Header Compression and Signal Processing for Wideband Communication Systems

BY:

RAFI –US –SHAN

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ABSTRACT

This thesis is dedicated to the investigation, development and practical verification of header compression and signal processing techniques over TErrestrial Trunked RAdio (TETRA), TETRA Enhanced Data Services (TEDS) and Power Line Communication (PLC). TETRA release I is a narrowband private mobile radio technology used by safety and security organizations, while TEDS is a widebandsystem. With the introduction of IP support, TEDS enables multimedia based applications and services to communicate across communication systems. However the IP extension for TEDS comes at a cost of significant header contributions with the payload. With small application payloads and fast rate application traffic profiles, the header contribution in the total size of the packet is considerably more than the actual application payload. This overhead constitutes the considerable slot capacity at the physical layer of TEDS and PLC. Advanced header compression techniques such as Robust Header Compression (RoHC) compress the huge header sizes and offer significant compression gain without compromising quality of service (QoS). Systems can utilize this bandwidth to transmit more information payload than control information. In this study, the objective is to investigate the integration of RoHC in TEDS and design a novel IPv6 enabled protocol stack for PLC with integrated RoHC. The purpose of the study is also to investigate the throughput optimization technique such as RoHC over TEDS and PLC by simulating different traffic profile classes and to illustrate the benefit of using RoHC over TEDS and PLC. The thesis also aims to design and simulate the TEDS physical layer for the purpose of investigating the performance of higher order modulation schemes. Current TEDS, standards are based on the transmission frequencies above 400MHz range, however with delays in the standardization of broadband TETRA, it is important to explore all possible avenues to extend the capacity of the system.

The research concludes the finding of the application of RoHC for TEDS and PLC, against different traffic classes and propagation channels. The benefit of using RoHC in terms of saving bandwidth, slot capacity and other QoS parameters is presented along with integration aspects into TEDS and PLC communication stacks. The study also presents the TEDS physical layer simulation results for modulation schemes and transmission frequency other than specified in the standard. The research results presented in this thesis have been published in international symposiums and professional journals. The application of the benefits of using RoHC for TEDS has been proposed to the ETSI TETRA for contribution to the TETRA standard under STF 378. Simulation results for the investigation of characteristics of $\pi/4$ DQPSK performance below 200 MHz have also been also presented to ETSI TETRA as a contribution to the existing TEDS standard. The Results presented for the design of IPv6 enabled stacked with integrated RoHC have been submitted as deliverable under the FP-7 project DLC+VIT4IP. All the results, simulations and investigations presented in the thesis have been carried out through the platform provided by HW Communication Ltd.

DECLARATION

These doctorial studies were conducted under the supervision of Prof. Bahram Honary and Dr. Hassan Ahmed. The work presented in this thesis has been carried out in the School of Computing and Communication Systems at Lancaster University between October 2008 and October 2012, is my own work except otherwise stated. This work has not been submitted for any other degree or award in any other university or educational establishment.

Rafi us Shan

October, 2012

DEDICATION

Allah - there is no deity except Him, the Ever-Living, the Sustainer of [all] existence. Neither drowsiness overtakes Him nor sleep. To Him belongs whatever is in the heavens and whatever is on the earth. Who is it that can intercede with Him except by His permission? He knows what is [presently] before them and what will be after them, and they encompass not a thing of His knowledge except for what He wills. His Kursi extends over the heavens and the earth, and their preservation tires Him not. And He is the Most High, the Most Great.

[2:255]

Alif, Lam, Ra; a Book which We have revealed to you, [O Muhammad], that you might bring mankind out of darkness into the light by permission of their Lord - to the path of the Exalted in Might, the Praiseworthy ;

[14:1]

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LIST OF PUBLICATIONS

- **R. Shan**, B. Honary, D. Lund, H. Ahmed, M. M. Kakhki, "Performance of VoIP over TETRA Enhanced Data Services with Header Compression" Proc. 4th IEEE International Symposium on Broadband Communications (ISBC2010), Melaka Malaysia, pp 057- 061***[Referring Section 3.6.1 & 3.8.1]***
- **R. Shan**, B. Honary, D. Lund, H. Ahmed, "Throughput Optimization and performance of RoHC over TETRA Enhance Data Service (TEDS) for UDP based applications" ***Submitted to Arabian Journal for Science and Engineering (AJSE) 2012 [Referring Section 3.6,3.7& 3.8]***
- **R.Shan**, B.Honary, H.Ahmed ,"Sub-Slot Phase Modulation with Square Root Raised Cosine filter for TETRA Channel" Proc. Tenth International Symposium on Communication Theory and Applications (ISCTA '09) Ambleside, UK. pp 426-429 ***[Referring Section 4.3.1 & 4.4.1]***
- **R.Shan**, B.Honary, H.Ahmed, M. Darnell "Performance Evaluation of Phase Modulation Schemes for TETRA Application" 7th EEE, IET International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP 2010), Newcastle U.K vol-1 , pp 435-439***[Referring Section 4.3 & 4.4.1]***
- **R.Shan,** B.Honary, H.Ahmed, D. Lund, M. Darnell "Complexity & Performance Analysis of Modulation Schemes for TEDS", Inderscience Publishers Int. J. of Vehicle Information and Communication Systems IJVICS, 2011 Vol.2, No.3/4 pp.269 - 285 ***[Referring Section 4.3 & 4.4]***
- Adebisi, B., Treytl, A., Haidine, A., R.Shan, Lund, D., Pille, H., Honary, B. "IP-Centric High Rate Narrowband PLC for Smart Grid Applications" Communications Magazine, IEEE , vol.49, no.12, pp.46-54, December 2011 ***[Referring Section 5.2,5.3 & 5.4]***
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- **R. Shan**, D. Lund, "Performance of RoHC over TEDS for VoIP , Video, Medical and Web traffic profiles" STF - 378 Project with ETSI (TETRA WG4) , WG409075r5 **Contribution towards TEDS Standard 2009.** ***[Referring Section 3.6,3.7& 3.8]***
- **R. Shan**, D. Lund, "Application benefits of ROHC for TEDS" STF - 378 Project with ETSI (TETRA WG4), TETRA04 (10)0040 **Contribution towards TEDS Standard 2009.** ***[Referring Section 3.6,3.7& 3.8]***
- **R. Shan**, D. Lund, "Implementation of ROHC into the standard" STF - 378 Project with ETSI (TETRA WG4), TETRA04 (10)0041 **Contribution towards TEDS Standard 2009.** ***[Referring Section 3.6,3.7& 3.8]***
- **R. Shan**, D. Lund, "Performance of π/4 DQPSK for TETRA at 138 MHz, " ETSI and TETRA Association Project (TETRA WG4 / TETRA Association), 2011 ***[Referring Section 4.6 & 4.7]***
- **R. Shan**, D. Lund, "Receiver Characteristics for π/4 DQPSK for TETRA at 138 MHz, " ETSI and TETRA Association Project (TETRA WG4 / TETRA Association), 2012 ***[Referring Section 4.6 & 4.7]***
- **R. Shan**, D. Lund, B. Adebisi "Interface Specifications and Cross layer integration for Smart Grid" Deliverable for WP-2 for **FP-7 Project** on **Smart Grid "DLC+VIT4IP"** study works a basic design of Smart Grid Design, 2011. ***[Referring Section 5.2,5.3 & 5.4]***
- **R. Shan**, D. Lund et, al. WP3 D3.1 "System Integration Report" **DLC+VIT4IP** Project; European Union Seventh Framework Programme (FP7/2007-2013) grant agreement no 247750; http://www.dlc-vit4ip.org/wb/pages/home.php https://projects.kema.com/sites/DLC-VIT4IP/default.aspx ***[Referring Section 5.2,5.3 & 5.4]***
- **R. Shan**, D. Lund et, al. WP3 D3.1 "Integration of RoHC in DLC+VIT4IP and Comparative analysis of RoHCv1 vs RoHCv2 " **DLC+VIT4IP** Project; European Union Seventh Framework Programme (FP7/2007-2013) grant

agreement no 247750; http://www.dlc-vit4ip.org/wb/pages/home.php https://projects.kema.com/sites/DLC-VIT4IP/default.aspx ***[Referring Section 5.2,5.3 & 5.4]***

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LIST OF ABBREVIATIONS

π/4 DQPSK	π /4-shifted Differential Quaternary Phase Shift Keying
π /8 D8PSK	π /8-shifted Differential 8 Phase Shift Keying
3GPP	3rd Generation Partnership Project
ACCH	Associated Control Channel
ACK	first ACKnowledgement
AL	Advanced Link
ASK	Amplitude Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CSI	Channel State Information
dB	Decibel (unit of measurement of ratios)
DLC	Distribution Line Carrier
DLC-VIT4IP	Distribution Line Carrier Validation , Integration & Testing of PLC for IP communications
DMO	Direct Mode Operation
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
HT200	Hilly Terrain 200 km/h
HTTP	Hyper-Text Transfer Protocol
ICI	Inter-Carrier Interference
IEEE	Institute of Electrical and Electronics Engineer
I-Frame	Intra-frame or Intra-coded frame
IP	Internet Protocol
IPv4	IP version 4
IPv6	IP version 6
ISI	Inter Symbol Interference
LLC	Logical Link Control
LTE	Long Term Evolution
MAC	Medium Access Control
MER	Message Erasure Rate
MEX	Multimedia Exchange Layer
MLE	Mobile Link Entity
NUB	Normal Uplink Burst

PDU	Packet Data Unit
PEI/TEI	Periphery/Terminal Equipment Interface
PHY	Physical Layer
PLC	Power-line Communications
PMR	Professional Mobile Radio
PSDR	Public Safety and Disaster Recovery
PSK	Phase Shift Keying
PSS	Public Safety Systems
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RCPC	Rate Compatible Punctured Convolutional
RFC	Request For Comments
ROCCO	RObust Checksum-based header COmpression
RoHC	RObust Header Compression
RTP	Real-time Transport Protocol
SNDCP	Subnetwork Dependent Convergence Protocol
SNR	Signal-to-noise-ratio
SwMI	Switching and Management Infrastructure
TCH	Traffic Channel
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TEDS	TETRA Enhanced Data Services
TETRA	TErrestrial Trunked Radio
TMO	Trunked-Mode Operation
TU50	Typical Urban 50 km/h
VoIP	Voice over Internet Protocol
WiMAX	Wireless Interoperability for Microwave Access

LIST OF SYMBOLS

µs	Micro Second
B	Bandwidth
C	Speed of Light
$D\varphi(k)$	Phase Transition of kth Symbol
f_c	Carrier Frequency
$G_{(f)}$	Square root raised cosine Filter
$g_{(t)}$	Symbol waveform at time t
G_H	Header Compression Gain
G_p	Pack Compression Gain
H	Header Size in Bytes
H_{RoHC}	RoHC Header Size
K	Number of bits
K	Boltzmann's constant
km/h	Kilometer Per hour
L	Payload Size in Bytes
M	Modulation Order
NF	Noise Figure
P_b	Bit Error Probability
P_s	Symbol Error Probability
R	Symbol Rate
$S_{(k)}$	kth Modulation Symbol
$S_{(0)}$	Symbol before the starting symbol
$S_m(n)$	Modulation Symbol at time tn on carrier m
T	Symbol Duration
T_0	Reference temperature for receiver
Y_m	Modulated signal
A	Roll off
φ_m	Phase over carrier m
ω_m	Angular frequency

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1. INTRODUCTION

1.1 HISTORY OF WIRELESS COMMUNICATION SYSTEMS

During the last century, remarkable technological advancements especially in the field of telecommunications have influenced the lives of billions across the world. Telecommunication technologies have not only impacted the cultures but are also helping making the world a global village. Although wireless telephony was invented in the late 19th century the commercial introduction of wireless systems only happened in the early 20th century motivated by the market demand and challenges faced by wired technology. Between 1880 and 1910 various scientists tested the viability of wireless communications systems and applications including, in 1880 Graham Bell & Summer Tainter's invention of the "PhotoPhone"; in 1888 Heinrich Hertz's explanation of electromagnetic waves theory [T. Sarkar, 2006]; Nikola Tesla's demonstration of wireless transmission of power and energy [N. Tesla and B. Johnston, 1999] and Marconi's patent [T. Sarkar, 2006] for radio are just few of the examples from the era. In the coming decades different applications and services based on these innovations were commercialized, based on the public interest. By the end of the 20th century, wireless technologies became public with a variety of applications in the public radio network domain. Professional or Private Mobile Radio (PMR) (Land Mobile Radio (LMR) in the US) services were also developed in parallel to the public radio network for the purpose of dedicated use of wireless communication systems by professional and private organizations. Use of wireless technologies by the public safety & security organizations and aid response teams in normal or emergency situations is one of the basic objectives of PMR systems. Mission critical requirements of public safety and security organizations have been corroborated by the communication networks for nearly a century. The availability of such services extends beyond the social contract and appeals to the moral responsibility to care for life, safety and well being of humanity at large. This requires that technologies used by PSS personnel must meet exceptionally high standards. With the introduction of wireless communication services during the 19th century, technology was used for both commercial as well as private communication around public safety and security organizations to address such requirements.

1.2 NARROWBAND PMR

PMR systems are based on the trunked radio system, which enables two way secure radio communication with a number of users. In 1912, the sinking of Titanic drove the public interest in public safety standards which resulted in the legislation of the first Radio Act in the same year [Public Safety Spectrum Trust, 2011]. This legislation encouraged the different public safety and security organizations across the world to adopt a number of PMR systems. One of the initial PMR systems was used by the Detroit Police Department in early 1920 and in 1933 a newly developed mobile transmitter facilitated the first two-way police system to operate in New Jersey. Initially, a limited number of operating frequency bands were issued to the public security organizations, but in 1946 the first Domestic Public Land Mobile Radio Service (DPLMR) was developed with a frequency ranging from 152-162 MHz. Small business and private organizations were also allowed, under the rules, to purchase airtime from common carriers [Department of Homeland Security, 1999]. A Rapid demand in the PMR industry led to the development of a number of standards in the mid-late 20th century. Project 25 or APCO 25 was developed as a digital communication standard for the use of public safety organizations such as police, fire brigade, federal security and safety organizations in North America. MPT-1327 is another PMR industrial standard, developed in 1988 with the objective of benchmarking the protocol for communication between participating agencies of systems in public safety and security industry [Ofcom, 1988]. Terrestrial Trunked Radio (Trans-European Trunked Radio) TETRA is the European Telecommunications Standards Institute (ETSI) standard for advanced PMR and Public Access Mobile Radio (PAMR) based networks and services [Dunlop, et al., 1999 & Ketterling, 2004]. ETSI is primarily responsible for developing a standard for Europe, however many of its standards have been implemented worldwide. First of such a kind is GSM which has been adopted as a global commercial mobile communication system. The aforementioned TETRA is another example, which has already been deployed across the world and recognised as a truly global standard [Association, 2006]. Initially the Mobile Digital TRunked Radio System (MDTRS) was designed to address the market needs in the PMR market in 1989. By the start of the 1990s there were around 4 million vehicle mobile and hand-portable subscribers for PMR services across Europe [Goddard, 1991]. The European Conference of Postal and Telecommunications Administrations (CEPT) entrusted the ETSI for standardization of MDTRS across Europe. MDTRS standardized the operating frequency, outlined the system operational parameters and QoS parameters [Application, 2011] and [ETSI TETRA ETR-300-1, 1997]. MDTRA was renamed Trans European Trunked Radio (TETRA), but in the mid 1990s its acronym was changed to TErrestrial Trunked RAdio. Similarly TETRAPOL is another open standard used by public safety organizations across the world and defined by Publicly Available Specifications (PAS). Figure 1.1

shows the evolution of Private Mobile Radio (PMR) standards and Commercial Mobile Technology. TETRA–I follows the 2G GSM standard but ensures the high reliability and security by end-to-end encryption. TETRA–II or TEDS offers packet oriented services as of GPRS and higher order modulation schemes of EDGE.

However the PMR market is slow in adapting to the innovative technological advancement i.e. not all EU countries have full PMR tele-density and mobile penetration nationwide while commercial mobile networks has better coverage. Limitations in the spectrum is another issue, due to which PMR manufacturers hesitate to adapt and invest in 3G PMR technologies, TETRA or any other PMR system. In contrast to PMR, the evolution of commercial mobile technologies has been inspired by the huge public demand, availability of spectrum and availability of consumer technological equipments.

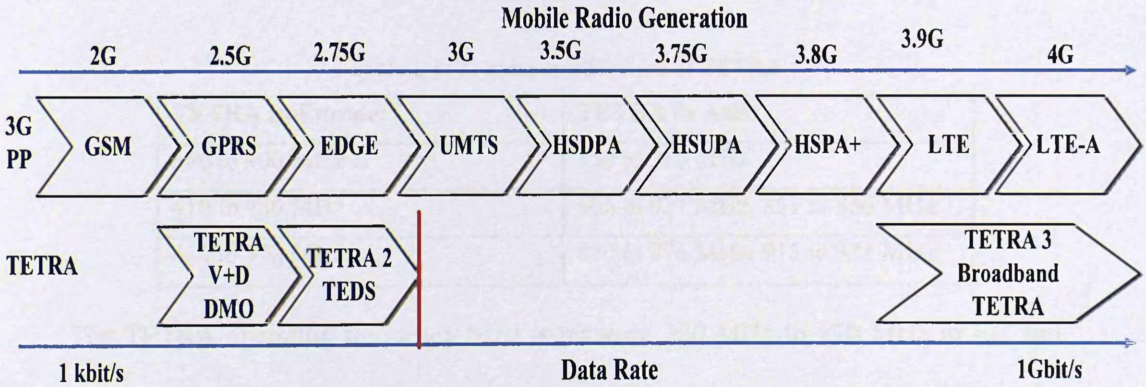


Figure 1.1 : Evolution of Private Mobile Radio (PMR) Standards and Commercial Mobile Technology

1.2.1 TErrestrial Trunked Radio (TETRA)

The TETRA forum was established in 1994 to represent the requirements of mobile communication industry experts, product manufacturers, regulatory bodies and private network users. The Anticipation was to standardize the digital technology for PAMR for voice plus data under TETRA and reduce the cost of equipment by 40%. The defining open interfaces, facilities and services were the primary objective for the TETRA standard. This enabled independent manufacturers to develop the network infrastructure and terminal equipment which would not only be interoperable but ensure the same QoS with a wide range of features tailored to the demand of PAMR organizations [Association, 2006]. TETRA services focus on guaranteed interoperability, versatility, efficiency, robustness and security. TETRA is designed to address the variety of time critical application requirements from the users which include police, ambulance and fire services, security services, military services, and fleet management/transport services. The targeted markets have specific, mission critical requirements for mobile communications, not offered by the existing public cellular systems. Table 1-1 shows the frequency allocation of TETRA in Europe & Asia.

Table 1-1: Frequency allocation of TETRA

TETRA in Europe:	**TETRA in Asia:**
380 to 400 MHz	350 to 380 MHz
410 to 430 MHz	806 to 821 MHz, 851 to 866 MHz
450 to 470 MHz	870 to 876 MHz, 915 to 921 MHz

The TETRA operating frequency band is between 380 MHz to 470 MHz in EU and 806 MHz and 912 MHz in Asia, defining 5MHz band for emergency services and 10MHz band for civil services for uplink and downlink channels. The standard defines the number of 25 kHz carriers for both uplink and downlink channels. TEDS was evolved from TETRA; the purpose of migration from TETRA Release 1 to TEDS was to address the needs of data extensive application. TEDS wideband data capacity offers a new secure, reliable radio carrier which supports packet based data applications. TEDS does not change the physical architecture but is viewed as a software improvement to the existing TETRA Release 1. The reason for the software extension is to keep the current TETRA market equipment in use and therefore cost effective. However, in essence TEDS offers the packaging of eight 25 KHz carriers into one multiplexed carrier to support narrowband - wideband application. This approach effectively reduces the range of TEDS but does offer higher throughput. Higher order modulations provide capacity to increase throughput. The capabilities of existing narrowband TETRA Release 1 and TEDS currently available in the market are not sufficient to meet the emerging market requirements. Steady growth of the existing services are hardly well served with the available technology However, due to the growing market demand and emerging trends in the public safety market, this is not sustainable in the longer term. It was concluded in a number of studies which were analyzed in a report [Analysys Mason, 2010] that to support broadband services make upgrade and to restructure the existing TETRA network is necessary. While the new generation of broadband based systems are made available by utilizing the extended bandwidth, re-engineering the TETRA technology with commercial networks is suggested as an alternative solution. Different studies have been carried out recently to investigate different aspects of integration of TETRA with other mobile and wireless technologies. [A. Durantini, et al., 2008, Wang, et al., 2011, Subik, et al., 2011 & Durantini, et al., 2008]. One of the major issues for the possible integration of TETRA with commercial broadband solutions is the coverage of the service. Public safety mobile services demand extensive and thorough coverage over a vast geographic area and with better penetration for urban areas while commercial mobile networks do not guarantee the extent and quality of service in challenging geographic terrains and urban build -ups. In contrast to commercial networks, service requirements of applications working in public safety networks are very challenging; delivery of such a level of requirements is very difficult to integrate in commercial networks. As a result, possible hardware upgrade and management overheads for each base station could be a financial overhead for the operators.

1.3 APPLICATION OF HEADER COMPRESSION AND SIGNAL PROCESSING

Although TEDS offers a better data rate TETRA and enables the IP support however this comes with a cost. The application payload based on RTP/UDP/IP protocols is appended with additional headers. Header contributions in the final packet are significant and for systems such as TETRA, optimal use of available bandwidth is critical. Objective of the study is the application of header compression techniques such as Robust Header Compression (RoHC) over TEDS and investigate the benefit in terms of effective throughput and outline possible integration issues of RoHC over TEDS. In this study we aim to apply RoHC over TEDS to analyse performance of header compression and illustrate application benefit of using RoHC over TEDS. Objective is also to apply the RoHC over wired system with similar characteristics as TEDS to compare the application benefits. For the purpose of which, Power line communication is selected based on the channel and bandwidth similarities with TEDS.

Power is distributed with a low voltage (LV) power line network, which makes it accessible to each home and possibly every electrical socket. Based on the frequency of operation PLC networks are divided into three categories, depending on the operating frequency, type of power line distribution network and data rate. Low data rate narrow band operates between 9 – 148.5 kHz and major application areas include home automation, load management and automatic meter reading. Medium voltage

PLC systems operate between 148.5 kHz to 500 kHz and can deliver up to 500 kbps, while broadband PLC operates up to a 300-400 MHz range and is capable of delivering around 200 Mbps. Medium voltage PLC systems process similar propagation channel characteristics as TEDS and application bandwidth for both systems is similar. TEDS offers different data rates based on the schemes applied physical layer, i.e it offer 400kbps data rate by employing multi-carrier based filter bank based QAM with 150 kHz. Although PLC is a wired channel but application throughput offered by PLC between 148.5 kHz to 500 kHz is similar to that of TEDS, moreover channel characteristics for TEDS and PLC are also similar.

