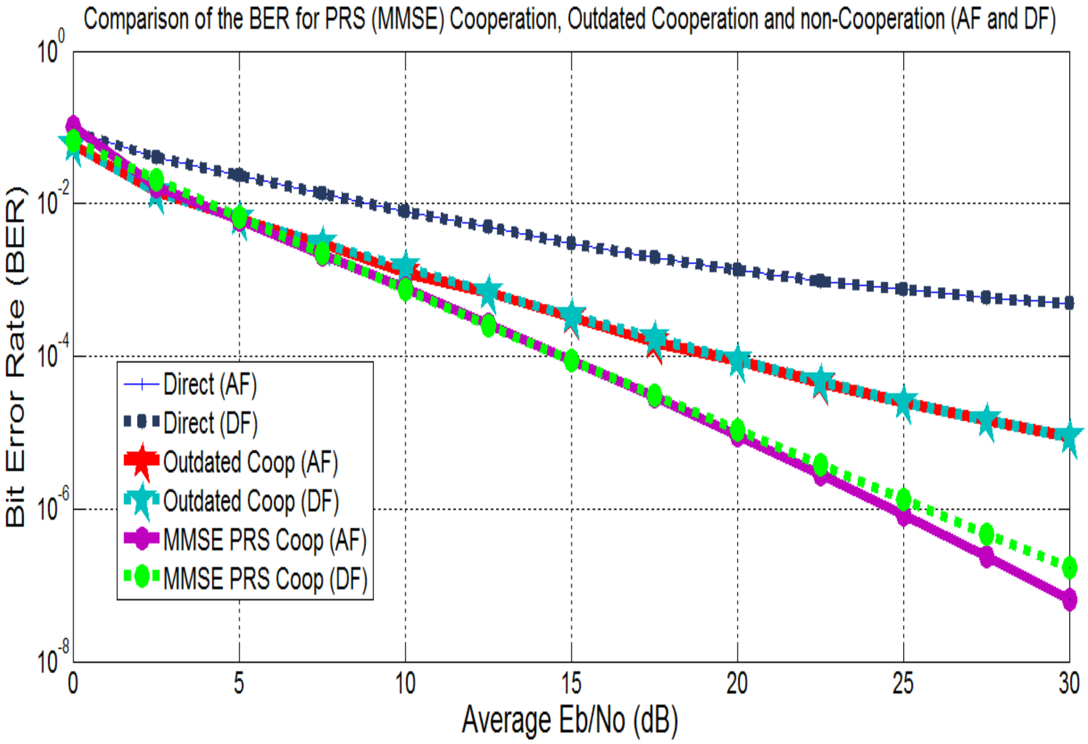

Fig.5.14. Bit error probability comparison of the PRS (MMSE) cooperation with outdated cooperation and direct communication