Application of RoHC over TEDS and PLC will help in understanding the performance of advance header compression schemes over wideband systems and outline the application performance over respective propagation channels and illustrate the integration issues. Performance of the RoHC is analysed in term of throughput. In chapter 3 we discussed the performance of RoHC over TEDS while in chapter 5 we presented the design of IPv6 based protocol stack for PLC with RoHC support. In both cases application performance and integration to existing systems is proposed.

Due to limited spectrum for PSS, performance of high rate data application suffers serious performance degradation over TEDS. To improve the application effective data rate it is vital to study all possible options for throughput optimization. The throughput is a vital QoS parameter for a wireless communication system which depends on a number of factors including transmission rate, packet size, and power spectral density of system, channel conditions, modulation schemes and received signal power. There are a number of techniques applied at the physical layer of the communication systems to achieve this task. [Romana Rafi, 2010] adaptive coding and modulation for 3G systems, while in [Shan R. , 2008] adaptive modulation schemes for TEDS is presented. The performance threshold for such adaptive coding and modulating techniques and adaptive signal processing techniques depends greatly on the channel characteristics at the moment of time. However the system throughput at the application layer of the receiver needs to be looked at against the information transmitted at the physical layer of the transmitter. In this study we have implemented the physical layer of TEDS and analysed the performance of TEDS over different modulation schemes other than those specified in the standard. In chapter 4 we have presented the performance of TEDS against various modulation schemes and frequencies below 200MHz in different channel propagation conditions.

1.3.1 POWERLINE COMMUNICATIONS

By the late 19th century, electric distribution grids were introduced for the purpose of data communication [P. A. Brown, 1999] . By the early 20th century a variety of control and monitoring applications were implemented over the power distribution lines. In the last few decades, with the introduction of advanced signal processing techniques, market surge for telecommunication based services and applications; the introduction of smart and interactive electrical devices made PLC a viable market technology and created a massive user interest. Electricity distribution is a complex process and involves a stepping up and stepping down of the transmission voltage at different stages of the transmission. Transportation of electricity is more efficient at high voltage over longer distances. High voltage is stepped down by the transformers for distribution to the end user. The distribution grid consists of Medium Voltage (MV) and Low Voltage (LV) networks. MV is distributed up to 60 kV and is targeted at medium voltage consumers such as industries while LV is distributed below 1 kV and targeted at end users or low voltage consumers. Power distribution networks are basically designed for the efficient delivery of electricity at 50-60 Hz, while the PLC systems are designed to use the same carrier but with frequencies around the transmission frequency of electricity. During the last decade there has been huge public interest in PLC related technologies specially smart grid and home automation. During 2009, there were 13(4 Small, 7 Medium and 2 Large) active projects across the EU on various aspects of PLC systems. [KEMA, 2009] Despite the simplicity and offered services, the technology has not found its way into the consumer market in the last decade. Possible reasons for this are lack of interoperability with other systems and the complex nature of power line distribution networks and high interference. Although standard and funding bodies are pushing for the integration and commercialization of the technology, in the absence of unified standard for PLC and reasonably priced PLC enabled electronic devices it seems difficult to make it as a major consumer technology.

1.4 MOTIVATION

There has been a high demand for data extensive multimedia application in wireless communication systems including public safety networks during the last decade. The motivation for such demand is driven by the exponential growth in multimedia based systems and the social urge to use such services on the move. Like other industries, communication technologies tend to provide the best option for the PMR systems. Growth in the demand of high data rate applications have pushed the current PMR systems to its limits and motivated for the evolution of TETRA-I to TEDS. Uses of data oriented applications have transformed the PMR industry and help public safety agents to communicate more efficiently and effectively. Additional information helps improve the responsiveness and efficient deployment of resources and facilitate the possible decision making process in daily public safety operations. Current market growth and trends illustrate the need for the next generation public safety networks. The TETRA industry is advocating the development of a new generation of mobile broadband networks for dedicated PMR use. Such development requires identification and allocation of a dedicated spectrum for the purpose and could only be possible by 2020 [Martin Steppler, 2011] . In a time of high commercial demand, such a process is very critical in nature, but the nature of PMR applications force the contributors to keep pushing the existing network for better throughput without compromising on any of the QoS parameters. Current narrow and wide band PMR networks have limitations in terms of range and volume of data and multimedia applications. However in the absence of such a network, our research is an attempt to look for all possible ways to improve the current network. Optimization and possible effective throughput increase by employing better adaptive techniques have also been consulted. In view of the above discussion, advance header compression technique such as RoHC need to be analysed in wide band PMR system such as TEDS. TEDS being an industrial standard it is vital to illustrate the integration issues of RoHC over TEDS. To analyse the performance of RoHC on another system with similar performance matrix and propagation conditions. A PLC system with operating frequency between 148.5 kHz to 500 kHz is a candidate wideband technology as TEDS with similar effective throughput and propagation conditions. To carry out such an investigation, the integration of IPv6 for PLC systems is also proposed under the FP-7 project. Integration and verification of PLC with IPv6 enabled technologies is one of the task carried out in this study while PLC being wideband communication system, header redundancies are also addressed.

Performance of TEDS over different modulation schemes requires investigation, for which we have presented performance of TEDS over different modulation schemes other than those specified in standard over different propagation channels. In addition to this, performance analysis of TEDS over any of the available spectrum below 200MHz is carried out.

Application of RoHC over TEDS and PLC will understanding the performance of header compression schemes over wideband systems while performance analysis of different modulation schemes and performance matrix below 200MHz for TEDS help in proposing better performance parameters for TEDS.

1.5 RESEARCH OBJECTIVES

The objective of this thesis is to investigate the performance of throughput optimization technique such as RoHC which is easily integrated into the existing communication protocol stack of band limited systems such as TEDS and PLC. RoHC compresses the header size to enable the transmission of more application payload at the physical layer of the system without compromising the quality of service. The objective is to investigate the integration of RoHC in TEDS and PLC with minimum integration dependencies and alteration, of the standard

The objectives of this research are as follows:

- To investigate the performance of RoHC over TEDS by simulating different traffic profile classes and the enumeration of application benefit against the transmission slots at the physical layer.
- To comprehensively investigate the benefit of using RoHC over TEDS and outline the parameters of constrains.
- To examine the delay propagation and tolerance level of Round Trip Time (RTT) for TCP based application in TEDS.
- To simulate and investigate the TEDS physical layer with higher order

modulation schemes and outlines the performance characteristics.

- To investigate and illustrate the performance of TEDS physical layer below 200MHz and recommend the new TEDS receiver performance characteristics which will update the current TEDS standard.
- To design the IPv6 enabled protocols stack for PLC system and investigate the performance of RoHC against the different traffic profiles.

1.6 CONTRIBUTION OF THE RESEARCH WORK

The major contributions of this research work are summarized below:

- A detailed analysis of the performance of RoHC over TEDS over selected traffic profiles representing different traffic classes.
- Performance analysis of RoHC over different TEDS propagation channels and modulation schemes.
- Results showing the throughput gain as a result of the application of RoHC over TEDS and integration of RoHC in to the existing TEDS standard under the TETRA project STF 378.
- Illustration of BER/SER/MER performance curves for phase modulation and QAM schemes over TEDS propagation channels.
- BER/SER comparison of different logical channels over different TEDS propagation channels below 200 MHz.
- Illustration of reference receiver sensitivity parameters for π/4 DQPSK below 200 MHz and amendments to the TEDS standard EN 300 392-2.
- Design of the IPv6 enabled protocol stack recommending convergence layer

for the integration of RoHC for PLC and adaptive QoS.

- Performance analysis and illustration of throughput optimization using RoHC over IPv6 enabled PLC.

1.7 THESIS OUTLINE

Chapter Two illustrates concepts of throughput optimization techniques and their effect on performance. It explains the evolution, methodology and application of RoHC in different communication systems. An overview of the header contribution across the protocol stack and its net effect on the system throughput is discussed. The chapter two explains the background of the selected technologies, explaining the evolution of PMR systems and TETRA along with the theoretical background of the PLC systems. The chapter two also illustrates the TETRA protocol stack along with its network architecture. The background of modulation schemes used by TETRA and propagation channels is also explained. The theoretical background of RoHC presented in this chapter helps understand its application in Chapter Three and Five, while concepts of TEDS physical layer help us understand the contributions in Chapter Four.

Chapter Three explains the application support for TEDS, the structure of its physical layer along with the traffic profile and different traffic classes supported by TEDS. The chapter explains the performance of RoHC, its integration and implementation for TEDS and systems design for the purpose of simulation for RoHC over different traffic profiles. It concludes with the illustration of results and comments on the performance of RoHC over TEDS. We applied RoHC for the wireless application of

TEDS, and will further investigate the performance of RoHC over a narrowband wired Power Line Carrier channel in Chapter Five.

Chapter Four explains the modulation schemes, propagation channel and physical layer implementation design for TEDS. Performance of higher order modulation schemes along with the performance characteristics of different slots' combinations are also presented. Characterisation of TETRA (π/4-DQPSK) at 138 MHz is presented along with the receiver reference sensitivity parameters, which are illustrated in the second half of the chapter.

Chapter Five presents a novel Internet Protocol (IPv6) system based on PLC that delivers high resilience communication solutions in order to achieve a smart grid purpose. Application requirements along with the systems design constraints are illustrated upon which the novel systems design is based. New technique of integration of IPv6, RoHC and End-to-End Quality of Service are also described; a selection of the results illustrating the performance of RoHC over PLC, are also presented.

Chapter Six gives an overall assessment of the research and suggests areas for further research.

2. BACKGROUND THEORY

2.1 INTRODUCTION

This chapter presents a brief overview of the theoretical concepts upon which the research documented in this thesis is based. The aim of this study is to analyze the narrow band systems like TETRA and PLC and investigate possible cross layer optimization techniques such as RoHC. This chapter is organized into five main sections.

- Throughput Optimization for TETRA and PLC
- Evolution & protocol architecture of TEDS and channel model for TEDS
- Modulation schemes for TEDS
- PLC and Smart Grids
- Evolution and working of RoHC

The first section briefly describes throughput optimization for narrowband and wideband communication systems followed by the evolution of public safety and security communication networks and in particular the evolution of TETRA over the years. This section overviews the services offered and challenges faced by the communication systems in the public safety networks communication industry. In the second section, the protocol stack for TEDS, network architecture and the propagation channel model are described. This section elaborates the layered protocol architecture and services offered by each of the layer in the stack, and also describe briefly, the protocols supported by the TEDS stack and its network architecture. The TEDS propagation model for both phase and amplitude modulation is also discussed in this section. More detail about the topics discussed in the first two sections can be found elsewhere [Dunlop, et al., 1999; Ketterling, 2004; Nouri, et al., 2006; ETSI EN 300 392-2, 2007-09 ; ETSI TETRA ETR-300-1, 1997; Association, 2006; Aiache, et al., June 2009; Application, 2011; Goddard, 1991 & Salkintzis, 2006].

In the next section, modulation types used by the TEDS are briefly explained. TEDS support five different modulation schemes with two different types of physical layer architecture and various burst formation structures. This section also describes in brief, types of filter used by TEDS, details of the topics can be explored in [Paroakis, et al., 2005; Nouri, et al., 2006; Annunziato, et al., 2000; & ETSI EN 300 392-2, 2007-09].

The next section in this chapter briefly describes the PLC, smart grid and its application, current protocol, application and services support offered by it. Details of the topics discussed can be explored in [Haidine, et al., 2011; Bumiller, et al., 2009; Pille, 2010 ; & Litos Strategic Communication, 2010].

The last section is dedicated to header compression schemes and their types, and explains the evolution, methodology and application of RoHC in different communication systems. An overview of the header contribution across the protocol stack and its net effect on the system through- put is discussed. The efficiency model for the header compression schemes is also discussed; in depth analysis is readily available in [C. Bormann et al, 2001; Couvreur, et al., 2006 ; Jung, et al., 2006; Wang, et al., 2004 & EFFNET Lab, 2004].

2.2 HEADER COMPRESSION AND SIGNAL PROCESSING FOR WIDEBAND SYSTEMS

As discussed in the previous chapter, throughput is one of the vital QoS measures in any communication system. Wideband communication systems such as TEDS and PLC effectively throughput is limited by challenging propagation conditions. The objective of the throughput optimization techniques is to maximise the utilization of the available resources especially at the physical layer of the system. Most of the signal processing techniques try to ensure the maximum utilization by employing spectrum efficient modulation schemes or efficient error control coding techniques. Many robust and intelligent techniques have been introduced such as adaptive coding & modulation and adaptive QoS management. In [Romana Rafi, 2010] adaptive coding and modulation for 3G systems is proposed, while in [Shan R. , 2008] adaptive modulation schemes for TEDS are presented. However, it is important to investigate the nature of information being processed at the physical layer and to quantify the amount of actual payload at the physical layer of the communication system against the total information. In light of such an investigation, a variety of cross layer optimization techniques are also applied to both wired and wireless communication systems. However in cases where the communication stack of the technology is strictly bounded by the industrial standards i.e TEDS, it is very difficult to propose any such technique which may affect the implementation of a partial or full communication protocol stack. Header compression techniques work just below the IP layer and do not affect the implementation of a logical link control (LLC) and medium access control (MAC) layer. Sophisticated header compression techniques work seamlessly and their processing is completely indiscernible to the following layers in a communication stack. The packet size at the logical link control (LLC) and medium access control (MAC) layer compose of application payload and header/control information appended by the protocol layers. The size of payload in most of the applications such as voice over IP, home automation and control applications and medical applications is small with a fast application rate. In such situations, header contribution in the total size of the packet is considerably more than the actual application payload.

To address the problem we have applied the RoHC technique to compress the headers in narrow and wideband systems, such as TETRA, a wireless communication system, and PLC a narrowband wired technology.

In the following sections a brief background of TETRA and PLC technologies are discussed, followed by the literature on header compression techniques in general and RoHC in particular.

2.3 EVOLUTION FOR TETRA ENHANCED DATA SERVICES (TEDS)

Tactical and emergency operations of Public Safety and Disaster Recovery (PSDR) organizations rely comprehensively on Professional Mobile Radio (PMR) communication systems. PSDR systems are the toughest challenge for any PMR network. TETRA is established as a reliable PMR system for mission critical applications and is used by safety and security organisations across the world. Some of the important features offered by TETRA include scalable architecture, mobile to mobile or mobile as repeater operation, group call, short call set-up time, Direct Mode Operation (DMO) or Trunked Mode Operation (TMO), support of data with voice and end-to-end encryption [ETSI TETRA ETR-300-1, 1997 & ETSI EN 300 392-2, 2007-

09]. TETRA utilizes a TDMA based 4 time slots per carrier with the channel spacing of 25 kHz. Each time slot carries 255 modulated symbols in different burst structures while data flow is managed with different logical channels [Dunlop, et al., 1999 & Goddard, 1991].

Due to the increased public demand for information access on the move, PSS systems require increased access to a wide range of information driven wideband and broadband services and applications. In order to address such demand, it was required to provide connectivity and interoperability with heterogeneous networks. The TETRA was upgraded to TEDS that fulfils the demand of professional users by providing them with high speed packet data services over wireless mobile channels. The technology overview is presented by [Nouri, et al., 2006]. The added features in TEDS are the introduction in IPv6 based network, a higher data rate with the introduction of a multicarrier-based modulation format, powerful payload and header encoding. With its enhanced features, TEDS not only maintains the QoS parameters such as efficiency, robustness and end-to-end security but also ensures IPv6 connectivity [ETSI EN 300 392-2, 2007-09].

2.4 TEDS PROTOCOL ARCHITECTURE

The TEDS protocol architecture is designed to be a stable, reliable and efficient PMR standard which can operate globally. The TEDS standard defines the protocols up to Layer 3 of the OSI model. The TEDS protocol and network architecture fully support the overall objective of reliability, security and trustworthiness for mission critical services. This section explains the TEDS protocol architecture, protocol stack network architecture and TEDS propagation model. TEDS protocol stack has not only inherited all the features of the TETRA protocol stack but also offers better service connectivity through IPv6 and some additional features for a better quality of service and reliability.

2.4.1 TEDS Protocol Stack

TEDS Mobile Stations (MS) support circuit mode calls and short data through the Circuit Mode Control Entity (CMCE). TEDS offers management of IP based application data connections through the Sub-Network Dependent Convergence Protocol (SNDCP) layer and management of multimedia data through the Multimedia Exchange (MEX) layer. The MEX layer performs the packet filtering and may assign precedence to the application associated streams, depending on the application demand. External application data terminals, such as biometric scanners, cameras and different application sensors are connected to the TEDS MS through the Peripheral Equipment Interface (PEI) and transmit packet based data via the MEX and SNDCP layer. Figure 2.1 illustrates the TEDS protocol architecture for MS illustration of which is presented in [ETSI EN 300 392-2, 2007-09 , Ketterling, 2004] while application based on the TEDS are discussed in [Salkintzis, 2006 , Burr, 2000]; Packet data and control information is categorised as signalling data and carried through the control plane (C-plane), while circuit mode data along with end-to-end user signalling is managed under the User plane (U-plane). Layer 3 is applicable to only C-place, and consists of network access functions such as SNDCP, CMCE, Mobility Management (MM), MEX and Mobile Link Entry (MLE). MM deals with registration, migration, roaming and group call setups. Layer 2 includes Logical Link Control (LLC) and Medium Access Control (MAC). Logical links between the MS and BS is controlled by the LLC. The LLC offers two types of connection establishment to Layer 3 and above, which are LLC basic links and LLC advance link. In LLC basic link connection between the MS and BS is established based on the application requirements without any additional acknowledgement and in LLC advanced link each PDU is acknowledged at the LLC layer from the receiver. Similarly the MAC layer is also divided into two sub-layers: the upper MAC which manages channel allocation, random access, fragmentation, air interface encryption and link adaption while the lower MAC manages the channel coding, interleaving and scrambling. The physical layer or Layer 1 features involve modulation/demodulation, burst generation for continuous and discontinuous operations, transmitter/receiver switching, frequency correction, channel estimation, filtering and synchronization. TETRA Release 1 had a similar protocol stack as discussed earlier, however in TEDS, significant changes were introduced in the SNDCP and MAC layers. The MEX layer was also introduced to manage multimedia connections over TEDS [Ramezani, et al., 2009].

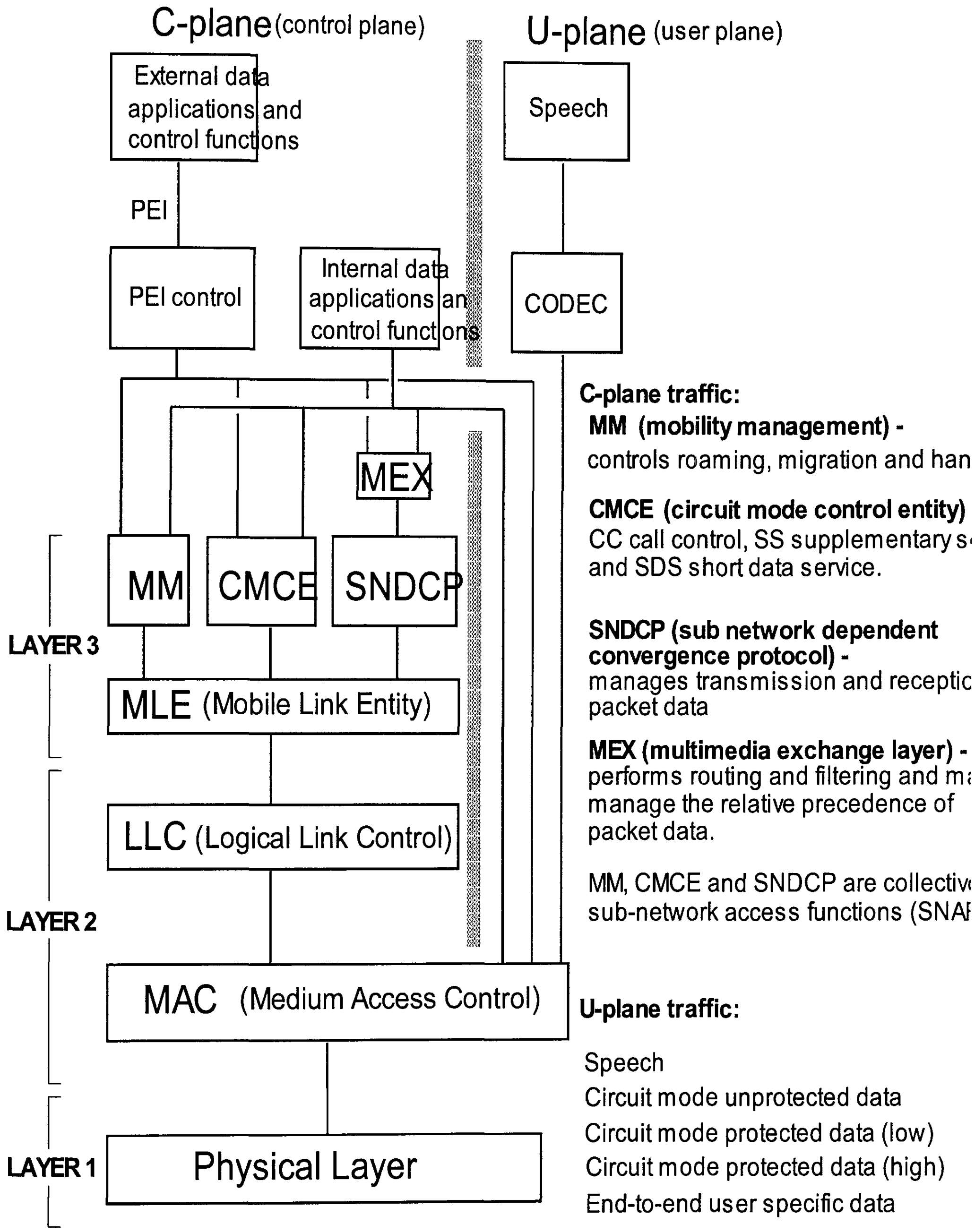


Figure 2.1 : Protocol Architecture for TEDS

[ETSI EN 300 392-2, 2007-09]

2.4.2 TEDS Network Architecture

TEDS offers more throughput and capacity than TETRA Release 1 with the same spectrum, TEDS carriers are dedicated to high speed data and cannot be used for voice communication simultaneously [Nouri, et al., 2006]. TEDS offer 50 KHz - 150 KHz channels compared to 25 KHz for TETRA Release 1. A Poly-Phase Filter Bank based multi-carrier Modulation for QAM – 4, QAM – 16 and QAM – 64 is offered. High order modulation offers more capacity with the coverage trade-off. TEDS extends the TDMA based access scheme with 4 channels per carrier and channel spacing of 25 kHz, 50 kHz, 100 kHz and 150 kHz. TEDS have adopted Multi-Carrier (MC) filter bank-based signalling to achieve robust performance even in frequency selective fading channels, for a total number of subcarriers ranging from 8 for a 25 kHz channel to 48 for a 150 kHz channel [Nouri, et al., 2006, Ketterling, 2004 & ETSI EN 300 392-2, 2007-09].

IP is used a as transport medium to connect base stations to the Switching and Management Infrastructure (SwMI) and rest of the TETRA network. The SwMI is responsible for switching, networking, service provision, management of the system and support for narrowband based services to a wide geographic area. The TETRA network architecture for packet data is shown. Figure 2.2 outlines the TETRA point to point protocol stack for packet data types i.e. voice, video, medical etc. through the TETRA network architecture. As the application packets are passed down to RTP/UDP/TCP/IP layers as Network Packet Datagram Units (N-PDU) each layer adds its own header. The IP passes down the N-PDU to the SNDCP layer with added headers. The SNDCP adds its header of 16 bits with PDU, and MLE adds a header of 3 bits with the received SDU and pass down to Layer 2. Additional data services like video and image data applications support were possible due to the restructured physical layer, support for QAM and IPv6 support for TEDS. Security features provided by the TETRA Release 1 are supported by TEDS including key management and smart card based security features. TEDS increase the data throughput approximately 10 times that of TERA-1.

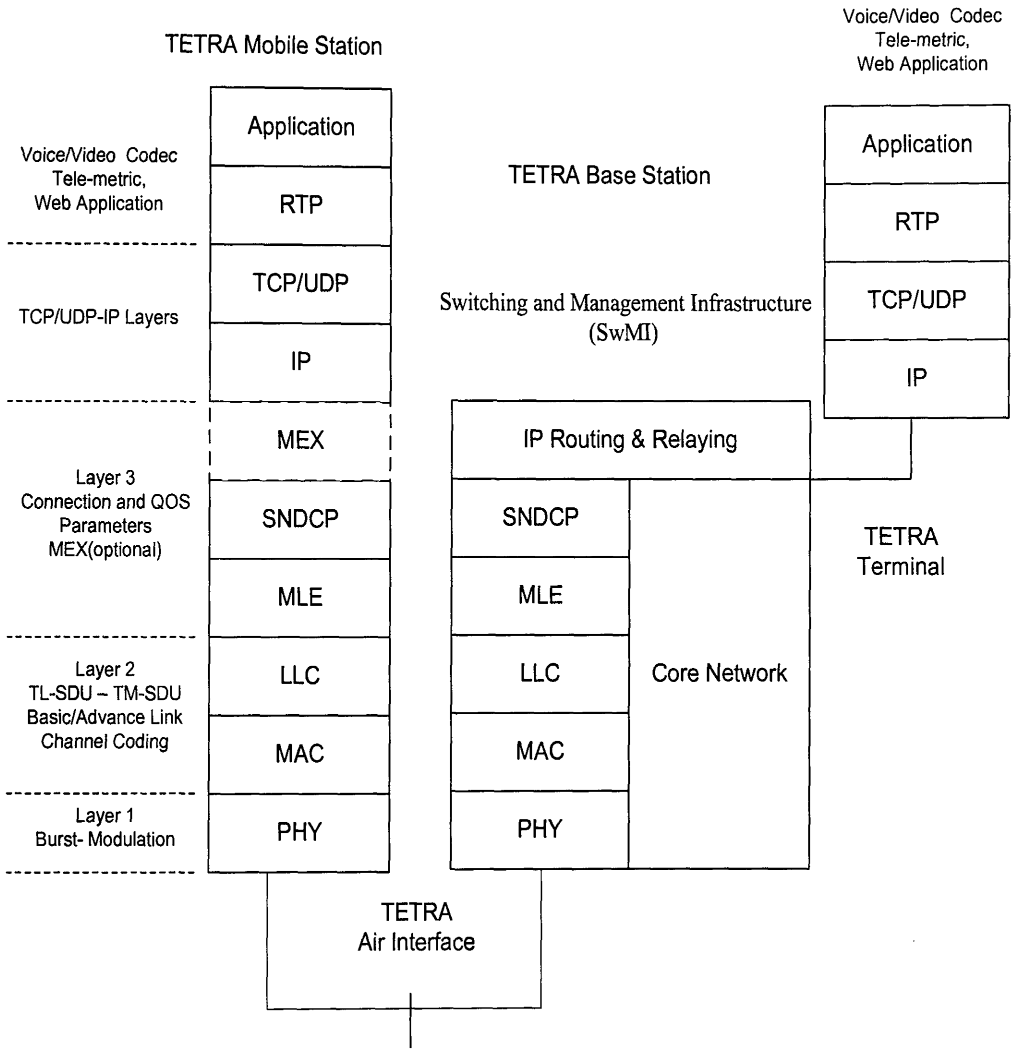


Figure 2.2: TETRA Network Architecture

Applications are based on basic 25 kHz channels or combinations of up to 150 KHz channels which can be allocated on application demand by possible compromise to other applications/users. A lower operating frequency provides a longer range and high geographical coverage with fewer transmitters. A small bandwidth of 25 kHz gives a high geographical coverage with less capacity while a 150 kHz bandwidth provides more capacity for a short coverage area.

2.4.3 TEDS Propagation Model

Radio wave transmission in the mobile radio environment is illustrated by a dispersive multi-path model based on reflection, diffraction and scattering phenomena. Different propagation paths may exist between BS and MS or a number of partial waves of different amplitude and phase constitute the final received signal. Since the MS will be moving, a Doppler shift is also associated with each partial wave which depends on the MS's velocity and the angle of incidence. The delayed and Doppler shifted partial waves interfere with the receiver causing frequency and time selective fading on the transmitted signal. In TETRA systems, bandwidth and propagation path lengths are scientifically small, and frequency and time selective fading for such processes can be simulated by a simplified propagation model. A simplified propagation model exhibits only a few discrete paths which are independently fade. Tapped delay models used for GSM in urban\rural areas are adopted for TETRA with a reduced number of taps\paths due to smaller system bandwidth [ETSI EN 300 392-2, 2007-09 & Ketterling, 2004] .The vehicle speed in km/h and transmission frequency is a selectable model parameter. For this study we have assumed vehicle speed of 50 km/h in urban areas (TU-50) and 200 km/h in rural areas (HT-200). The Doppler shift is computed based on the equation: Doppler shift = V / λ. V is vehicle speed (m/s) and the wavelength λ (m). While λ is calculated as c / f; c is speed of light in free space equals 3×108 m/s and f is the transmission frequency in Hz. Assuming transmission frequency to be 430 MHz, the Doppler shift is calculated as 20 [Hz] for TU–50 channel conditions and 80 [Hz] for HT – 200 [ETSI EN 300 392-2, 2007-09]. Table 2-1 shows the TETRA propagation channel model for phase modulation over static, TU and HT propagation conditions for phase modulation and QAM.

Table 2-1: TETRA Propagation Model For Phase Modulation & QAM

Modulation Type	Propagation Model	Tap Number	Relative delay (μs)	Avg. power (dB)
Phase Modulation	Typical Urban (TUx)	1	0	0
		2	5	-22.3
	Hilly Terrain (HTx)	1	0	0
		2	15	-8.6
QAM	Typical Urban (TUx)	1	0.0	-3.0
		2	0.2	0.0
		3	0.6	-2.0
		4	1.6	-6.0
		5	2.4	-8.0
		6	5.0	-10.0
	Hilly Terrain (HTx)	1	0.0	0.0
		2	0.2	-2.0
		3	0.4	-4.0
		4	0.6	-7.0
		5	15.0	-6.0
		6	17.2	-12.0

The Doppler shift is specified to be 20 Hz for TU–50 channel conditions and 80 Hz for HT – 200 [ETSI TETRA ETR-300-1, 1997]. TU-5 is a pedestrian model which is modelled for a person walking in the terrestrial urban environment at 5 km/h. The Doppler shift used is 2 Hz for TU-5 channel; each symbol has a symbol duration of 55.556 μs.

2.5 MODULATION SCHEMES FOR TETRA

Transmitter and receiver techniques strive towards obtaining reliable communication by encoding of an information signal in a manner so that it is suitable for transmission over a certain media. Modulation involves mapping of the input signal over a sine wave and then transmitting it over the channel which is remapped at the receiver to the closer copy of the original transmitted signal. Once the carrier is mapped with the information to be transmitted, it is no longer a sine wave; it is now a signal which will be corrupted by the channel. In all of the modulation techniques, certain parameters of the sinusoid that represent the information is varied. The three important parameters of this sinusoid are amplitude, frequency and phase. During modulation, certain characteristics of carrier waves can be varied according to the baseband message signal. On this basis, it can be said that there are three basic types of digital modulation i.e. amplitude modulation (AM), phase modulation (PM) and frequency modulation (FM) [Paroakis, et al., 2005].

A desirable modulation scheme is one that is easy and cost effective in implementation, best for the channel conditions, occupies minimum bandwidth, offers lower bit error rate (BER) at a lower signal to noise ratio (SNR) and performs well in the fading and multipath conditions. The modulation performance is often measured in terms of two important factors i.e. bandwidth efficiency and power efficiency. When, after modulating a signal, the chosen technique has the ability to preserve the digital message fidelity over the lower power levels, it is considered as a power efficient modulation technique. On the other hand, bandwidth efficient modulation is one technique that has the ability to accommodate data within a limited available bandwidth. [Dunlop, et al., 1999, Paroakis, et al., 2005]

2.5.1 Phase Modulation

Phase modulation schemes have a good ability to resist the impairments of the channel and so have the lowest probability of error comparing with other digital modulation schemes. QPSK systems are capable of transmitting 4 symbols (2 bits per symbol) where the symbols are orthogonal to each other. The orthogonality in the two implementations ensures that upon transmission of one symbol there will be no interference from the adjacent symbols; as they are separated by 90° [Paroakis, et al., 2005] The incoming bit stream is mapped into a modulation symbol defined by equation 2.1. Each constellation point can represent a bit, $K = \log_2(M)$ where K is the number of bits and M is the modulation order. These K bits are arranged through gray coding or differential encoding to map against the modulation symbols. If the constellation symbols are gray encoded, then the bit pattern representing the adjacent constellation symbols differs by only one bit. For implementation, MSB for the original binary sequence is kept the same in a gray encoded sequence, while i^{th} gray encoded bit is the XOR of the ith of the binary bit and $i+1^{th}$ of the binary bit. This ensures that only 1 out of K bits will be affected if the constellation crosses the decision threshold due to noise. The relation between bit error and symbol error is

$$\mathrm{P}_b \approx \frac{\mathrm{P}_s}{k}.$$

TETRASIM is only available simulation tool for the TETRA physical layer which simulates only TETRA- I [Annunziato, et al., 2000]. TETRA–I is a π/4 DQPSK based TDMA system, whereas to facilitate high data applications like multimedia based services and medical data. TEDS support higher order modulation schemes, such as an extension of π/8 D8PSK for phase modulation along with three QAM based modulation schemes i.e. QAM – 4, QAM – 16 and QAM – 64 [Nouri, et al., 2006 & Ketterling, 2004].

2.5.2 Quadrature Amplitude Modulation (QAM)

In TEDS, higher order QAM modulation schemes were adopted to support higher data rates for data-extensive applications. The support of multimedia and data extensive applications for TETRA makes it unique with proven reliability and security. Higher order modulation schemes provide a higher throughput.

Unlike phase modulation, QAM modulation schemes has a multicarrier modulation scheme. With channel bandwidth ranges from 25 kHz to 150 kHz it is difficult to resolve individual multi-path echoes in the limited bandwidth. It is important to keep the channel delay to a fraction of the symbol period. Channel delay less than the symbol period induces insignificant inter symbol interference. Each of the QAM carriers is divided into a number of frequency-division multiplexed sub-carriers where each of the sub carriers, carries a complex signal modulated using QAM modulation. Smaller bandwidths, hence a low symbol rate, in each subcarrier enables the subcarrier to resist against inter symbol interference (ISI). As a result a multi subcarrier approach with 8 subcarriers per 25 kHz is used, i.e 8,16, 32 and 48 subcarriers in 25 kHz, 50 kHz, 100 kHz and 150 kHz carriers respectively. The modulation rates for each of the subcarriers is 2400 symbols/s. The overall carrier symbol rate is 19200 symbols/s for 25 kHz carriers, 38400 symbols/s for 50 kHz carriers, 76800symbols/s for 100 kHz carriers and 115200 symbols/s for 150 kHz carriers [ETSI TETRA ETR-300-1, 1997].

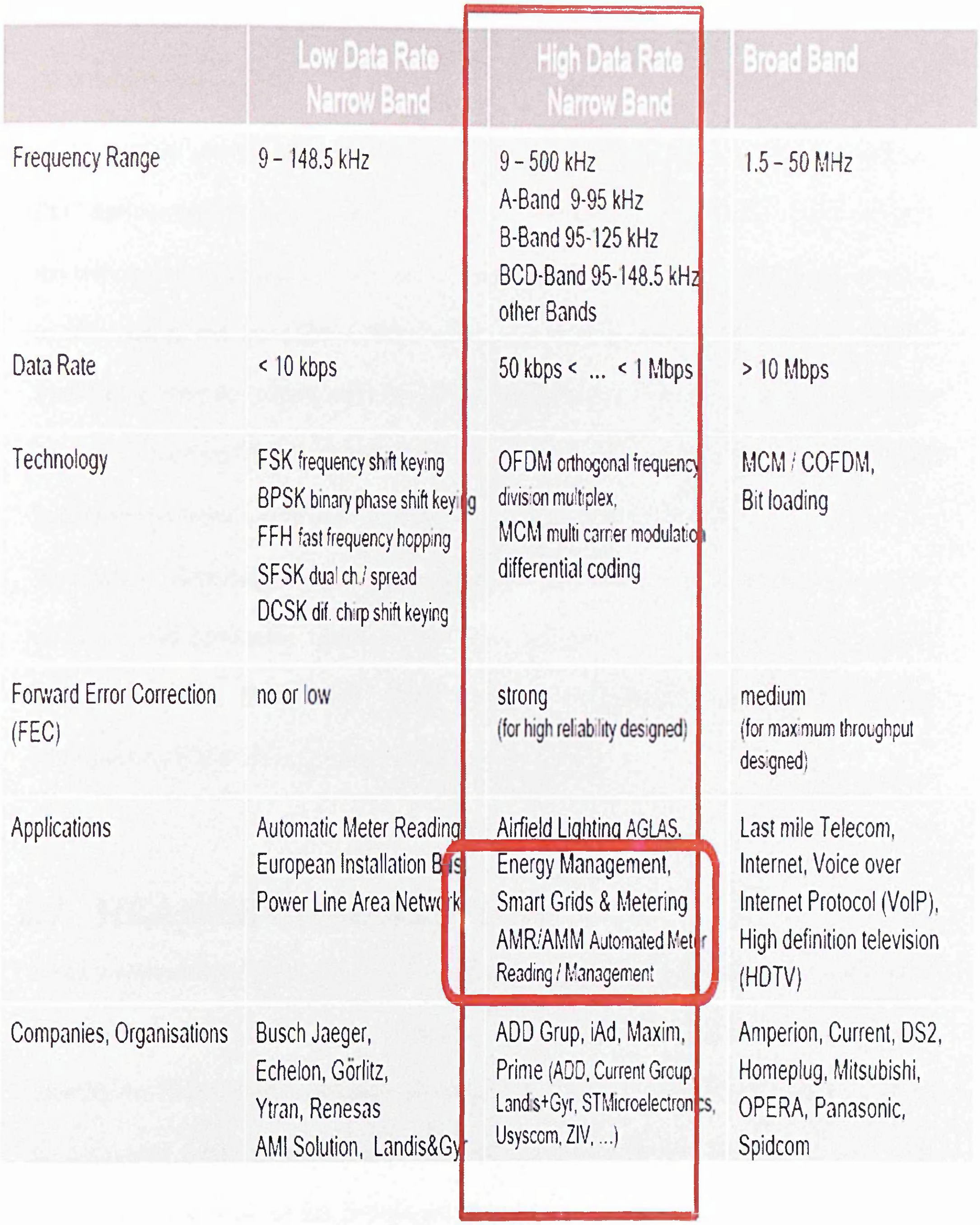
2.6 POWER LINE COMMUNICATION & SMART GRID

The Smart Grid is referred to by variety of definitions and terminologies. It is also referred to as the technology of efficient utilization of Distribution Line Carrier (DLC) networks or PLC networks. The IEEE 802 standard for Smart Grid defines the technology as an energy and information delivery autonomous network for efficiency, autonomy and control. The IEEE 802 also elaborates the aspect of information sharing over the energy or power line network for the purpose of management and control of the overall network. Information sharing over the network along with the power help address various applications and services for a variety of consumer applications. Haidine, et al. [2011] define the technology as the combination of state of the art systems implemented over energy and power networks for efficient power delivery, management and control. Systems also facilitate with real time bidirectional communication over the power line networks [Die Nationale Technologieplattform Smart Grids– Austria]. Litos Strategic Communication [2010] defines Smart Grid as the application of tools, techniques and technologies available over PLC systems for the better system efficiency and optimal use. This elaboration encourages all such technologies which could be integrated to the Smart Grid for optimal use of the power line network. Smart Grid has emerged as one of the most researched areas in the last decade. During 2009, there were 13 (4 small, 7 medium and 2 large) active projects across EU on various aspects of PLC systems. KEMA study, November 2009] One of the major projects was the Distribution Line Carrier - Verification, Integration and Test of PLC Technologies and IP Communication for Utilities DLC+VIT4IP [Haidine, et al., 2011]. The purpose of the study was to investigate the verification, integration and testing of IPv6 based high speed application and services for narrow-band PLC. Based on the project description the DLC+VIT4IP project was designated to perform the following research on [Pille, 2010].

- Verification & development of physical layers, topology and network models.
- Integration of PLC technology and energy applications using IP(v6) efficiently.
- Test of PLC technologies and systems in one or more field installations to gain reliable measurement results for application design.

- High performance IP(v6) transmission over power lines providing an ICT infrastructure for new applications
- Contribution to standardization including more precise channel models, network planning tools or rules for compliance tests

High speed narrow-band PLC systems work within the range of 9 - 500 kHz, but in Europe these systems are actually limited to the frequency range between 9 – 148.5 kHz [CENELEC EN 50065-1, 1995]. DLC+VIT4IP aims to prepare input to standardization in order to widen this band in Europe to the international range of 9 - 500 kHz. Narrow band PLC uses techniques including OFDM and Spread Spectrum modulation and offers data rates between 100's of kbps to 1 Mbps [Haidine, et al., 2011]. Figure 2.3 [Haidine, et al., 2011] illustrates the PLC technology overview over different frequency bands. DLC systems can use existing electrical distribution networks in the medium voltage (MV), Low Voltage (LV) and building voltages. The applications are divided in three keys areas: home automation, remote metering and intelligent power management. Home automation (Home Control) designates the automation of household appliances and features in residential dwellings.



	Low Data Rate Narrow Band	High Data Rate Narrow Band	Broad Band
Frequency Range	9 - 148.5 kHz	9 - 500 kHz A-Band 9-95 kHz B-Band 95-125 kHz BCD-Band 95-148.5 kHz other Bands	1.5 - 50 MHz
Data Rate	< 10 kbps	50 kbps < ... < 1 Mbps	> 10 Mbps
Technology	FSK frequency shift keying BPSK binary phase shift keying FFH fast frequency hopping SFSK dual ch./ spread DCSK dif. chirp shift keying	OFDM orthogonal frequency division multiplex, MCM multi carrier modulation differential coding	MCM / COFDM, Bit loading
Forward Error Correction (FEC)	no or low	strong (for high reliability designed)	medium (for maximum throughput designed)
Applications	Automatic Meter Reading European Installation Bus Power Line Area Network	Airfield Lighting AGLAS, Energy Management, Smart Grids & Metering AMR/AMM Automated Meter Reading / Management	Last mile Telecom, Internet, Voice over Internet Protocol (VoIP), High definition television (HDTV)
Companies, Organisations	Busch Jaeger, Echelon, Görlitz, Ytran, Renesas AMI Solution, Landis&Gyr	ADD Grup, iAd, Maxim, Prime (ADD, Current Group, Landis+Gyr, STMicroelectronics, Usyscom, ZIV, ...)	Amperion, Current, DS2, Homeplug, Mitsubishi, OPERA, Panasonic, Spidcom

Figure 2.3: PLC Technology Summary

Remote metering is a technology that allows remote measurement and reporting of information. Although the term commonly refers to wireless data transfer mechanisms (radio or infrared systems), it also encompasses data transferred over other media;

such as a telephone or computer network, optical link, power line or other wired communications.

DLC systems use the electrical power wiring as a transmission medium. Typically PLC devices operate by modulating in a carrier wave of between 20 and 200 kHz into the wiring at the transmitter. The carrier is modulated by digital signals. Each receiver in the system has an address and can be individually commanded by the signals transmitted over the wiring and decoded at the receiver. The first generation is based on mono carriers (FSK, S-FSK and BPSK) with low data rates. The second generation is based on the Differential Code Shift Keying (DCSK) spread spectrum modulation technology with low data rates. Yitran IT800 PLC modem is an example of the second generation solutions. The third generation is the present competition between DCSK Turbo and Multi carriers Orthogonal Frequency Division Multiplexing (OFDM) technology with high data rates.

2.7 HEADER COMPRESSION

Header compression techniques exploit the field redundancies in headers of packets of the same data flow in a packet switch network. Header compression techniques identify the fields of the headers of the same data flow which remains the same and try to compress them to save bandwidth. Many header fields such as source and destination addresses remain unchanged throughout the duration of a communication session, similarly many of the header fields change predictability or values of some of the fields can be inferred from the other periodic /static fields. This behaviour of the header fields highlights the importance of the header compression techniques. The objective of the header compression techniques is to transmit fewer bytes of header/control information without compromising the QoS and communication context between transmitter and receiver. Compression and decompression algorithms work at the transmitter and receiver respectively to ensure the accurate reconstruction of the original header. One may argue that size of these fields is not huge to save bandwidth, however fast rate applications based on any of the real-time application-to-transport layer protocols generates packets between 10ms~100ms. These applications are mostly voice or real time data applications with a relatively small payload size between 20~100 bytes approximately. These applications use UDP/IP protocols and the combined headers of these protocols is between 40~60 bytes which is comparative to the payload itself, thus header compression give us a significant advantage for fast rate applications. Such a gain is critical for band limited systems like TETRA.