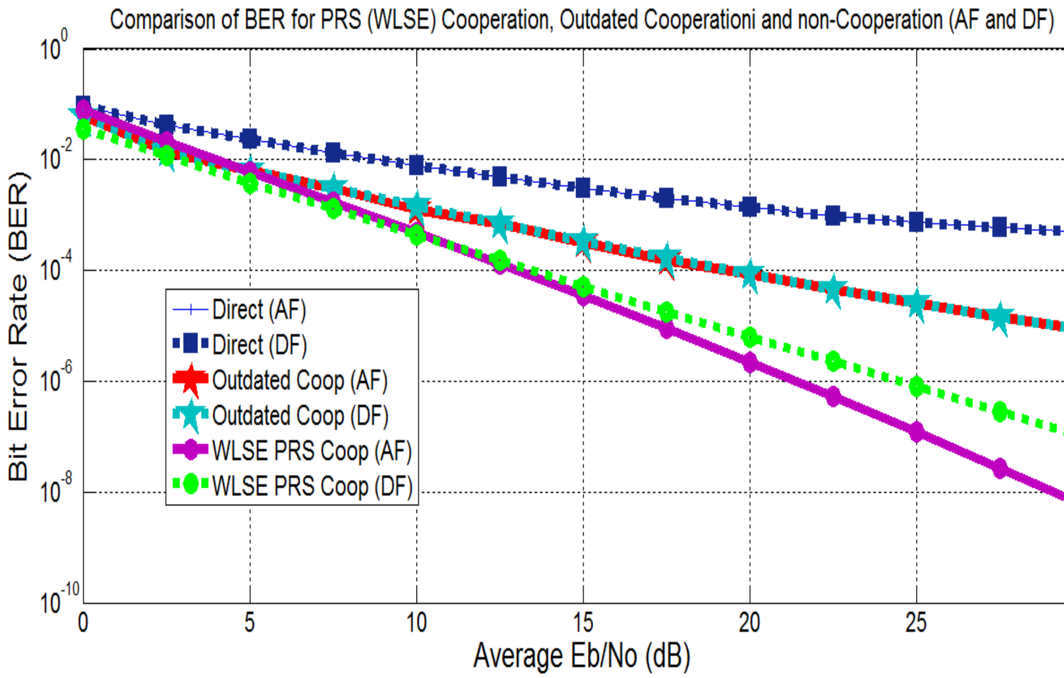

Fig.5.15. Bit error probability comparison of the PRS (WLSE) cooperation with outdated cooperation and direct communication

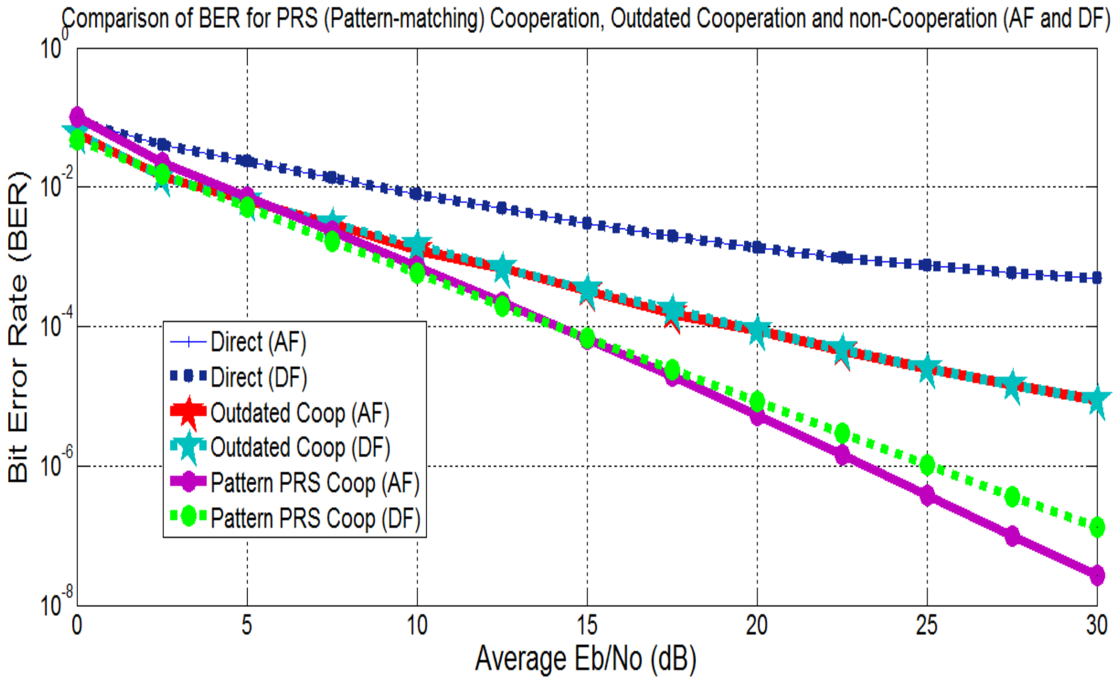

Fig.5.16. Bit error probability comparison of the PRS (Pattern-Matching) cooperation with outdated cooperation and direct communication

From the outage probability and bit error probability results, it can be easily concluded that the PRS cooperative diversity performs better than either direct communication (non-cooperation) or cooperation with outdated cooperative diversity.

Finally, the performance of the three PRS cooperative schemes for two different environment types (rural and urban which gives the extreme cases of environment types) is investigated. The results of the outage probability and the bit error probability are shown in Fig. 5.17. and Fig. 5.18. respectively. The results show that both outage probability and bit error probability are generally better for the rural environment than for the urban environment. This is because the fading effects are higher in the urban than in the rural environment, thus making the probability of an outage in the urban environment greater. The WLSE linear prediction algorithm showed best performance in terms of outage probability and bit error probability (for both AF and DF schemes) as compared to the MMSE linear prediction and the pattern-matching prediction schemes in both environment types. The reason for the best performance of the WLSE linear prediction is that it adaptively changes its coefficients in order to meet the minimum WLSE criterion. In computational complexity however, the pattern-matching prediction model is a lot less easy than the linear prediction models in that it simply makes patterns from past measurements and makes prediction based on these past measurements.