2.7.1 Types of Header compression

A Thin-wire Protocol for connecting personal computers to the internet; RFC released in 1984 by IETF includes the possibility of connecting personal communication device with the internet [Farber, et al., 1984]. Due to the limited connectivity throughput it was termed as “Thin-Wire", which highlights possible bottlenecks and their recommended solutions. TCP/IP based connectivity cost the valuable bandwidth which would be saved by employing header compression technique. This study proposes three different approaches for such compression depending on the situation complexity and performance. A proposed solution compresses the 41 byte TCP/IP telnet packets to 17 bytes and down to 13 bytes with Thin-wire-I and Thin-wire-II respectively [Farber, et al., 1984]. Jacobson has improved the "Thin-wire" protocol and proposed a more generic solution for header compression [1990]. Compression is based on Thin-wire-II proposed by Farber, et al.[1984], In Thin-wore-II compression gain is improved and it addresses more complex topological situations and protocols such as FTP, SMTP and NNTP, which were not feasible at the time of release due to the limited bandwidth. Variations of header compression improvements were later proposed under the IETF RFC 2508 and 2507 in 1999 addressing compression of IP/UDP/RTP Headers for Low-Speed Serial Links and IP header compression respectively. Compression gain proposed by Degermark et.al. [1999] the techniques was claimed to be around 4-7 bytes and proposed techniques also addressed IPv6 [Casner S. J. V., 1999]. Motivation for the improvement were improving interactive response time, allowing small packets for volumetric data transmission with improved link efficiency, allowing small packets for delay-sensitive low data rate links, decreasing header overhead and reducing the packet loss rate over erroneous transmission links [Degermark, et al., 1999]. Acknowledged or unacknowledged low-speed serial links based on IP protocol, experience the same gains from the header compression also known as CRTP [Casner S. J. V., 1999]. RObust Checksum-based header COmpression (ROCCO) was drafted in late 1999 and improved the existing header compression techniques by reducing the lost packets for large round trip time (RTT) links [Jonsson, et al., 1999].

The wide use of wireless communication systems and the introduction of data oriented mobile technologies have motivated the upgrade of existing header compression techniques. ROHC protocol was introduced in 2001, adopted as standard header compression protocol in RTP/UDP/IPv6 based wired and wireless application [C. Bormann et al, 2001]. RoHC offers a compression gain of about 90% over wireless links and robust recovery of "context" between the communication end points.

2.7.2 Application of RoHC

RoHC has already been included in the 3GPP specification presently only for UDP/IP, RTP/UDP/IP and ESP/IP profiles [3GPP TR 25.844, 2001 & 3GPP TS 25.323, 2000]. The application of RoHC over the wireless applications is of special interest due to the erroneous nature of the channel. Over time, different studies have been carried out to investigate the effect of RoHC over various communication technologies. Fortuna, et al., [2009] have investigated the impact of the implementation of RoHC over for VoIP based applications in IEEE 802.11 and the study shows the compression gain of RoHC U-mode when applied to VoIP over IEEE 802.11 and researchers have analysed the RoHC performance in terms of compression gain and throughput gain. [Lee H. K.-D., 2009] has investigated the impact of using RoHC over proposed algorithms for VoIP codecs in Mobile WiMAX systems. Performance is analysed based on average throughput gain packet dropping and packet aggregation against delay; similarly [Couvreur, et al., 2006] investigated the impact of RoHC for UMTS over RTP/UDP/IPv6 based application. The study presents the bit error rate against the percentage packet loss, which shows a significant improvement in percentage packet loss with the application of RoHC. Couvreur, et al. [2006] has only considered the unidirectional mode of RoHC and analysed the performance by describing a Markov chain model. In [H.P., et al., 2005] the author has investigated the RoHC performance for multimedia applications in 3G/4G wireless networks. The study has analyzed the compression gain, throughput optimization and error propagation due to the RoHC, over wireless technologies. The study has selected various multimedia application profiles and tested the RoHC performance against each profile Jung, et al. [2006] has investigated the effect of RoHC and packet aggregation on multi-hop wireless networks based on mesh technology. This study was able to achieve a similar compression gain; it also presented the findings in a packet aggregation scenario. Wang, et al. [2004] has investigated compression gain and effect on BER of header compression for U-Mode, while Taylor D. , et al. [2005] analysed the RoHC performance in terms of implementation complexity and RTT delay. EFFNET Lab [2004] has summarized the RoHC implementation, advantages, limitations and performance gains. Although the authors of the study represent a commercial organization offering RoHC implementations, performance claims and measures are independently verified by the other research studies.

2.7.3 RoHC Architecture

RoHC header exploits the similarity in the header fields over the transmission interval. It can be observed that very little of the information within the IP layer header fields change during a transmission. Some of the fields need to be transmitted only once and with some fields only the difference in the value of field over the course of transmission needs to be sent. Similarly some of the fields can be inferred from the values of other fields. Based on this, RoHC classify each field in the RTP/UDP/IPv4/v6 header into different categories. Fields which do not change or are defined as static are referred to as "STATIC" and "STATIC-DEF" respectively. Similarly depending upon the changing nature of the fields, they are defined as "CHANGING". Some field values can be inferred, based on other fields' values and some fields are static and known, these are termed as "INFERRED" and "STATIC-KNOWN". Once these fields are classified with the headers, RoHC compression decides how and when to send them. RoHC compressors and de-compressors work in context, the former send the current state of header compression to the de-compressor as context information and the latter uses that information to decompress it. At any point during the transmission, RoHC compressor and de-compressor are in “context” to each other, which is very important for successful decompression of the packets.

ROHC is based on a three-state compressing and decompressing machine. In the first compression state, Initialization and Refresh (IR), headers are uncompressed. Packets sent in the second state, called First Order compression (FO) are either packets carrying an uncompressed header without its static context, as defined previously, or compressed headers which cannot be compressed enough to fit in the third state, the Second Order compression (SO). Orthogonally to these states, ROHC supports three modes. The Unidirectional (U) mode is designed for networks where no return link is available [Wang, et al., 2004]. In this mode, transitions between the different states are periodical. Upward and downward transitions are designed in order to guarantee that at every moment, the decompressor is able to decompress headers from the compressor. In this mode, feedback is optional and there are no negative acknowledgments. Figure 2.4 shows the RoHC state diagram in U-Mode.

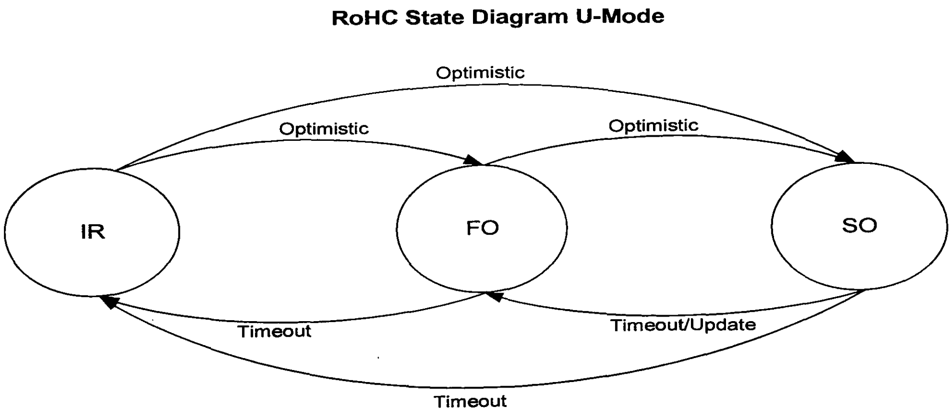
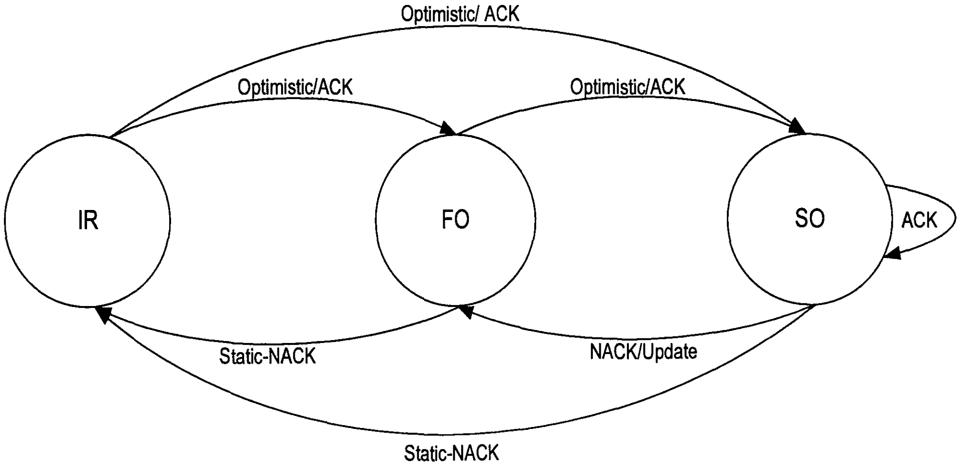


Figure 2.4: RoHC State Diagram U-Mode

The Optimistic mode (O) relies on upward periodical transitions. But, in contrast o this in U mode, feedback is necessary in order to carry negative acknowledgments. Upon reception of a negative acknowledgment (NACK), the compressor transits at a lower compression level. Figure 2. shows the RoHC state transitions in compressor in optimistic mode in case of reception of feedback from the decompressor. The compressor starts in IR mode and transits to FO and SO in a stepwise manner on the reception of ACK. The frequency of the feedback channel is not high and ACK/NACK for each packet is not required, rather it is a controlled parameter.



RoHC State Diagram O-Mode

Figure 2.5: RoHC State Diagram Bi-Directional O-Mode

Finally, the Reliable mode (R) corresponds in a mode where the compressor completely trusts the feedback from the decompressor. Reception of an ACK or a NACK causes the compressor into transit to an upper or a lower compression state respectively. It is also possible to transit dynamically between these modes. Figure 2.6 shows the state transition diagram for a RoHC compressor for a bi-directional R-

Mode. Use of a feedback back channel is higher than the O-Mode to avoid the packet losses due to context invalidation.

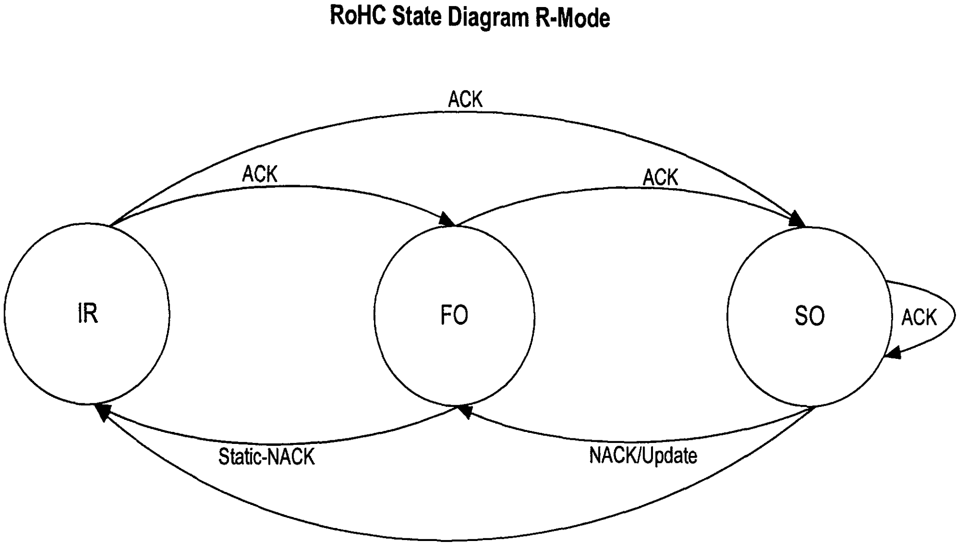


Figure 2.6 : RoHC State Diagram Bi-Directional R-Mode

In summary, context repair techniques include context request / acknowledgements in O and R mode and periodic refreshing of context for U mode. Context prevention includes ACK for R-mode, repetitions in U and O mode and CRC which protects the context update information. A CRC over the original header is the primary mechanism used by RoHC to detect incorrect decompression. To reduce the computational complexity, header fields are rearranged such that CRC is first computed over static fields (CRC –STATIC) and then on fields whose values are expected to change over the period of transmission (CRC-DYNAMIC).

2.7.4 RoHC Efficiency

The objective of the header compression is to compress the header size without affecting system performance; in such a situation efficiency of the header compression technique is defined by the amount of compressed header against the full header size. This is also referred to as header compression gain and has been used as an efficiency measure in a number of studies. Various other studies have also used these performance measurement parameters for RoHC such as [Fortuna, et al., 2009, Lee H. K.-D., 2009, Couvreur, et al., 2006 & Jung, et al., 2006] which focuses on header compression, throughput benefits, and packet drop rate against different packet aggregation scenarios. If the size of the packet header without the compression is denoted by H (in bytes) and payload size is denoted by L (in bytes), and the average size of the header compressed by RoHC is denoted by H_{RoHC} (in bytes), the header compression gain shown in Equation 2.2 G_H and Packet compression gain G_P calculated by [H.P., et al., 2005] is expressed as follows:

$$G_H = (H - H_{RoHC}) / H \qquad (2.2)$$

Equation 2.2 can be simplified to

$$G_H = 1 - (H_{RoHC} / H) \qquad (2.3)$$

Similarly percentage header compression gain of RoHC is the percentage of the header compressed. G_H can only be 100% if size RoHC header is reduced to zero. Packet compression gain, G_P as shown in equation 2.4 is impact of the reduced header on overall packet size is defined as,

$$G_P = (H + L) - (H_{RoHC} + L) / (H + L) \qquad (2.4)$$

$$= (H - H_{RoHC}) / (H + L)$$

It is clear from Equation 2.4 that the Packet compression gain is dependent on the compressed header and the packet payload size [H.P., et al., 2005]. The packet error rate due to RoHC is the number of packets detected as erroneous due to malicious headers or misinterpretation of header fields, which may happen as a result of loss of context between transmitter and receiver. Erroneous headers may cause a propagation delay which is also important in the evaluation of RoHC. Error handling mechanisms/policies need to be implemented to handle such conditions. Throughput improvement is the most important efficiency parameter for RoHC evaluation.

2.8 SUMMARY

In this chapter, the evolution of public safety and security systems are discussed, along with the application challenges for the industry. The evolution of TEDS, salient features of the TEDS protocol stack, network architecture, propagation channels and physical layer have been briefly discussed. The literature highlights the significance of better throughput for PSDR systems without compromising the quality of service. Throughput optimization for IPv6 based systems could be possible by compressing the header and employing higher order modulation schemes. Chapter also summarizes the PLC system and its application in smart grids. The section also highlights the importance of the application of IPv6 for smart grid applications. Lastly, a brief history of header compression techniques, methodology and possible compression efficiency of RoHC is presented.

In Chapter Three, the application of RoHC over TEDS and its impact on the effective throughput is analysed. Chapter Four presents the IPv6 based protocol stack design for smart grids and the application of RoHC over PLC systems.

3. Throughput Optimization & RoHC for TEDS

3.1 INTRODUCTION

TEDS was developed as a major upgrade to the existing narrow-band ETSI TETRA system to supply professional users with high-speed IPv6 packet data services over wireless mobile channels [Nouri, et al., 2006]. Applications based on Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) uses Internet Protocol (IP) for terminal connectivity and packet delivery across the TEDS network. TEDS through its inherited features not only maintains the QoS parameters such as efficiency, robustness, fast call set up, simultaneous voice and data services, interoperability and end-to-end security but also ensures IP connectivity [Nouri, et al., 2006]. Voice over IP, video application for surveillance and monitoring, medical imaging, and support for internet connectivity has enormous application benefits for PSS industry. Such applications and services use variety of protocols above layer 3 for end-to-end connectivity, header contribution of these protocols is often significant and application of RoHC can help save effective bandwidth [Frank H.P. Fitzek, 2005]. This chapter presents the design, investigation and results of RoHC application on selected traffic profiles over TEDS. The Investigation presented in this chapter is a derivative of a study carried out as part of project for ETSI standardisation efforts.

In the section 3.2 application supports for TEDS is discussed, while section 3.3 explains the detailed structure of TEDS physical layer and integration issues of RoHC. The Next Section shows the header contribution of different header formats in traffic payloads and application support of RoHC for TEDS is also discussed. In following sections different traffic profile and impact of RoHC over these profiles are elaborated. Contributions in this chapter are also presented in [Shan R. , et al., 2010 & Shan R. , et al., 2012] and number of ETSI standard contribution mentioned earler.

3.2 APPLICATION SUPPORT FOR TEDS

The of selection of the communication protocol for layer 3 and above is based on number of factors but importantly on the application requirements, communication link, and transmission bandwidth. A variety of voice oriented application such as VoIP, short data applications like short message alerts for disaster relief systems, video camera and surveillance equipment, telemetric application for sending medical imaging and live video streams, patient records and secure files are some of the application domains supporting variety of connectivity protocols. VoIP over TEDS use RTP/UDP protocols for application data delivery. Different voice codec generate voice packets at different rates and variable payload sizes, performance of different voice codec over wireless channels is presented in [Marzuki, et al., 2010]. Video based services have enormous applications in PSS systems. Personnel in emergency and public safety situations equipped with video camera and surveillance equipment help in decision making during emergency situations. Enormous video application areas for PSS system have been discussed in detail in [Ford Carolyn, 2010]. Video applications mostly use UDP/IP protocols for transmission which enables connectionless, un-acknowledged and fast delivery and minimal delay over IP network. Medical application use RTP/UDP/IP for terminal connectivity to transmit medical data, such as medical imagery, ECG data and other data generated by medical sensors. In [Issa, et al., 2008] challenges for the medical applications over heterogeneous mobile communication systems are discussed. The TCP/IP based HTTP traffic is considered to analyse HTTP based services over TEDS.

3.3 TEDS CROSS LAYER SCHEDULING

TETRA supports two types of link service at LLC layer, unacknowledged basic and acknowledged advance link. In advance link each of the TEDS LLC Service Data Units (TL-SDU) is acknowledged by the receiver node. Table 3-1shows the TEDS class types and LLC link support type. Applications classified under different classes may use different link types at the LLC layer to justify their requirements. In this study, sample data profiles from each of the class are considered and simulated for the cross layer optimization.

Table 3-1: TEDS Class Type and LLC Link Type

Class Type	**Link Type**
Background	Acknowledged advanced link
Telemetry	Acknowledged advanced link
Real-time	Unacknowledged basic link
QoS not negotiated	Acknowledged advanced link

VoIP based applications use real-time un-acknowledged basic link over TEDS. Illustration of un-acknowledged basic link and advance link is shown in Figure 3.1 and Figure 3.2 respectively. SNCP and MLE add 16 and 3 bit of headers respectively and SDU is passed down to LLC and MAC layer. TL-SDU is marked with 4 bits of the LLC header, and the MAC layer then segments the TL-SDU to number of TM-SDUs. In the case of advance link each TM-SDU is added with separate MAC header of 23 bits, while in basic link each TL-SDU will have one LLC and one MAC header. CRC is added to each TM-SDU packet which is referred as MAC block as shown in Figure 3.1 [Casner S. J. V., 1999].

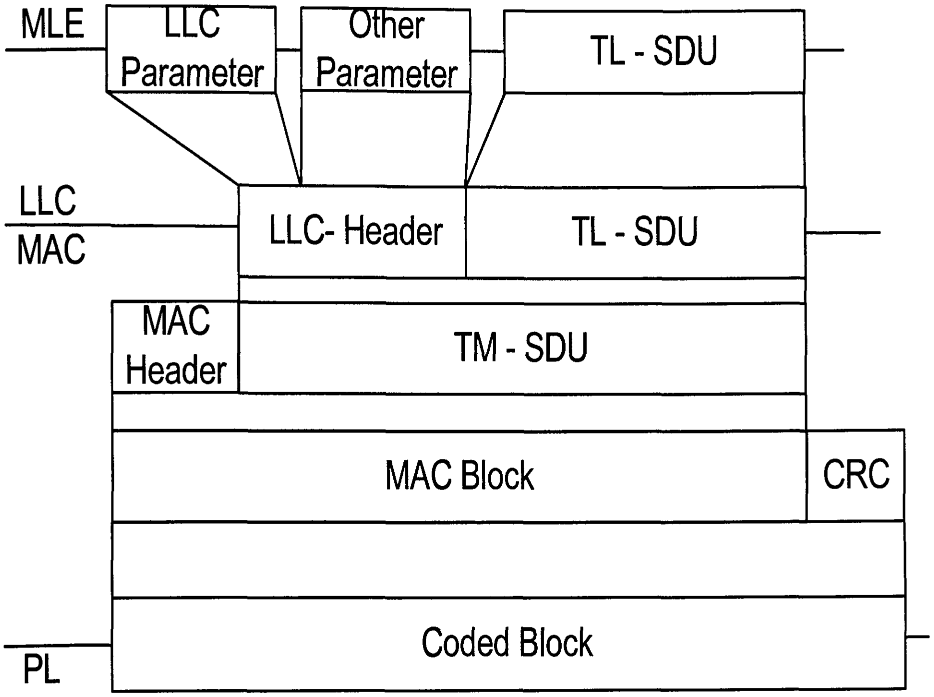


Figure 3.1: Data Structure for Basic link of TEDS

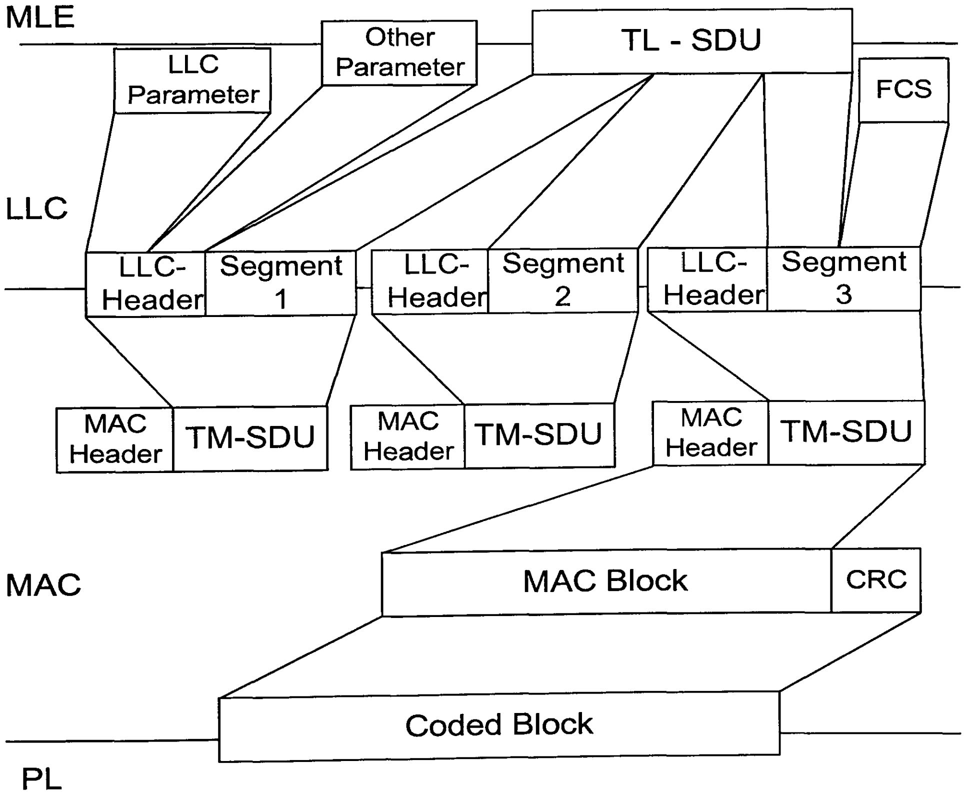


Figure 3.2: Data Structure for Advance link of TEDS

Segmentation at the LLC layer depends on the physical layer characteristics. Table 3-2 presents the TL-SDU capacity in bits mapped against modulation & coding schemes. TL-SDU at the LLC layer is mapped to the physical slot sizes of the physical layer.

Table 3-2: TL-SDU capacity (bit) of the respective Modulation and Coding scheme

PHY \ Bits	25 kHz	50 kHz	100 kHz	150 kHz
QAM – 4 Rate ½	185	421	893	1365
QAM - 16 Rate ½	389	861	1805	2749
QAM - 64 Rate ½	593	1301	2717	4133
QAM - 64 Rate 2/3	797	1741	3629	5517

Due to small VoIP packets, QAM 4 & 16 with 25 & 50 kHz are considered in the study, small TL-SDU capacity slots will help understand the slot gains due to header compression in the TDMA frame. TEDS supports 4 TDMA timeslots; however a user is only allowed to transmit on specified slots. Applications should be tolerant to the additional delay introduced at the physical layer due to limited allocation of transmission slots. One time slot for TEDS is 14.1667ms. If application is allocated one time slot per TDMA frame, there will be static delay of three slots on the receiver side. Applications can request more timeslots per TDMA frame, slot allocation depends on channel conditions, network traffic and application requirements. All of the 4 time slots are used for transmission in this study based on the recommendations given in [ETSI TETRA TR-102-580, 2007-10].

3.4 HEADER CONTRIBUTIONS

VoIP packets when carried through IP based protocol stack, application, transport and network layer adds a respective header to the payload. As a result the payload becomes just a portion of the total size of the packet. In VoIP packets with small payload size the header contribution percentage is significantly higher than the application with large payloads. RTP/UDP/IP layers add a header of 40 bytes to the payload, while payload size of audio frames ranges from 20-40 bytes [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. The size of RTP header is 12 bytes [Schulzrinne, et al., 2003] and some of the key information added by the RTP header is 7 bit payload type to identify the type of the payload generated by the application. A 16 bit sequence number and a 32 bit timestamp are used to identify the packet sequence and their timestamp with respect to the generated packet stream [Schulzrinne, et al., 2003]. A 32 bits synchronization source identifier is chosen randomly with the intent that no two synchronization sources within the same RTP session will have the same SSRC identifier. The size of UDP header is 8 bytes with source and destination ports, payload length and checksum of 2 bytes each. Similarly the size of IPv4 header is 20 bytes, while the size of IPv6 header is 40 bytes [Defense Advanced Research Projects Agency, 1981]. Each of these layers will increase the packet size by certain fraction depending on the voice codec used. A summary of header size and rate contribution to the payload for the respective layer is given in Table 3-3. These header contributions make a significant portion of the actual transmission bandwidth of the systems. It is shown in the table that if faster codec is chosen than header contribution will be more

Table 3-3 : Header contributions of header types against the rate

Protocol	**Header Size (bits)**	**Rate (kbits/s) at period 20ms**	**Rate kbits/s at period 30ms**
RTP	96	4.69	3.13
UDP	64	3.13	2.08
TCP	160	7.81	5.21
IPv4	160	7.81	5.21

The performance of VoIP over narrowband systems and behaviour of different codec over wireless channels is discussed in [Nguyen, et al., 2001 & Lee H. K.-D.-H., 2009]. Although not significantly very high but for a system like TEDS, large header sizes are an overload and bandwidth can be saved without compromising the QoS. Similar header contributions effect the video and medical data application. The size of video frames range from a few hundred bytes to a few thousand bytes. The header percentage contribution in small payloads is more than the bigger payloads. Large header sizes affect the performance especially over narrow bandwidth systems such as TEDS.

3.5 APPLICATION OF RoHC FOR TEDS

RoHC was proposed to compress the large RTP/UDP/IP headers and increase the system throughput without compromising the QoS [C. Bormann et al, 2001]. RoHC can compress the RTP/UDP/IPv4 header up-to 3-7 bytes [Wang Hui, 2004 & Frank H.P. Fitzek, 2005] over wireless link and 3-5 bytes for wired / on-chip solutions [EFFNET Lab, 2007 & Taylor D. , et al., 2005] with promising header compression gain between 84% - 94% [Piri, et al., 2008]. Real time multimedia applications exhibit similar traffic profile which qualifies for the application of RoHC. TETRA uses 4 slot based TDMA scheme for transmission. Size of each slot is fix, while size of the payload depends on the logical channel used. However application payload for most common application profiles is in tens of bytes while the header appended before the SNDCP layer is up to 60 bytes depending on the protocol combination. In case of VoIP based traffic application payload is about 20-30 bytes while IPv6 header contribution is around 60 bytes. If header can be compressed down to 2-3 bytes then the application packet may fit in to one TDMA slot. This will not only save the bandwidth but also improve the rate of packet drop rate but potentially saving the header being affected by the erroneous slot. These benefits highlight the significance of header compression for narrow band systems with limited transmission bandwidth running high rate short payload application.

RoHC could be a benefit on both phase modulation and QAM channels. Particular applications of interests would be sending the TETRA coded speech frames as packet data in form of VoIP and using RoHC to minimize the bandwidth used by the speech so that other packet data can be sent at the same time. However there is no published information on the performance of RoHC in narrow band systems such as TETRA or any of the PMR technologies. The purpose of this study is to quantify the benefits to be obtained from the use of RoHC and provide a numerical analysis on the implementation, and actual benefits to be expected from using RoHC. It is important to note that the benefits of using RoHC could be extended to all TETRA based MS that can use IP based data.

Any new enhancement such as RoHC added to the TETRA standard would increase its competitiveness and hence results in an increased performance. RoHC is expected to increase the efficiency of IP packet transmission, particularly for smaller packets (VoIP etc) and hence enhance the system throughput. This results in a cost reduction per call and therefore adds to TETRA's global market. This enhancement is expected to have a higher impact on TEDS systems and beyond (wide-band and broadband TETRA) in which IP traffic is highly dominant. In addition to improving the global read of the TETRA standard, the use of RoHC (together with other optimization enhancements) ensures a longer life span for TETRA standard. TETRA users can benefit from increased packet data transmission efficiency in dealing with a range of existing and new applications and TETRA manufacturers and suppliers can gain earlier market entry and higher revenues. Challenges for the possible integration

TETRA could be the RoHC performance under sever channel conditions such as HT-200.

This study aims to investigate the application of RoHC for TEDS for various traffic models including VoIP. Video profiles, medical ECG type data and web traffic models are also briefly discussed.

3.6 TRAFFIC PROFILES FOR TEDS

Some of the traffic models discussed in [Maui, 2006] are used in this study, which outlines the traffic profiles for CDMA2000 testing environment, which is a mobile communication channel similar to TETRA. For TEDS we selected four traffic profiles, voice streaming of VoIP based data for voice streaming type, CCTV data traffic for video streaming, ECG data traffic for medical class. All of these three traffic types are based on UDP/IP, voice and video profiles use real time data class while medical type data use telemetry class. HTTP traffic type is used for acknowledgments based TCP type which is based on background class.

3.6.1 VoIP Traffic Profile

The choice of codec is a trade-off between voice quality, processing power and bandwidth requirements. The size of packet and the rate at which the packets are sent depends on the corresponding voice codecs and compression schemes. Table 3-4 present different vocoders and their corresponding bit rate, frame size and symbol period.

Table 3-4: Audio Codec rate, Frame size and Period (ms)

Voice/Audio Codec	kbits/sec	Frame size (bits)	Period (ms)
TETRA	4.57	137	30
GSM-FR	13	264	20

GSM-HR	5.6	132	20
GSM-EFR	12.2	248	20
AMR	4.75 -12.2	95-224	20
AMR-WB (G.722.2)	6.6 -23.85	132-477	20
AMR-WB+	48	960	20

The TETRA codec is used for this study which generates 137 bits for each frame after every 30 ms resulting in a bit rate of 4.57 bit/s [Byun, et al., 2008 ,TETRA ETS 300 395-1, 1997]. In [Dimitrios I. Axiotis, 2008] impact of voice traffic on the performance of packet data transmission in TETRA networks is discussed.

In some applications it may be desirable to concatenate more than one audio stream into the same RTP/IP packet. Similarly, to decrease the proportion of headers, several VoIP packets can be combined and passed down to the respective layers as one packet. The previous assumption is an interesting potential method for broadcasting several simultaneous streams from one or more sources. Another more interesting method is where packets from a single TETRA voice stream are buffered and sent together as a single larger packet. By applying such a technique, payload efficiency is improved. Latency is increased and error tolerance may degrade as more data is lost in the event of a burst error. Piri, et al., [2008] applied the similar scenario over WiMax and Table 3-5 shows the number of VoIP packets concatenated together as one packet. The packet interval is 30ms for each concatenated packet. Payload size is the total size of the packet generated at the interval plus the added header, which includes the payload RTP/UDP/IP header along with SNDCP and MLE headers.

Table 3-5 : Concatenation of VoIP packets

Packets Concatenated	Period Interval(ms)	Payload Size (Bytes)
1	30	18
2	60	35
3	90	52
4	120	69
5	150	86
6	180	103
7	210	120
8	240	137
9	270	155
10	300	172

3.6.2 Video Traffic Profile

Effective application bit rate offered by TEDS is not suitable for good quality video streaming applications. Maximum slot capacity of 64 QAM with channel coding rate 2/3 is under 700 bytes as shown in Table 3-2 while size of I frame is between 3000 bytes to 10000 bytes. The consequence video streaming over TEDS suffers high packet drop and frame skipping. Table 3-6 shows the characteristics of the video files simulated over the TEDS test bed for the purpose of verification of RoHC performance. Two video trace files were selected with properties to analyze the performance of low and medium quality video over TEDS. A higher percentage of I frames in medium quality video can affect the performance of the profile. In a study of video codec performance over 3GPP a frame rate of 12-15 frame/sec is employed [3GPP TR 26.902 V8.0.0 , 2008-12]. Results for header compression of 12 frames/sec and 24 frames/sec with and without RoHC are presented.

Table 3-6: Video Trace Data

MPEG Footage quality	Mean Bit rate (kbits/s)	Peak Bit rate (kbits/s)	Mean Frame (kbytes)	% of I frames	Variance Frame Size
Low	42	690	0.21	~20%	230
Medium	58	690	0.29	~30%	220

Video streaming over TEDS experiences jitter and QoS is compromised for critical real time applications. However for managing the streaming attributes like, frame rate and video quality, non-critical and offline video applications can perform considerably better. Large I frames can cause packet congestion at layer 2 which is managed through a dynamic buffer. Frames are temporarily stored before LLC to give enough time for the scheduling each frame. We introduced a buffer with considerable size to decrease packet drop due to congestion at LLC layer caused by difference in slot capacity and frame size. Similar techniques are applied for packet congestion at layer 2 in various studies [Hussain, 2009 , Wu, et al., 2001, Chang, et al., 2003]

3.6.3 Medical Traffic Profile

In Table 3-7 different traffic profiles for medical data types are shown. These data rates are typically presented as packets between 25 to 300 byte based samples at the variable rates depending upon the waveform/dataset selected. Data rates for application vary between 100ms to few seconds. The nature of medical data and level of detail required determines the application data rate. Fast rate medical data application will have more header contributions against the slow rate application. Medical data use acknowledgement based advance link at LLC layer and use telemetry class for data delivery. By employing these features mean that TETRA offers more reliability for sensitive information. To investigate RoHC performance over telemetry class we have selected ECG impedance data profile. Data is streamed at 25bytes every 100ms and variation of slow data rates [Hauzner, 2008 & Maui, 2006].

Table 3-7: Medical Data profiles for TEDS

Model Ref	8bit Samples/s	Unit
M1.x	300	ECG x: µV
	300	EEG Bispectral index
M2.x	100	EEG 1/10 µV
	100	Invasive blood pressure x: 1/100 mmHg
M3.x	25	CO2 concentration
	25	02 concentration
	25	N2O concentration
	25	Anaesthesia agent
	25	Airway pressure
	25	ECG impedance
	25	Tonometry catheter pressure: 1/10 mbar

3.6.4 TCP Traffic Profile

The HTTP Service uses TCP/IP as standard protocol for process to process delivery from HTTP server to HTTP client. In this study a HTTP server is considered hosted at TETRA base station and mobile station hosts the HTTP client. At the HTTP Server the HTTP protocol is transported on to TCP/IP layer as stream of bytes which are packaged into packets of Maximum Transmission Unit (MTU) length. MTU is the Maximum number of bytes which can be packaged into one TCP/IP packet. MTU length of 1460 Bytes and 576 Bytes are investigated. Statistics given in [ComScore, 2010] show that 76% of IP systems are configured with a MTU=1500 bytes and 24% are given as 576 bytes.

The HTTP traffic model is defined by size of main object in page, number of embedded objects in a page, size of an embedded object in page, reading time and parsing time for the main page. We have selected minimum, mean and maximum attributes of these parameters for investigation purpose. Different HTTP traffic patterns are investigated for the RoHC performance over TEDS. Header compression ratio and round trip time are the major parameters investigated. HTTP traffic use background class, which can be used with basic or advance link at LLC layer. The transmitter sends one packet and waits for the acknowledgement for certain time. Round Trip Time is calculated based on the time taken by one MTU packet received at receiver and sending back the acknowledgement. Different flow control strategies are used based on the nature of application, system performance, channel conditions, bandwidth and memory limitations defined in [ComScore, 2010 & IEEE 802.16m, 2007] Flow control strategies are used to manage the ACK/NACK the transmission rate, window size and buffer size also depends on the flow control strategies like Stop-and-wait ARQ, Go-Back-N ARQ, Selective Repeat ARQ.

3.7 SIMULATION DESIGN OF RoHC OVER TEDS

The investigation of performance of RoHC over TEDS is carried out over the simulation design given in Figure 3.3. The application generates the payload size based on the traffic profile models discussed in previous section. The payload is passed on to the respective RTP/UDP-TCP/IP layers. Each layer adds its own header and passes down the packet to the SNDCP layer. The SNDCP layer will negotiate the QoS parameters prior to the transmission on behalf of application with the receiver. Once QoS context is set, application packets are passed down to the layer 2 &1 for segmentation, coding/modulation and transmission. RoHC compression and decompression is placed at SNDCP layer on both transmitter and receiver respectively. RoHC implementation is for TEDS is modified version of open source library at [Launchpad , RoHC, 2009] RoHC feedback in bidirectional mode works between RoHC compression & decompression. Selection of the compressed header is based on the static nature of the fields over the transmission session. RoHC promises to compress the header to 3-6 bytes [C. Bormann et al, 2001, EFFNET Lab, 2007 & Launchpad , RoHC, 2009]. Figure 3.3 shows the system architecture used for the study of RoHC over VoIP, video, ECG and HTTP traffic profiles for TEDS.

Voice and Video traffic uses real-time class based on the unacknowledged basic link at LLC layer. TL-SDU capacities for respective physical layer parameters are shown in Table 3-2. Medical data use telemetry class with advance link, while HTTP traffic uses background class with both basic & advance link.

TETRA VoIP packets carried 137 bits generated by the TETRA audio codec which is carried by the RTP, UDP and IPv4 layers to the SNDCP layer while each of these layers add its own headers. SNDCP layer selects the TL-SDU and physical layer specification as given in Table 3-2. The RoHC header is calculated based on the field information from the RTP/UDP/IPv4 header fields. The compressed header is semantically identical to the original header and there is no ambiguity in translation on either end. LLC and MAC layer segmentation over the packet processed by SNDCP will result in TL-SDU & TM-SDU respectively based on basic link as shown in Figure 3.3. TL-SDU size capacities are managed by the SNDCP layer based on the chosen QoS class parameters. QAM – 4 and QAM – 16 at 50 – kHz with ½ rate channel coding is selected for the simulated. Slot capacities for the selected profiles are shown in Table 3-2. Segmented packets with layer 2 headers are passed to the physical layer for channel coding and modulation. Simulation is carried out on

TETRA propagation channel models i.e TU-5, TU-50 and HT 200. We have simulated the VoIP traffic over 1%, 2%, 5% and 10% message error rate (MER) at the channel. Message is termed erroneous if one bit out of whole packet is received erroneous. Message error rate is the ratio of erroneous messages/packets over the total number of transmitted messages. MER values were calculated against the specified SNR values given in [ETSI TETRA TR-102-580, 2007-10 & Casner S. J. V., 1999]. At the receiver side packets are received and reassembled at layer 2 and passed the packet to SNDCP layer. VoIP packet aggregation is employed to simulate the runtime multi-packet scenarios. VoIP packet aggregation would affect the payload size, header contribution and delay. RoHC decompression will re-calculate the original header and pass the packet encapsulated with the recalculated RTP/UDP/IPv4 headers to respective layers. Simulation traffic is analysed for RoHC compression, header compression gain and number of packet drops over the channel. A similar environment is setup for ECG traffic model.

Due to large video frame size, the frame buffer is implemented at LLC layer, large frames are buffered at the LLC layer before they are passed on to LLC layer for TL-SDU segmentation. At the LLC layer on the receiver segmented packets are combined to form a video frame. The simulation environment for the study is carried out over the propagation model for TETRA at various message error rate values. MER percentage is number of erroneous messages against certain SNR. For 10% MER simulation was setup at specific SNR for the duration of length of video stream. Video profiles are simulated over the TU-50 TETRA propagation channel for 2%, 5% and 10% MER. At Physical layer QAM 64- rate 2/3 with 150 kHz bandwidth is simulated over the TETRA Channel for each traffic profile.

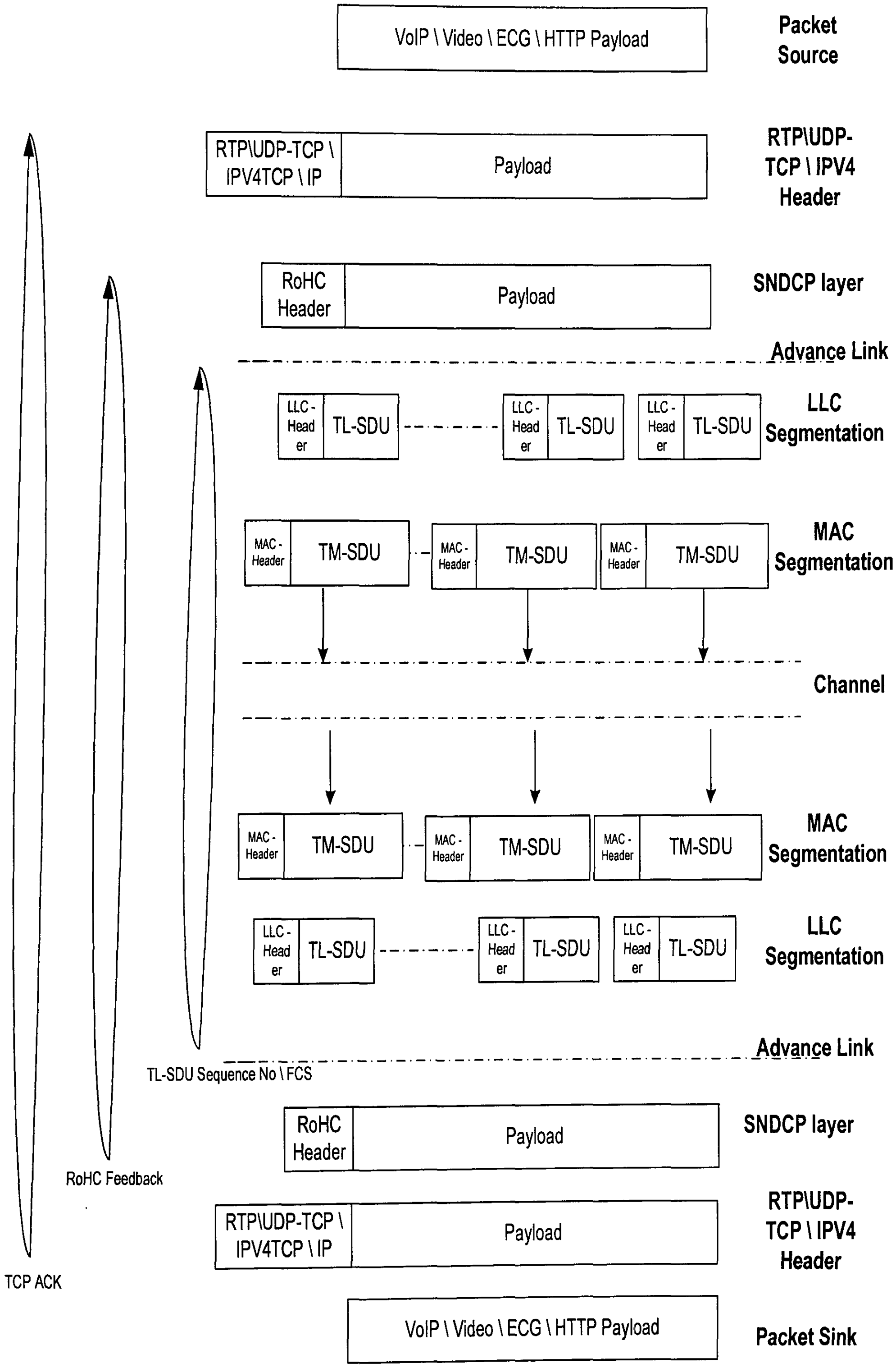


Figure 3.3 : Simulation Setup for Performance analysis of RoHC over VoIP, Video, ECG & HTTP profiles for TETRA

3.8 OBSERVATION ON ROHC PERFORMANCE OVER TEDS

This section explains the results and observation on the RoHC performance over TEDS for VoIP, Video, ECG and HTTP traffic models. Results are presented for VoIP, Video, ECG and TCP profiles.

3.8.1 RoHC Performance over VoIP

TEDS Simulation scenarios discussed in Section 3.6 are tested for TETRA codec generating VoIP packets of various payload sizes. Table 3-8 in Uncompressed Header Percentage column shows the percentage of uncompressed RTP/UDP/IPv4 header in the VoIP packet with various concatenation of payload. The payload size shown in Table 3-5 suggests that uncompressed header percentage is significant with single VoIP payload, and header percentage will decrease with increase in the payload size i.e in case of VoIP packet aggregation. We have concatenated TETRA codec payload to observe the RoHC performance over various payload sizes. As a result of large header contributions and limited slot capacities as shown in Table 3-2, VoIP packet do not fit into one time slot. VoIP codec payload is only the small fraction of the total packet size. It is observed that due to header compression, compressed packets can fit into one time slot. VoIP packets fitting into one time slot due to reduced header results in less packet errors and save some of the transmission slots.

In case of QAM 4, 25 kHz rate ½ we have TL-SDU capacity of 185 bits, one VoIP payload is 137 bits and with RTP/UDP/IPv4 headers make it 60 octets and takes 2 slots for transmission. If the header can be compressed to 4-6 bytes we can fit the VoIP packet into one slot which is significant gain in effective throughput. The transmission of VoIP packet in one timeslot reduces the chances of header being lost during the transmission. However, in case of payload concatenation slot gain may not be uniform, but header compression does save number of transmission slots and increase the effective throughput. We have analysed the RoHC performance over QAM 4, 50 kHZ rate ½ and QAM 16, 50 kHZ rate ½ over TU-50 propagation channel.