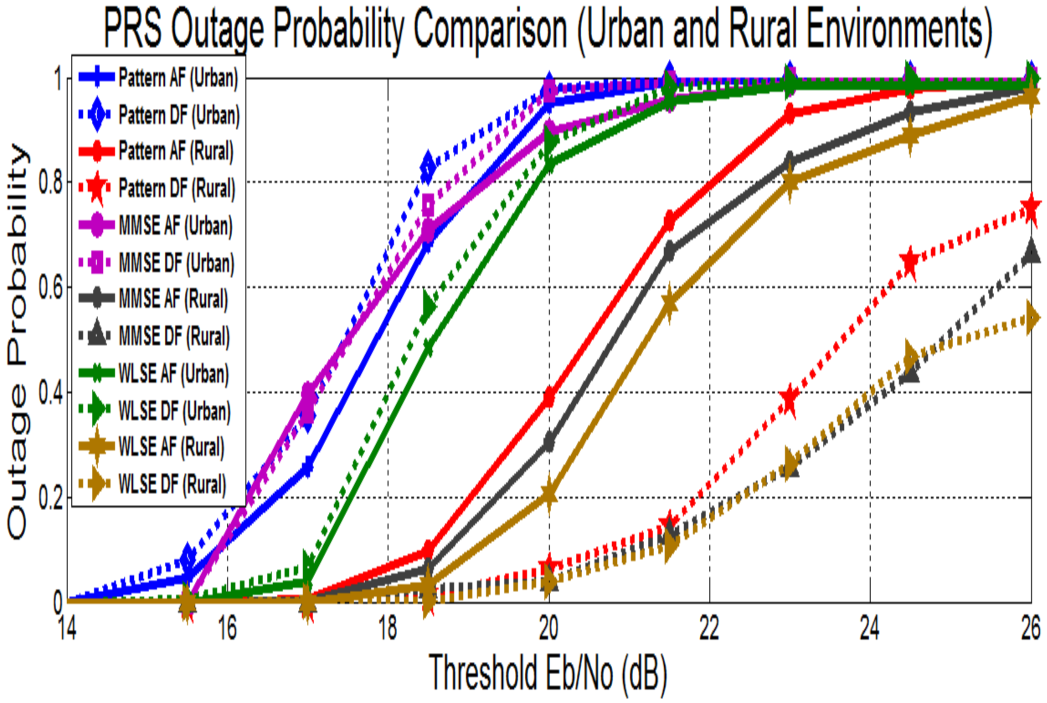

Fig.5.17. Outage Probability comparison of the PRS cooperative diversity schemes for rural and urban environments