Table 3-8: Average* RoHC header percentage over different MER based on QAM 4, 50 kHz rate ½ over TU-50 Channel

Payload Concatenation	Uncompressed Header Percentage	Average RoHC header percentage with respective MER			
		MER 1.01%	MER 1.59%	MER 4.13%	MER 9.5%
1	66.67(%)	13.01(%)	13.06(%)	13.85(%)	14.48(%)
2	51.95(%)	7.45(%)	7.6(%)	8.26(%)	8.92(%)
3	42.55(%)	5.27(%)	5.52(%)	6.21(%)	6.81(%)
4	36.04(%)	4.11(%)	4.4(%)	5.01(%)	5.74(%)
5	31.25(%)	3.45(%)	3.66(%)	4.27(%)	4.88(%)
6	27.40(%)	2.95(%)	3.16(%)	3.75(%)	4.33(%)
7	24.54(%)	2.65(%)	2.85(%)	3.39(%)	3.92(%)
8	22.22(%)	2.41(%)	2.6(%)	3.09(%)	3.63(%)
9	20.30(%)	2.21(%)	2.4(%)	2.87(%)	3.4(%)
10	18.69(%)	2.06(%)	2.27(%)	2.7(%)	3.2(%)

*Average RoHC header percentage is calculated over 10,000 VOIP packets

Table 3-8 shows the RoHC header percentage in the IPv4 packet which is reduced significantly as compared to uncompressed header percentage shown in Table 3-8 in Uncompressed Header Percentage column. Uncompressed header contributes significant percentage in the VoIP packet; RoHC has compressed the long IP header considerably reducing the header percentage. Increasing MER affects the average header percentage this is due to more channel errors which cause the RoHC decompression to fail and increase the compress header percentage. Channel errors affect the RoHC performance and RoHC context is lost. Header percentage is increased due to updating context initialization between RoHC compression and the decompression. header size simulated with over 5 minutes call duration over VoIP which makes 10,000 VoIP packets. It is observed that RoHC header size is from 3-6 bytes, which is significantly less than the RTP/UDP/IPv4 header. It is also noticed that with increasing MER from approximately 1% to 10% RoHC header size increases from just over 3 bytes to just over 6 bytes.

Header compression gain shows the efficiency of RoHC to compress the RTP/UDP/IPv4 headers against different MER for various packet concatenations. For single concatenation and low MER RoHC was able to compress up to 92.5% of the header while with bigger payload and bad channel conditions i.e 9.5% MER compression gain is approximately 85.5%. RoHC compression gain shows the potential saving of bandwidth and efficiency of the RoHC compression/ decompression. There is a gradual decline in header compression gain with increase in MER. However RoHC successfully compressed 92.5% to 84.5% of the RTP/UDP/IPv4 headers. The Performance of RoHC over Multimedia transmission for 3G/4G networks is 84%-93% [Frank H.P. Fitzek, 2005 & Wang Hui, 2004] compression gain. Bandwidth saved due to this compression gain may be less significant for wideband systems but this is vital for band limited systems.

Figure 3.4 shows Percentage Gain Header Compression for QAM 4 & QAM 16 over HT-200 Channel at specified MER. HT 200 is 12 tap delay line channel model which exhibits harsh channel conditions and performance of specified modulation schemes for such harsh channels is challenging. Performance of RoHC under such challenging environment is slightly worse than TU-50 channel. Header compression gain for both modulation schemes under specified parameters ranges from 86% to 92.5% approximately. Performance of QAM 4 is better and it offers better compression gain than QAM 16 which is due to the performance difference between the two modulation schemes. Similarly RoHC is tested for TU-5 channel model, which is a 6 tap delay line pedestrian channel [ETSI TETRA ETR-300-1, 1997] with small Doppler spread and performs better than HT-200 and marginally better than TU-50 channel. Performance of RoHC under TU-5 exhibits the similar behaviour

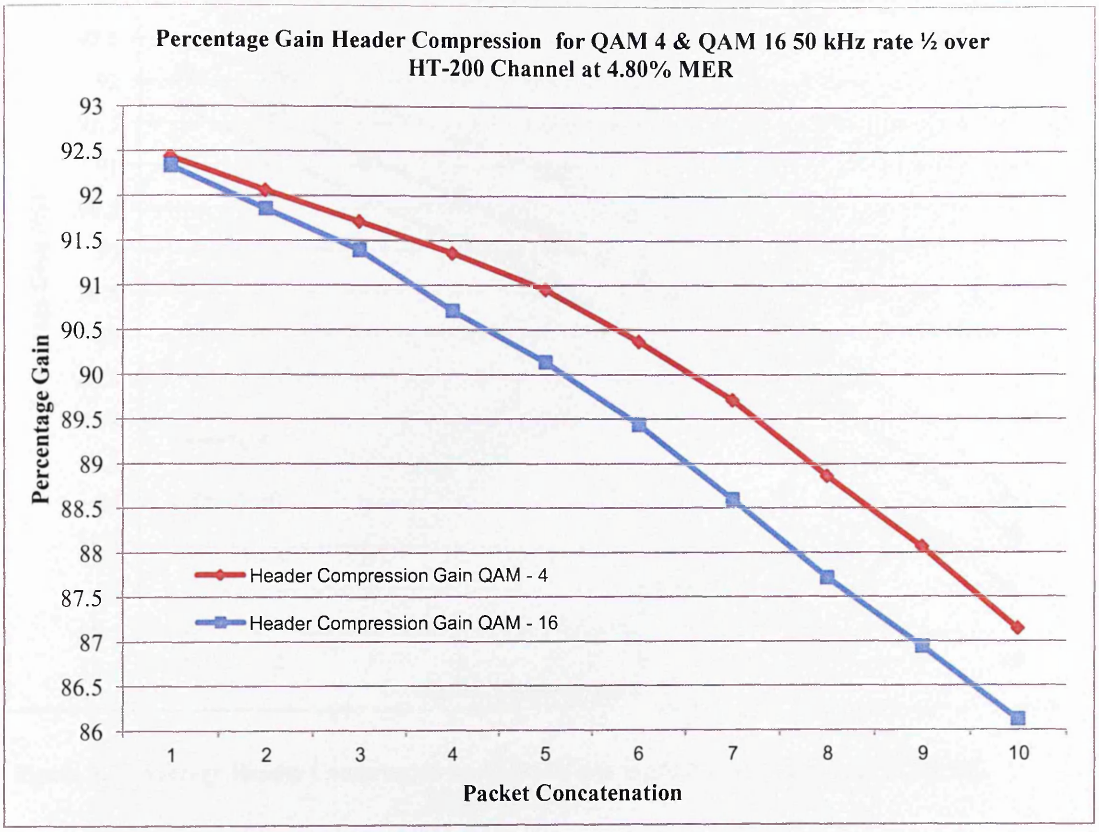


Figure 3.4 : Percentage Gain Header Compression for QAM 4 & QAM 16 50 kHz rate ½ over HT-200 Channel at MER 4.80%

Figure 3.5 shows the average header compression gain for QAM 4 over different propagation channel models for TEDS and sums the performance of RoHC over discussed channel models for 5% MER. We can observe the HT-200 has the worst compression gain; due to the challenging channel conditions and high Doppler value. Due to packet drops the RoHC compressor losses the context more frequently and context initialization is required for RoHC compressor to work more effectively. Similarly performance of RoHC over TU-50 is marginally less than the TU-5 channel model, again it is due to the properties of channel model and RoHC context needs frequent initialization than TU-5 channel. RoHC offers compression gain of 86% to 92.5% for QAM 4 at 5% MER, which is valued for band limited systems like TEDS.

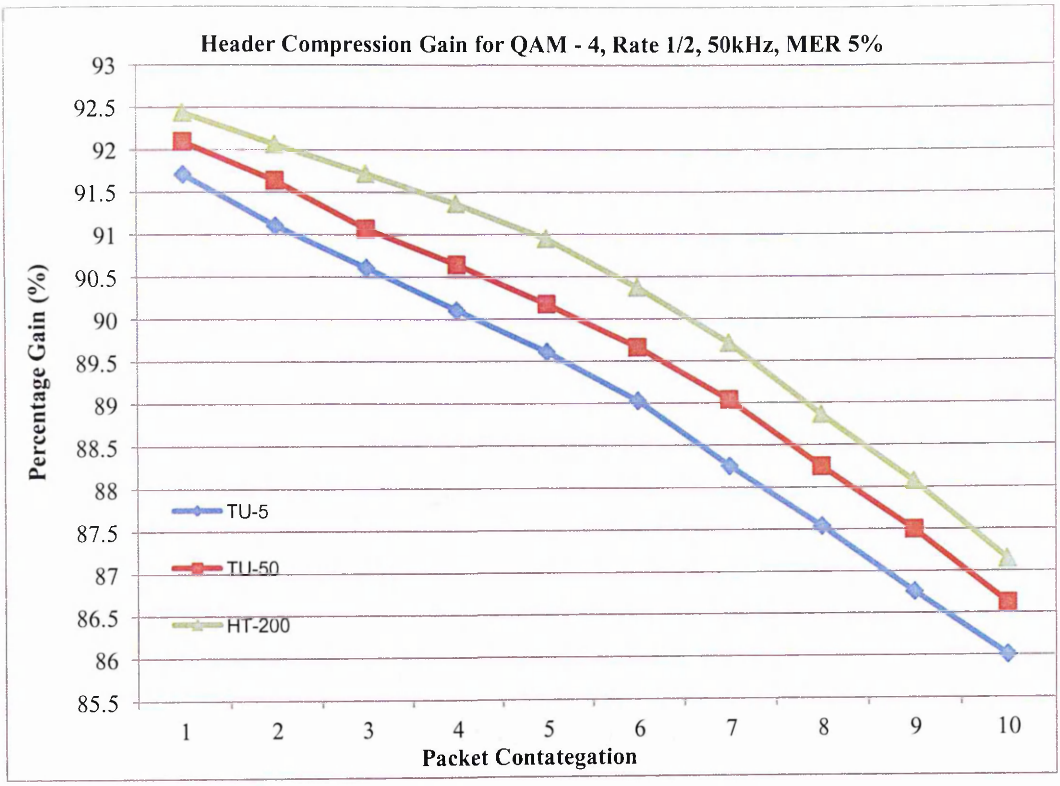


Figure 3.5 : Average Header Compression for QAM-4, rate ½ 50 kHz at 5%MER for TU-5, TU-50 and HT-200

Figure 3.6 shows the overall gain in bandwidth due to header compression. Gain in the bandwidth in kbps, due to header compression, is shown against the rate of IP packets generated by different RTP based applications. It is evident that fast rate RTP applications have higher gain in terms of bandwidth than the slow rate RTP applications. UDP gain is less than RTP gain as header contribution for RTP /UDP/IP is 40 bytes and UDP/IP is 28 bytes. Application of RoHC is more beneficial for small payload size applications such as voice and medical applications over TEDS.

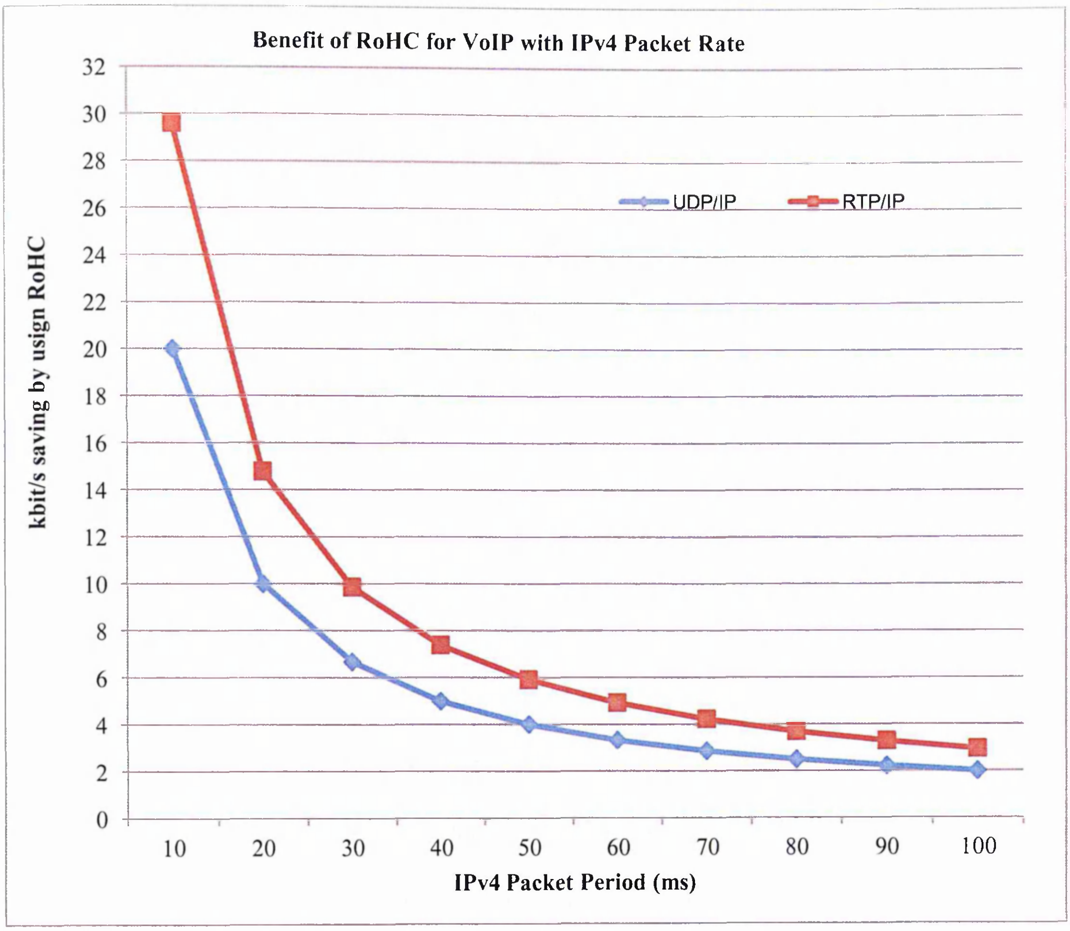


Figure 3.6: Bandwidth saved by using header compression for over RTP/UDP/IP for VoIP packets generated at different packet rates

3.8.2 RoHC Performance over Video

Based on the video profile statistics, the percentage of uncompressed header is uniform against the similar payload size. RoHC compresses the large header, thus reducing the header percentage in the frame. Channel errors affect the RoHC performance and RoHC context is lost. Header percentage is increased due to updating context initialization between RoHC compression and the decompression. It is observed that the header percentage in the compressed header for higher MER is slightly more than the header percentage for low MER. Physical layer parameters used in the study are QAM 64, rate 2/3 at 150 kHz. This is the maximum slot capacity available for TEDS. For slot capacities smaller than mentioned parameters will have degraded performance. For low quality video the average header percentage against 8.73% MER is 1.83%.

Table 3-9: Average Header Percentage for Low & Medium Quality Video over QAM 64 rate 2/3 150MHz at TU50

Message Error Rate(MER)	Average Header Percentage Low Quality Video over TEDS		Average Header Percentage Medium Quality Video over TEDS	
	Average Header % uncompressed	Average Header % compressed	Average Header % uncompressed	Average Header % compressed
1.84(%)	13.67(%)	1.56(%)	9.18(%)	0.98(%)
4.82(%)	13.67(%)	1.72(%)	9.18(%)	1.09(%)
8.73(%)	13.67(%)	1.83(%)	9.18(%)	1.18(%)

In the case of average header percentage for medium quality video over specified physical layer parameters, it is observed that, header percentage of uncompressed header for medium quality video is smaller than low quality video. The difference is due to the larger frame size for medium quality video. RoHC have compressed the header and reduced the header percentage to 1% of the average packet size. For medium quality video the average header percentage against 1.84% MER is 0.98%. The gain for the low quality video is slightly higher than the medium quality video. The difference is due to the fact that medium quality video carries larger frame size packets than low quality video, thus having a lesser uncompressed header percentage as shown in Table 3-3. Increase in the MER will affect the RoHC performance. Higher Message error requires more frequent context exchange, thus decreasing the header compression gain. Figure 3.8 and Figure 3.9 show the average packet drop of the system at the RoHC and application end. Significant packet drop causes frame skipping, flicker and poor video quality at the receiver. The residual errors were managed by dropping the erroneous headers at the RoHC receiver.

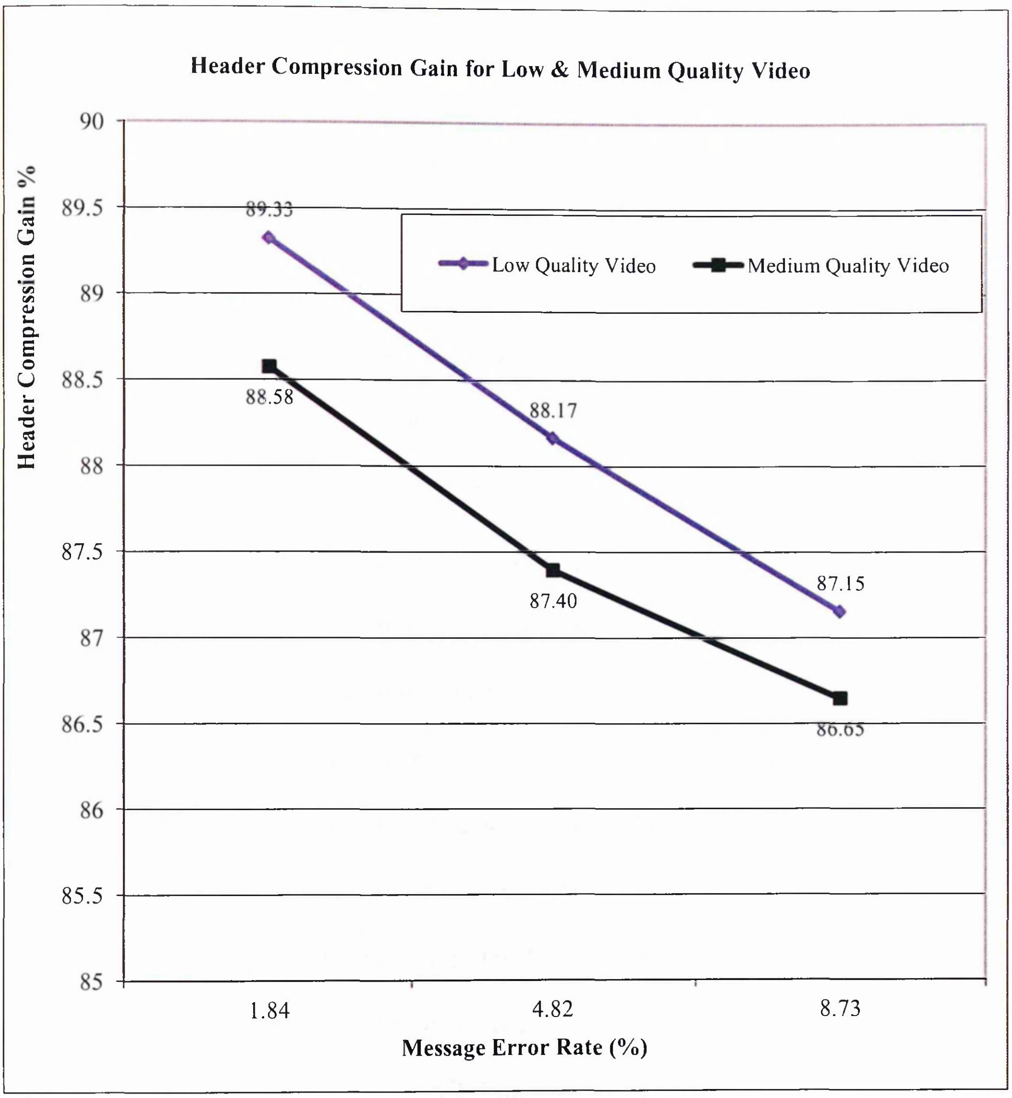


Figure 3.7: Header Compression Gain Percentage of RoHC for Low and Medium Quality Video over TEDS.

The average number of slots used by the specified video profile based on the used physical layer parameters can be calculated from the average packet size with compressed header against slot capacity. These values are averaged over 25,000 frames transmitted. For low quality video profiles fewer slots are required on average for low MER values than higher MER values. For Medium quality video the average number of slots is more than the low quality video due to large frame size. Higher MER will increase the average number of slots. P and B frames are carried in up to two slots while I frame, being the biggest of all, is carried in up to twelve timeslots. The average size of I frames in the sample profiles is 5Kbyes with a range from 3Kbyes to 12Kbytes. Due to the large size of I frame, not only is the average number of slots increased but also packet drop due to packet congestion and delay at the receiver. A video frame rate at 25 frames/sec will generate one I, P or B frame every 40 ms while one TDMA slot takes 14.167ms. I frames can take more than 4 time slots which will cause delay and packet drop. The large frame size also affects the performance of RoHC as loss of frame due to congestion or channel error affects the context information at the RoHC receiver. During the study it was observed that there is a significant packet drop due to large frame size, fast frame rate, limited bandwidth and no buffering at the transmitter and receiver for large frames. The packet drop observed at the receiver application is higher than the channel MER. Under perfect conditions, application errors are always less than the channel errors, but due to factors mentioned above application errors are more than channel errors. Large packets are stored for short time before the LLC layer to ensure smooth LLC/MAC scheduling. However another solution to the problem is to transmit the video at slower frame rate. Slow frame rate, i.e. 16-12 frames/sec will also help decrease the packet drop.

Figure 3.8 shows the application packet drop percentage for low and medium quality video with RoHC at the rate of 25 frames/sec over QAM 64 rate 2/3 150MHz at TU50. The graph shows the higher application packet drop than the channel message error rate. This abnormality is due to the large size of video frames and limited bandwidth of TEDS.

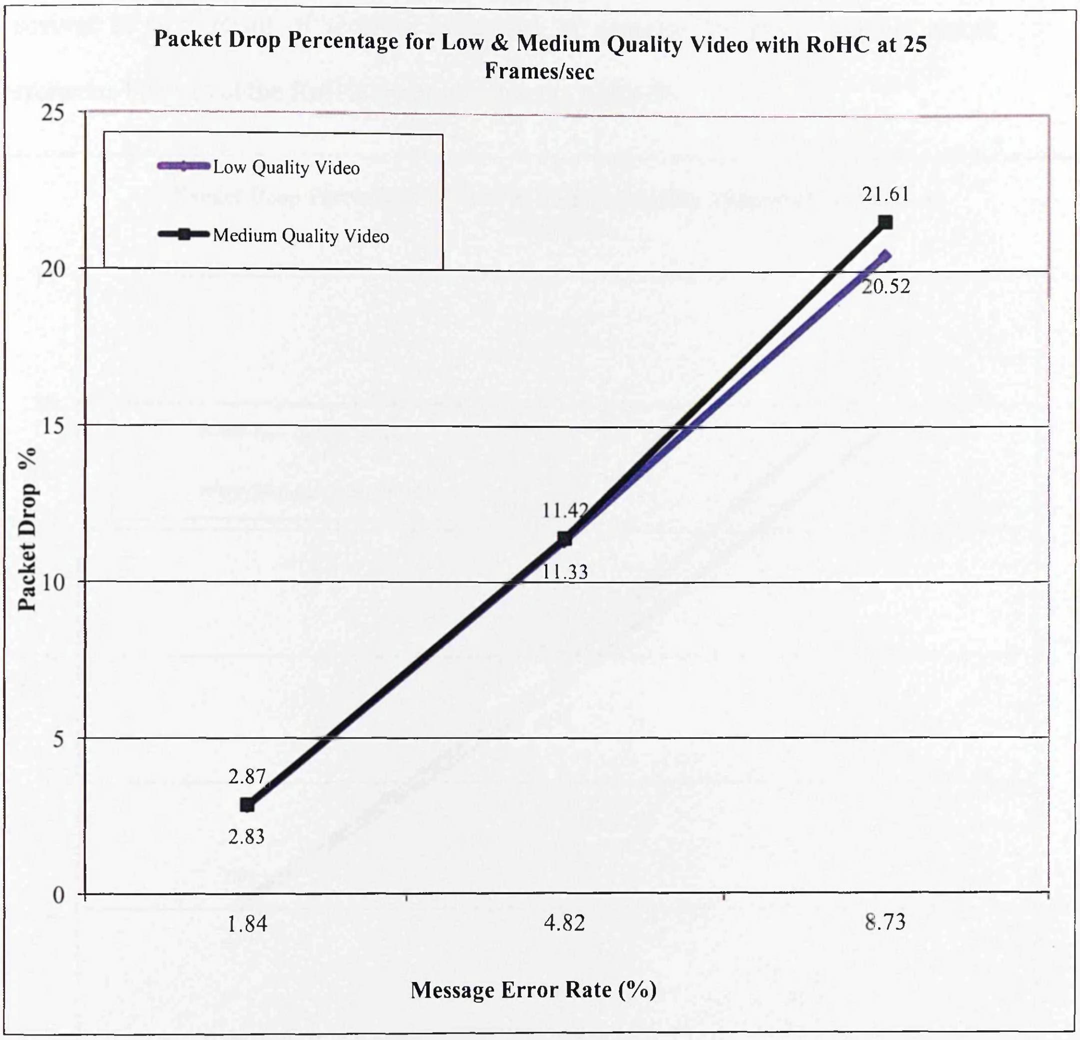


Figure 3.8 : Application Packet Drop Percentage for Low & Medium Quality Video with RoHC at 25 Frames/sec simulated over QAM 64 rate 2/3 150MHz at TU50

Figure 3.9 shows the application packet drop percentage for low and medium quality video with the RoHC at reduced frame rate with added buffer at layer 2 on both transmitter and receiver. There is a significant decrease in the average packet drop rate due to the introduction of buffer at layer 2 and reducing the frame rate. Reduction in frame rate also introduces a delay at the receiver. These packet drops are observed at the application which includes the packet drops due to RoHC. It is observed that there is approximately 1% or less, packet drop rate due to the RoHC. Packet drop at RoHC receiver is as a result of receiver being out of context. To avoid residual errors erroneous headers at the RoHC are dropped at the SNDCP

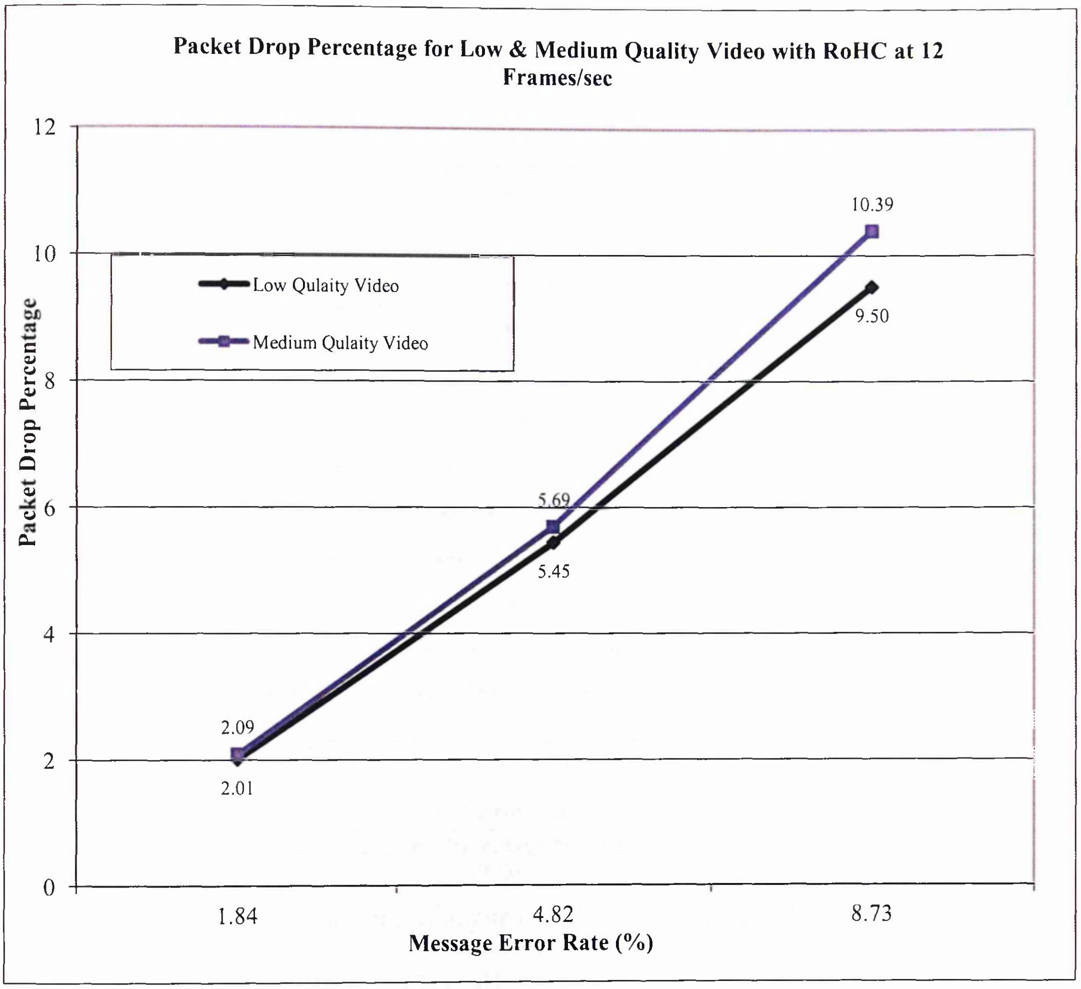


Figure 3.9 : Application Packet Drop % for Low & Medium Quality Video with RoHC at 12 Frames/sec & buffer at layer 2 simulated over QAM 64 rate 2/3 150MHz at TU50

3.8.3 RoHC Performance over Medical Data

ECG data profile is simulated over the TEDS stack to analyse the RoHC compression. Header percentage in an uncompressed header is around 6.25% which is then compressed down to 0.5% of the packet size. ECG data is medical class data transmitted over an acknowledged LLC link type. Figure 3.10 shows the average header compression percentage for medical data using advance link over TETRA channel. Over advance link there would be additional delay for which the target application must compensate while defining QoS.

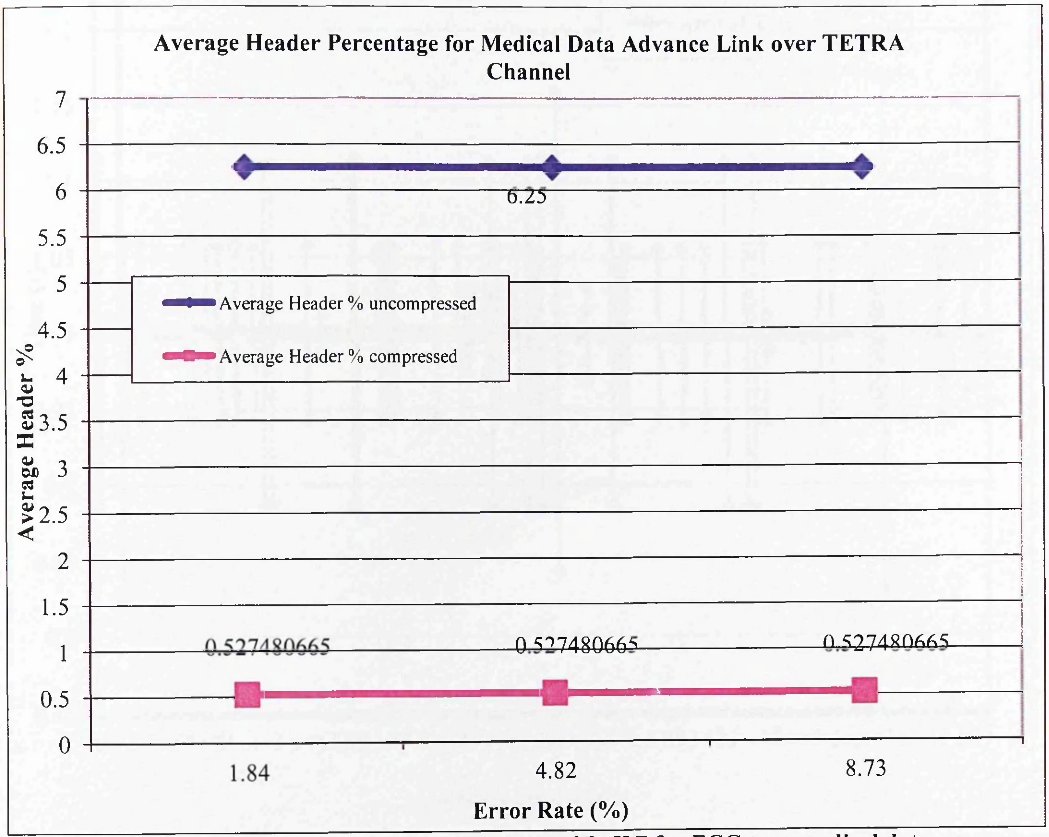


Figure 3.10 : Header Compression Gain Percentage of RoHC for ECG type medical data over TEDS.

Figure 3.11 shows the arrival time at application level for medical data over advance link for TETRA channel at 8.73% MER. Although medical data packets are transmitted every 1 sec, the difference in inter arrival time can be observed. Delay in the packets is distinctive; similarly we can see the mutual difference of the packets to be approximately 1 sec or slightly over.

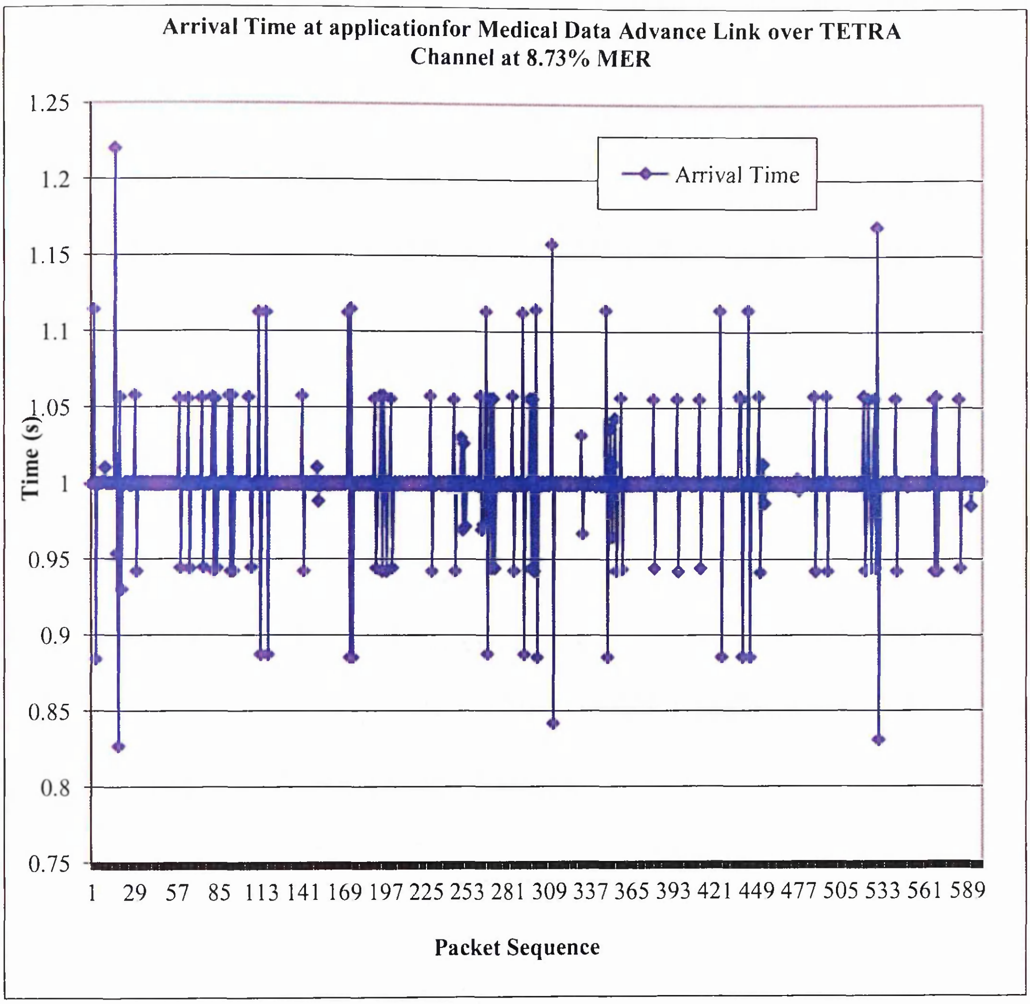


Figure 3.11: Packet Arrival Time for Medical Data Advance Link over at MER equals 8.73 %

3.8.4 RoHC Performance over HTTP Traffic

RTT for each MTU is calculated based on the number of TL-SDU in one MTU multiplied by the average time taken by one TL-SDU under same environmental parameters. In case of RoHC, due to reduced header size, the number of bits in each MTU is reduced. This will reduce the number of TL-SDUs for each specified modulation \ coding \ bandwidth. Reduction in the number of TL-SDU per MTU will reduce the RTT for MTU, and will contribute to the QoS for HTTP link over TCP \ IP. All the TCP \ IP acknowledgements will be transmitted over QAM -4 25 KHz and acknowledgements will not fit into one slot due to large header. This gain in RTT will save the transmission time, as well as Bandwidth per session. The number of slots saved by RoHC will increase the capacity. A reduction of 30ms is observed per session. 70 slots are saved excluding the TCP \ IP ACK over QAM 4 rate ½ per session.

Figure 3.12 shows the gain in RTT with RoHC for mean traffic model for MTU length of 576 Bytes with extended advance link window size of 15. The gain in RTT for mean traffic model for MTU length 576 bytes is same as MTU length 1460, however number of MTU studied for 576 bytes are 10 which are less than number of MTU studied for MTU size 1460. In case of MTU length of 1460 bytes, there is less compression gain due to large payload size however there is more header compression gain for MTU length of 576 bytes.

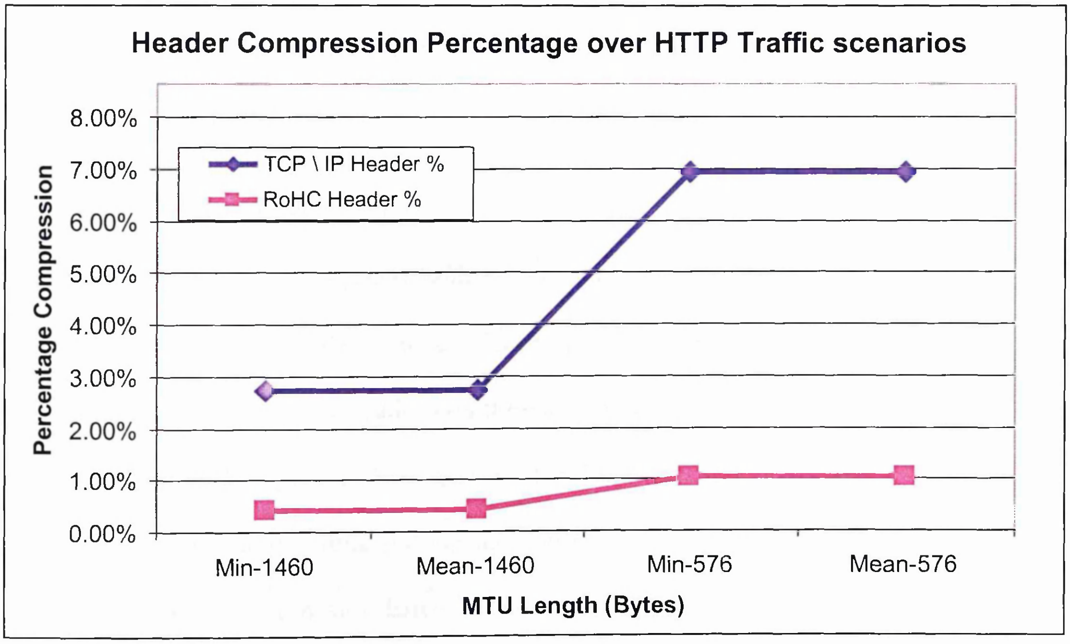


Figure 3.12 : Header compression Percentage for each Traffic parameter

The study shows that there is significant gain in number of slots if we use RoHC for TCP/IP traffic for TETRA, and that in traffic session of 30 seconds there is reduction of 30ms in RTT due to RoHC. HTTP traffic performance normally depends on link between client and server, RTT and response time of the server. It is assumed that there is no congestion at HTTP server and HTTP server is hosted at base station. In such an environment RTT and the number slots are the only parameters which can be used for the evaluation of RoHC for TCP/IP over TETRA. Short RTT will increase the system throughput and more data can be transmitted over the link for a specified time. I.e. in case of approximately HTTP traffic session of 30s there is a reduction of 30ms in RTT which is about 0.1% improvement for a single session of 30 seconds. In case of multiuser and multi session environment this improvement is significant. Using a more effective flow control strategy can further reduce the RTT hence improving the TCP throughput. Gain in number of slots is about ~3%. In the case of QAM 4 rate ½ 25 KHz there is a gain of 70 slots over 2155 slots. TCP/IP acknowledgements don't find into one slot of QAM 4 rate ½ 25 KHz while compressed header of TCP/IP will fit into one slot thus there is a significant improvement due to RoHC.

3.9 SUMMARY

Header compression for low bandwidth system with smaller payload size can save significant bandwidth. In the case of TETRA, VoIP packets are typically small compared to the header size header compression therefore forms a significant gain. Concatenating VoIP payloads into one packet reduces the header percentage. Large packets do not fit into one time slot header compression reduces the large packets to fit in one transmission timeslot. Error in one timeslot for uncompressed packet may result into whole packet retransmission. The bandwidth for a fast rate codec application is significantly more than for a slow rate application. It is evident that fast rate RTP applications have high gain in terms of bandwidth than the slow rate RTP application. Voice application improves the throughput by using the header compression in TETRA. It is clear from the study that, the performance of high data rate multimedia applications over TEDS suffers delay and significant packet drop. Multimedia applications with fast rate packet generation with significant packet/frame sizes suffer more application packet drop than channel errors. This problem is overcome by introducing a buffer at layer 2 or controlling the packet generation rate. RoHC helps to reduce the header percentage and the gain due to this compression is significant with P and B frames while I frames is managed by introducing a buffer at layer 2 or reducing the frame rate for high quality video application over TEDS. In one of the examples, it was shown that RoHC is capable of compressing the header size of 40 bytes down to 3-4 bytes (i.e. 86% reduction). By reducing the frame rate, the packet drop can also be reduced. It is observed that the bandwidth saving due to header compression for fast rate codec applications is significantly higher than for slow rate applications. It was also observed that although there is a significant compression gain for medical data and TCP based application but as these traffic classes may employ acknowledgement based advance link there will be additional acknowledgement delay. This helps providing additional reliability at the cost of transmission delay.

4. An Insight into TEDS Modulation Schemes

4.1 INTRODUCTION

Reliability and high QoS for TEDS systems is ensured with a number of modulation schemes mapped against application requirements. Phase modulation schemes have been extensively used in mobile systems. TETRA -1 supports π/4-DQPSK, whereas TEDS supports π/8-D8PSK along with QAM schemes in order to achieve higher data rate. In this chapter the performance of phase modulation schemes along with sub-carrier based QAM-4 over TEDS propagation models is presented. Comparison of performance and complexity of single carrier and multi-carrier system designs are discussed. Comparison of both designs & modulation schemes over TU-50 and HT-200 channels help in the understanding of the performance of TEDS. Implementation efficiency is analysed in terms of Message Error Rate against Es/No over SCH\F channel for downlink bursts in the 400MHz TETRA frequency bands.

The rest of the Chapter is organised as follows: Section 4.2 gives an overview of TEDS modulation schemes, while section 4.3 presents TEDS Physical Layer and noise models. In section 4.4, TETRA modulation schemes are presented. The system Implementation is also discussed 5. The performance of the phase modulation schemes over TEDS obtained through simulations is shown; Characterisation of TETRA (π/4-DQPSK) at 138 MHz is presented in section 4.7. Section 4.8 concludes the chapter. Contributions in this chapter are presented at [R.Shan, et al., 2009,Shan R. , et al., 2010 & R.Shan B. H., 2011] and ETSI standard contributions.

4.2 TEDS ARCHITECTURE

TETRA–I supports π/4-DQPSK, whereas TEDS employs π/8-D8PSK and higher-order QAM schemes [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. In TEDS, higher order QAM modulation schemes were adopted to support higher data rates for data-extensive applications. The support of multimedia and data extensive applications for TETRA makes it unique with proven reliability and security. Higher order modulation schemes provide a higher throughput at the cost of complexity [Mark Rice, 1997 , Dimitrios I. Axiotis, 2008]. Their application in multipath fading propagation channels requires implementation of complex channel estimation and equalization techniques [McLaughlin, et al., 1989]. Implementation of channel estimation techniques increases computational complexity at the low-powered mobile receiver. The improved performance achieved with higher-order modulation schemes take in to account the computation complexity and processing delay in a multipath fading channel like HT-200 [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. Phase Modulation schemes have been extensively used in the mobile environment. Higher order phase modulation schemes are less complex and signals can be recovered without implementing any channel estimator or equalization technique at the resource limited TETRA receiver [GÓMEZ D. S., 2006, Joiner, et al., 1999 & Memon, et al., 2009]. Analysis of the performance of π/8-D8PSK and 16-PSK is required in the TETRA propagation environment; 16-PSK is less complex to implement and the receiver can be implemented without channel estimation. The addition of 16-DPSK will improve the throughput and reduce the complexity compared to higher order QAM discussed in [Le, et al., 2008]. The performance of the physical layer of TETRA is presented in the TEDS standard [ETSI TETRA TR-102-580, 2007-10] over TETRA propagation models TU-50 and HT-200.