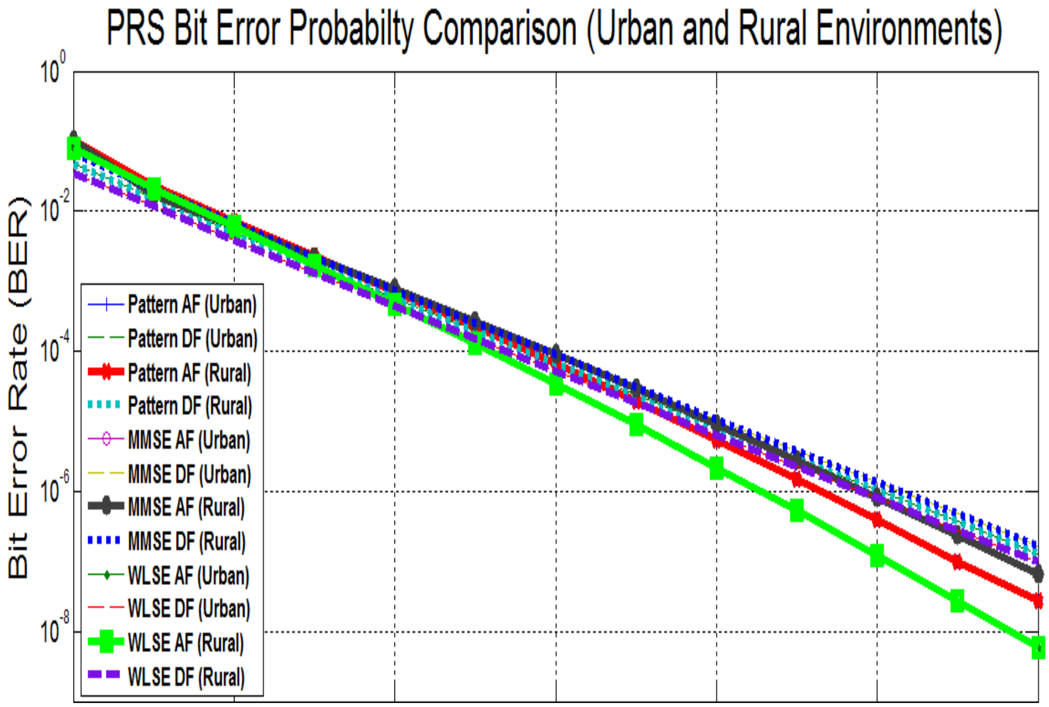

Fig.5.18. Bit Error Probability comparison of the PRS cooperative diversity schemes for rural and urban environments

Some important conclusions can be drawn from the results and discussions so far provided in this chapter for the novel PRS cooperative diversity scheme. These conclusions are summarized as follows:

a) The average SNR values delivered by cooperative diversity systems for the LMSS are much higher than for direct communication. The predictive relay-selection (PRS) cooperative diversity gives higher values than the outdated cooperative diversity.
b) Outage probability generally increases with an increasing threshold SNR value. The outage probability of the PRS cooperation performed better than both the direct communication and outdated cooperation.
c) Bit error probability generally decreases with an increasing average output SNR value. The bit error probability of the PRS cooperation performed better than both the direct communication and the outdated cooperation.
d) From the results of average SNR, outage probability and bit error probability, it can be concluded that the PRS cooperation helps in overcoming the challenge of outdated channel quality information and guarantees better performance for the LMSS.

e) WLSE PRS cooperation gave the best performance of the three predictive schemes considered and is thus recommended for implementation in the LMSS.
f) In terms of computation complexity of the predictive models, the pattern-matching prediction model is the easiest to compute. The choice between accuracy and ease of implementation for the PRS cooperative scheme has to be carefully decided.

5.11 Conclusion

The effects caused by the mobility of the relay terminals and also the long propagation delay are a major limitation to the effectiveness of cooperative diversity in LMSS communication. In this chapter, a novel predictive relay-selection (PRS) cooperative diversity scheme for LMSS was developed to curtail the effect of user mobility and long propagation delay. Prediction models were employed in determining the future channel qualities of the available relay terminals to determine the best relay for selection. Linear prediction and pattern-matching prediction models were selected for the LMSS cooperation because of their long-range predictability as well as the low complexity in their algorithms' implementation.

Furthermore, analytical models of performance for the predictive relay-selection (PRS) cooperative diversity scheme for LMSS in terms of the outage probability and bit error probability were developed. The analytical results obtained show a good match to results obtained from simulations thus confirming the accuracy of the analysis. In all results, the predictive cooperation outperformed the outdated cooperation both in the rural and the urban areas considered. Also, the WLSE predictive cooperative scheme gave the highest performance amongst the prediction models that were considered in AF and DF cooperation as well as in rural and urban environment types.

CHAPTER 6

CONCLUSION AND FUTURE WORKS

6.1 Conclusion

This research work had focussed on investigating the advantages of cooperative diversity as applicable to the Land Mobile Satellite Systems (LMSS). The aim of bringing cooperation to the LMSS had primarily been to help improve quality of service for the LMSS communications even in the face of unpredictable service conditions and fading characteristics. The unpredictability is mostly felt in urban environments where obstructions in form of tall buildings and heavy traffic are a common sight. During cooperative communication, selected relay terminal(s) close to the destination terminal help in sending the signal from the source (and in this case, the satellite) thereby making up for a likely shortfall at the destination terminal's received signal. Several results obtained from the various cooperative diversity schemes employed proved that the LMSS communication can be greatly improved through cooperative diversity.

In Chapter 2, a literature survey on cooperative diversity techniques and schemes was carried out. Various techniques like the amplify-and-forward (AF), decode-and-forward (DF), coded-cooperation (CC) were discussed and reviewed. Their characteristics and practical applications were briefly highlighted. Similarly, various relay-selection cooperative schemes like opportunistic relay-selection (ORS) and incremental relay-selection (IRS) were discussed with their advantages and disadvantages mentioned. The challenges of cooperative diversity were highlighted. The chapter also included a review of the applicability of cooperative diversity in LMSS channel as several issues of the LMSS were mentioned.

In chapter 3, the feasibility of cooperative diversity in Land Mobile Satellite Systems (LMSS) was carried out. This was done by using an appropriate LMSS channel model (two-state Markov model for LMSS was used in this study). The incremental relay-selection (IRS) cooperative scheme was employed for the LMSS because of its obvious reduction in channel resource demands. Using parameters for a two-state Markov model for LMSS as obtained in the literature, the store-and-forward (SF) technique was investigated. The results obtained are also comparable to the amplify-and-forward (AF) technique by simply assuming an amplification factor of one. The results showed great improvement in the quality of service (QoS) for the LMSS as compared to either the direct communication alone or communication using single faded channels.

In chapter 4, the IRS cooperative diversity communication is extended to the decode-and-forward (DF) cooperative technique. The DF technique also showed great improvement in the quality of service (QoS) for the LMSS as compared to either the direct communication alone or cooperative communication using single faded channels. From the results obtained in chapter 3 and chapter 4, it is therefore safe to conclude that in investigating and implementing cooperative diversity in LMSS, it is essential to use appropriate channel models as this gives a better picture of the complexities, practicality as well as the advantages the cooperative system can give as compared to the direct communication. Furthermore, both AF and DF cooperative techniques give a better performance than the direct communication, irrespective of the environment type being considered. Cooperative diversity is therefore recommended for consideration in future LMSS architecture and design.

Chapter 5 has the most important contributions of this research work. A major part of chapter 5 was first dedicated to investigating the challenge of (and probable solution to the challenge of) long propagation delay for the LMSS. This problem is further compounded by the fact that the channel is experiencing a constantly changing faded pattern. In investigating relay-selection cooperation for LMSS therefore, it was important to consider how this affects the choice of the 'best' relay(s) selected for cooperation. It became obvious that the delay in propagation and the inconsistent fading condition of the LMSS generally results in an imperfect (or outdated) channel quality of the relay terminals. This problem (generally referred to the problem of outdated channel quality information) had to be combated if the advantages of cooperative diversity as already investigated have to be sustained. To mitigate the problem of outdated channel quality information therefore, a novel cooperative diversity scheme referred to as Predictive Relay-Selection (PRS) cooperation was developed. In the developed PRS cooperative scheme, prediction algorithms were introduced into the system model, whereby the future channel quality information of each relay is determined beforehand. The relay with the highest predicted value of channel quality is selected for cooperation. Several already established prediction models like the linear prediction model and the pattern-matching prediction model were employed in the PRS cooperative scheme to determine which prediction model is optimal.

In the concluding part of the chapter 5, several results of the new PRS cooperative scheme were analysed and also simulated for validation. The results of the PRS cooperative scheme were compared with results from both cooperation with outdated channel quality information and non-cooperation (direct communication). The performance comparisons between direct communication and cooperative communication generally showed that remarkable gain in service quality is obtained when cooperative communication is used for LMSS than is obtainable when direct communication alone is employed. Better still, the predictive cooperative (PRS) communication also performed better than the outdated cooperative communication, making the proposed predictive relay-selection (PRS) cooperative diversity scheme a significant contribution to the cooperative diversity works. The WLSE predictive relay-selection cooperative scheme was recommended for the LMSS because it gave the best performance.

Finally, it is important to conclude that the proposed PRS cooperative diversity satellite communication model would be most applicable for web browsing, email access, broadband internet access, vehicle location tracking, mobile TV, et cetera.

6.2 Future Work

Bringing cooperative diversity into LMSS communications is still an on-going research area. With the feasibility studied and several physical layer performance metrics analysed, further work can focus on the MAC layer performance criteria. Also, helps with practical implementation of cooperative diversity into existing LMSS architecture are a much welcomed development. Furthermore, the novel predictive relay-selection (PRS) cooperative scheme is a nascent cooperative communication scheme really opened to be explored. The PRS cooperative diversity system model can still be greatly improved upon. First, the effects of the time difference between the times of estimation of received signal by the relays to the times of transmission of signal from relays to destination can be further analysed. This is currently being worked upon. Similarly, there are other types of prediction models other than the linear prediction and the pattern-matching prediction models that were not analysed in this work. These other prediction models can also be studied for the LMSS. A further comparison in performance of several other prediction models could result in even better performance of the PRS cooperative diversity scheme. Finally, other cooperative diversity schemes like coded-cooperation (CC) can be investigated for the PRS cooperative diversity model and their performances compared.

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