This paper was first introduced in [Shan R. , et al., 2010], which focused on performance analysis of phase modulation schemes over TETRA propagation channels TU-5, TU-50 & HT200. In this extended paper we have also discussed multicarrier based modulation proposed for TEDS. Design of multicarrier modulator is elaborated in this paper along with the performance comparison of QAM – 4 over TU-50 & HT-200 channel with results presented in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09].The simulation of QAM–4 along with high order modulation schemes over the TETRA channel is discussed in TEDS standard [ETSI TETRA TR-102-580, 2007-10], however comparison between the modulation performance over the TU-50 and HT-200 channel is not studied yet [Zhang Qin, 2007 & Kasra G. Nezami, 2008] have studied the timing and synchronization for TEDS based on multi carrier modulation. The performance of the Phase modulation schemes over TU-50, HT-200 and TU-5 is also described in the following sections. Message Error Rate is analyzed as a function of the E_s/N_0 over the SCH\F channel for downlink bursts in the 400MHz and 800MHz TETRA frequency bands.

4.3 TEDS PHYSICAL LAYER

TETRA is one of the most reliable and efficient mobile systems designed for demanding operating conditions given in [Memon, et. al., 2009].It is the only agreed PMR standard in Europe and is also accepted worldwide. TETRA operating frequency bands are 400 MHz and 800MHz. TETRA defines a 5 MHz band for both uplink and downlink for emergency services and a 10 MHz band for civil services. The access scheme is TDMA with 4 channels per carrier and channel spacing is 25 kHz stated in [ETSI TETRA TR-102-580, 2007-10]. The lower operating frequency provides longer range and high geographical coverage with fewer transmitters. It supports data rates of 36 kbps, 54 kbps and 72 kbps for QPSK, 8-DPSK and 16-DPSK respectively.

Unlike Phase modulation, QAM modulation scheme have multicarrier modulation scheme. Channel bandwidth ranges from 25 kHz to 150 kHz it is difficult to resolve individual multi-path echoes in the limited bandwidth. Each of the QAM carrier is divided into a number of frequency-division multiplexed sub-carriers where as each of the sub carriers, carry a complex signal modulated using QAM modulation. Smaller bandwidth hence low symbol rate in each subcarrier enables the subcarrier resist against ISI, as a result a multi subcarrier approach with 8 subcarriers per 25 kHz is used, i.e 8,16, 32 and 48 subcarriers in 25 kHz, 50 kHz, 100 kHz and 150 kHz carriers respectively. Table 4-1 shows the gross bit rates for QAM carriers in kbit/s. Modulation rate for each of the subcarrier is 2400 symbols/s. The overall carrier symbol rate is 19200 symbols/s for 25 kHz carriers, 38400 symbols/s for 50 kHz carriers, 76800 symbols/s for 100 kHz carriers and 115200 symbols/s for 150 kHz carriers.

Table 4-1 : Gross Bit Rate for QAM Carriers (Kbit/s)

Modulation	25 kHz	50 kHz	100 kHz	150 kHz
4-QAM	38.4	76.8	153.6	230.4
16-QAM	76.8	153.6	307.2	460.8
64-QAM	115.2	230.4	460.8	691.2

4.3.1 TEDS Physical Layer Slot Structure

A Hyper frame consists of 60 multi frames of total duration of 61.2 seconds. One multi frame contains 18 TDMA frames and each TDMA frame consists of 4 timeslots, each of 14.16667 millisecond duration. Using four carriers in a single TDMA frame gives greater call setup time than public mobile systems. GSM time slots are much smaller than TETRA, which gives less service time for each user. A TDMA frame of GSM consists of 8 timeslots of total duration of 4.615 milliseconds. TETRA ensures that each user gets sufficient service time by providing longer time slots and a lesser number of slots in a TDMA frame. Fast switching of timeslots may introduce frequency domain interference on allocated frequencies. More timeslots within each TDMA frame and a lesser time for each timeslot makes the system faster, supports more users and higher data rates, compromising at the QoS. Table 4-2 shows the how many symbols have been modulated over the signalling channel (SCH\F) for each modulation scheme. The number of bits used for each modulation scheme is also shown.

Table 4-2: Number of Symbols and Bits per Time Slot Used By Respective Modulation Schemes

Per time slot for each Modulation Scheme		Time slot	Sub slot
Modulated Symbols	Phase Modulation	255	127.5
	QAM	34	17
Data Symbols	Phase Modulation	216	108
	QAM	200	100
Number of Data Bits	DQPSK	432	216
	D8PSK	648	324
	16DPSK	864	432
	QAM – 4	800	400

For TETRA with fewer timeslots in the TDMA frame, allocating more time for each timeslot may limit the system capacity but will ensure the QoS. TETRA ensures reliability of performance and service level for each user connected by exploiting these design parameters. The time slot can be subdivided into two sub slots each of equal interval length of 7.08ms.

4.3.2 TEDS Physical Layer Burst Structures

Logical channels represent the interface between the protocol and the radio subsystem. The logical channels may be divided into two categories: the traffic channels carrying speech or data information in circuit-switched mode, and the control channels carrying signalling messages and packet data. A Physical channel is defined by a pair of radio carrier frequencies (downlink and uplink) and a TDMA slot; there are 4 physical channels per pair of radio frequencies. A burst is a period of RF carrier that is modulated by a data stream. A burst, therefore, represents the physical content of a timeslot or sub slot. A given physical channel uses the same timeslot number in every TDMA frame [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. The detailed relationship, along with the operation of each logical and physical channel can be found in [ETSI TETRA TR-102-580, 2007-10]. The TETRA standard [ETSI TETRA ETR-300-1, 1997] shows the mapping of logical channels into physical channels. A full size SCH/F is a bidirectional channel used for full size messages. For a detailed traffic analysis between MS and BS, SCH/F is selected for the implementation because it requires the establishment of at least one SCH per BS and SCH/F to carry a full size control packet from MS to BS, or vice-versa. SCH/F can be used for both uplink and downlink traffic channels; Normal Uplink Burst (NUB) or Normal Downlink Burst (NDB) for the phase modulation are shown in Figure 4.1 & Figure 4.2 shows the sub-carrier based NUB & NDB structure for QAM. Similar to the phase modulation case, the QAM channels use sub-slots for uplink control signalling referred as NUB and random access purposes. The IP traffic is transmitted by timeslots (full slots) in uplink and downlink directions.

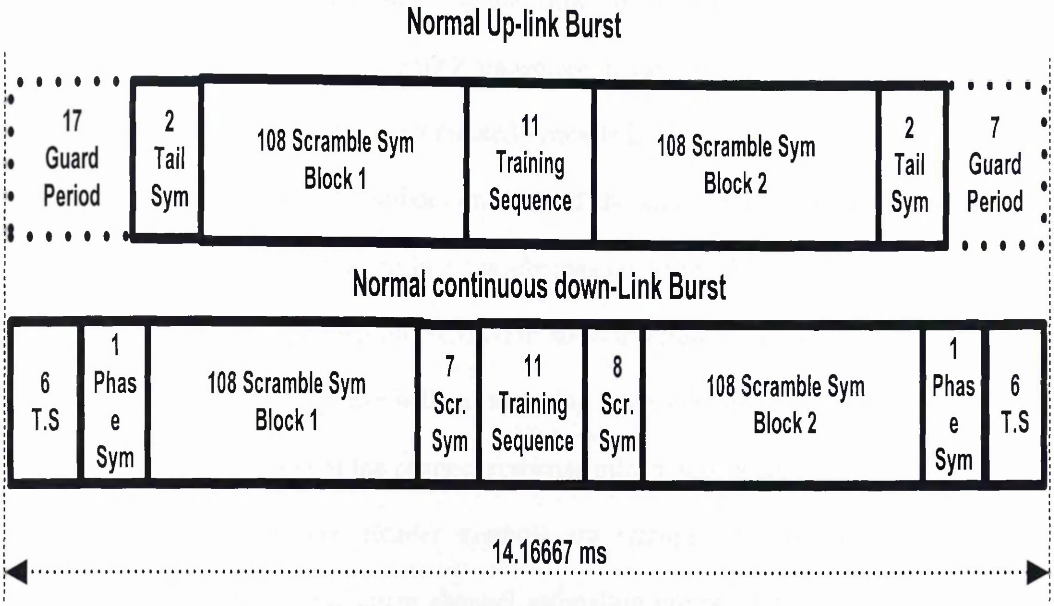
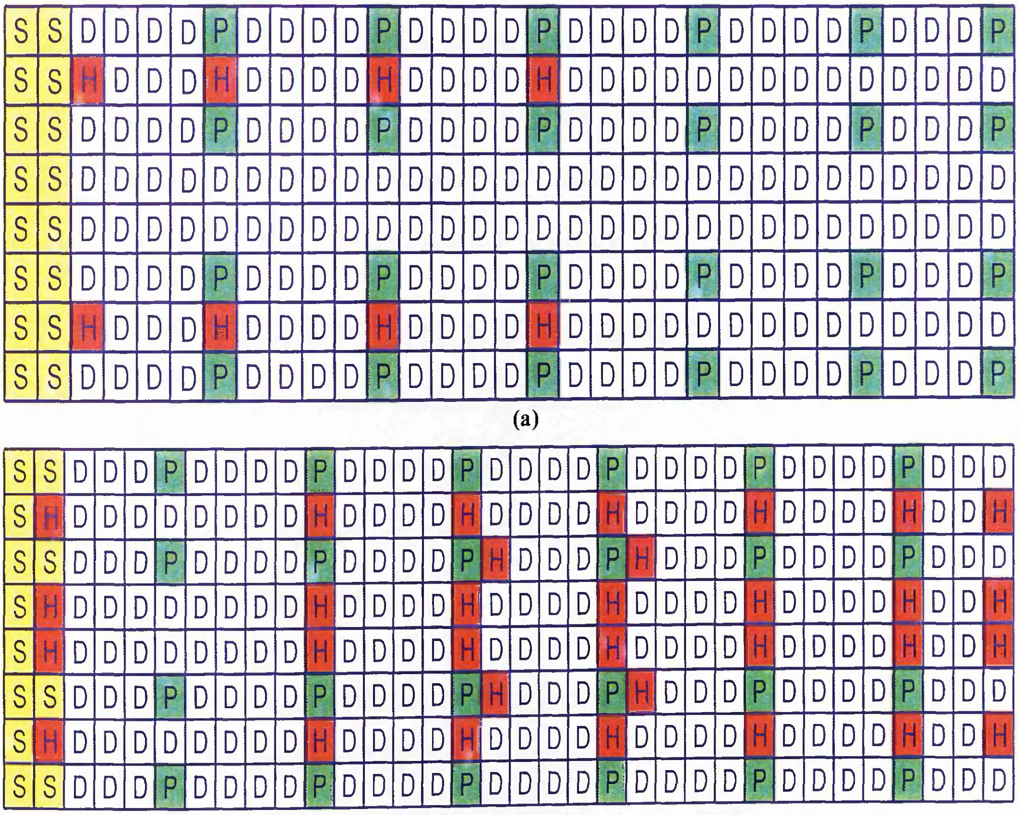


Figure 4.1 : NUB & NDB Structure for Phase Modulation



S	S	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	P
S	S	H	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	D	D	D	D	D	D	D	D	D	D
S	S	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	P
S	S	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
S	S	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
S	S	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	P
S	S	H	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	D	D	D	D	D	D	D	D	D	D
S	S	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	P

(a)

S	S	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D
S	H	D	D	D	D	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	H
S	S	D	D	D	P	D	D	D	D	P	D	D	D	D	P	H	D	D	D	P	H	D	D	D	P	D	D	D	D	P	D	D	D
S	H	D	D	D	D	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	H
S	H	D	D	D	D	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	H
S	S	D	D	D	P	D	D	D	D	P	D	D	D	D	P	H	D	D	D	P	H	D	D	D	P	D	D	D	D	P	D	D	D
S	H	D	D	D	D	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	D	D	H	D	D	H
S	S	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D	D	P	D	D	D

(b)

Figure 4.2 : Structure of NUB (a) & NDB (b) for a 25 kHz (8 subcarrier) QAM channel

[ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]

Again because of the need to ramp up and down of the MS transmitter power and allow for guard periods the downlink transmission capacity is slightly greater than uplink capacity. NUB carries 31 modulated symbols in each of the subcarrier whereas NDB carries 34 modulated symbols on each of the sub carrier. Within NUB/NDB modulated symbols are arranged in a two-dimensional time/frequency grid. The 24 pilot symbols are arranged within NUB/NDB so as to allow a reasonable sampling of the channel frequency response without incurring a considerable efficiency loss. Due to the accurate estimation of the channel response pilot symbols are spaced in the time and frequency dimensions. Header symbols are arranged across the grid to de-correlate the channel to minimize channel estimation errors. Each subcarrier starts with two known synchronization symbols used for frequency and clock synchronization and are also used as additional pilot symbols in channel estimation the residual positions within the burst are used for 200 payload symbols. Synchronization symbols are marked 'S', pilot symbols are marked 'P', header symbols are marked 'H' and data symbols are marked 'D' in the Figure 4.2.

4.4 TEDS MODULATION SCHEMES

Performance of three phase modulation schemes π/4-DQPSK, π/8-D8PSK and 16-DPSK and QAM – 4 are analysed with improved filtering over TETRA propagation channel. TETRA-I supports π/4-DQPSK and TETRA II extends it to π/8-D8PSK, along with higher order QAM.

4.4.1 Phase Modulation Scheme

We have also implemented 16-DPSK with similar transmitter parameters defined by TEDS.TETRASIM [Sorbara, 2000] simulates only π/4-DQPSK for TETRA. The reason for selecting 16-DPSK is to analyse the performance against QAM modulations in TEDS. There is no such comparison of 16-DPSK and 16 QAM over

TEDS channels; also 16-DPSK is easier to demodulate than 16-QAM. In 16 DPSK, equalization is not needed to recover the signal. The modulation symbol definition for π/4-DQPSK is [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] defined in equation 4.1

$$\begin{aligned} S_{(k)} &= S_{(k-1)} e^{(jD\phi(k))} \\ S_{(0)} &= 1 \end{aligned} \tag{4.1}$$

The above expression for S $_{(k)}$ corresponds to the continuous transmission of modulation symbols carried by an arbitrary number of bursts. The symbol S $_{(0)}$ is the symbol before the first symbol of the first burst and transmitted as phase reference. Phase transition Dφ(k) is related to the modulation bits defined by [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. This means that $S_{(k)}$ is obtained by applying a phase transition Dφ(k) to the previous modulation symbol $S_{(k-1)}$.For π/4-DQPSK, the complex modulation symbol $S_{(k)}$ takes one of the eight values exp (j nπ/4), where n = 2, 4, 6, 8 for even k and n = 1, 3, 5, 7 for odd k. For π/8-D8PSK the complex modulation symbol $S_{(k)}$ takes one of the sixteen values exp(j nπ/8), where n = 2, 4, 6, to 16 for even k and 1, 3, 5, to 15 for odd k. Dφ(k) for π/8-D8PSK and 16-DPSK are computed based on reference phase in . For 16-DPSK the complex modulation symbol S $_{(k)}$ takes one of the 32 values exp (j nπ/16), where n = 2, 4, 6, to 32 for even k and 1, 3, 5, to 31 for odd k. The modulated signal, at carrier frequency f_c is given by equation 4.2, where φ is an arbitrary phase.

$$M_{(t)} = \mathrm{Re}\{S_{(t)} e^{j2\pi f_c t + \phi_0}\} \tag{4.2}$$

$S_{(t)}$ is complex envelope of the modulated signal defined as in equation 4.3

$$S_{(t)} = \sum_{k=0}^{K} S_{(k)} g_{(t-t_k)} \tag{4.3}$$

K is the maximum number of symbols and T is symbol duration. t_k which is equal to kT defined as the symbol time corresponding to modulation symbol $S_{(k)}$. $g_{(t)}$ is the ideal symbol waveform obtained by the Inverse Fourier Transform (IFT) of a square root raised cosine spectrum $G_{(f)}$ defined in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] as in equation 4.6.

4.4.2 Quadrature Amplitude Modulation for TEDS

Similarly for QAM – 4 the complex envelope $s(t)$ of the modulated signal is defined as

$$s_m(t) = \sum_{n=1}^{N} S_m(n) g(t - t_n) e^{j(\omega_m t + \varphi_m)} \qquad (4.4)$$

$$s(t) = \sum_{m=0}^{M-1} s_m(t) = \sum_{m=0}^{M-1} \sum_{n=1}^{N} S_m(n) g(t - t_n) e^{j(\omega_m t + \varphi_m)} \qquad (4.5)$$

Whereas M is the number of sub-carriers, N is the number of modulated symbols on each sub-carrier in one slot, T is the symbol duration on each sub-carrier, t_n equals to nT which is the symbol time corresponding to modulation symbol $S_m(n)$. $S_m(n)$ is the modulation symbol at time t_n on subcarrier m. ω_m equal $2\pi f_m$which is subcarrier angular frequency. Similarly φ_m is the phase control for subcarrier m during the slot. For equation 4.3, 4.4 & 4.5 g(t) can be defined by in equation 4.6.

$$G(f) = 1 \qquad for \quad |f| \leq (1-\alpha)/2T$$

$$G(f)\sqrt{0.5(1 - \sin(\pi(2|f|T - 1)/2\alpha))} \; for (1-\alpha)/2T \leq |f| \leq (1-\alpha)/2T$$

$$G(f) = 0 \qquad for \quad |f| \geq (1-\alpha)/2T \qquad (4.6)$$

The roll-off factor α determines the width of the transmission band at a given symbol rate. The value of α is set to 0.35 for phase modulation and α is set at 0.20 for QAM – 4. For practical implementation a time limited windowed version of g $_{(t)}$, designed under the constraints given by the specified modulation accuracy outlined by the TETRA standard [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] , [ETSI TETRA TR-102-580, 2007-10] & [ETSI TETRA ETR-300-1, 1997]is used. QAM modulated signal at the carrier frequency f_c is defined as in following equation 4.7

$$M(t) = \mathrm{Re}\{s(t)\exp(j(2\pi f_c t + \phi_0))\} \quad (4.7)$$

As discussed QAM sub-carrier based modulation, Sub-carrier centre frequency fm in Hz shall be defined by the following equation 4.8,

$$fm = (0.5625 - (M/2 - m) \times 1.125)/T(5.5) \qquad (4.8)$$

For $m = 0, 1, \ldots\ldots\ldots.., M-1$ and T is the symbol duration in seconds, this defines the subcarrier spacing of 2.7 kHz.

The sub-carriers are spaced 2.7kHz apart in order to reduce the interference from/on the adjacent channel and achieve a computationally efficient multi-carrier transceiver architecture based on a poly-phase filter bank and FFT [Kasra G. Nezami, 2008].

4.4.3 TEDS Modem for Phase Modulation and QAM

Bursts of length specified in Table 4-2 are managed according to the respective modulation schemes. Data bits used by each modulation scheme differ, for example phase modulation data symbols in the SCH\F channel are limited to 216. Other 39 symbols are header, pilots and synchronization symbols. The buffer will pass on the packet data to the mapping block; which also incorporates an adaptive control unit. The buffer block is mapped into groups of 2, 3 and 4 bits based on the modulation scheme which is being used after the bit mapping block. These mapped bits are passed on to the modulation block which will modulate them based on the TETRA specified modulation symbol defined in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09].Depending on the burst type, the burst builder will form these modulated data symbols into blocks. SCH\F is implemented to support NUB\NDB. The output of the burst building block is 255 symbols, of which 216 are data symbols.

Phase modulation schemes, π/4-DQPSK, π/8-D8PSK and 16-DPSK will have bits defined in table 2 to form 216 data symbols that are used in NUB\NDB. The rest of the slots in NUB\NDB are filled by the symbols specified in [ETSI TETRA ETR-300-1, 1997]. Figure 4.3 shows the system architecture for phase modulation. A modulated burst is then filtered with a square root raised cosine filter whose sink is defined by the TETRA standard. The SRRC filter carries out the pulse shaping and minimizes the ISI [Joiner, et al., 1999]. Filter parameters can be a trade off between performance and complexity. The output from the FIR-SRRC filter is transmitted across the channel. The receiver processes the received signal with a matched filter having an impulse response equal to that of the FIR-SRRC used at transmitter. Filtered data is then down-sampled and compensated for delay. The bursts are demodulated using the maximum likelihood demodulator.

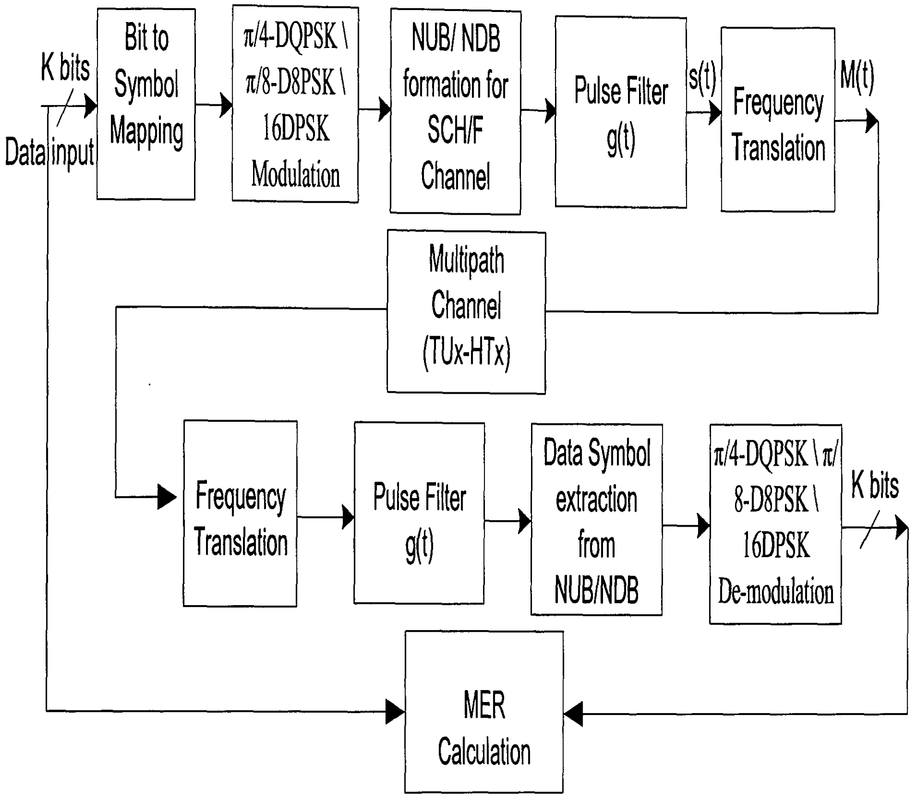


Figure 4.3: System Architecture for Phase Modulation schemes

Figure 4.4 shows system design for subcarrier base QAM. The input n-QAM sequences are grouped in blocks of size N, where k bits are taken as input sampled and modulated using the QAM based on equation 4, 5 &7. There will be total M the sub-carriers depending upon the bandwidth used i.e. 25 kHz, 50 kHz, 100 kHz and 150 kHz. Each sub-carrier is up-sampled by a factor D and separately shaped with a root-raised-cosine filter. Impulse response of the filter is based on equation 6 which is given in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]. Each subcarrier is then frequency up-converted by multiplying with the complex exponential. The multiplication results are then summed to produce the composite multi-carrier modulated sequence packed into time / frequency grid.

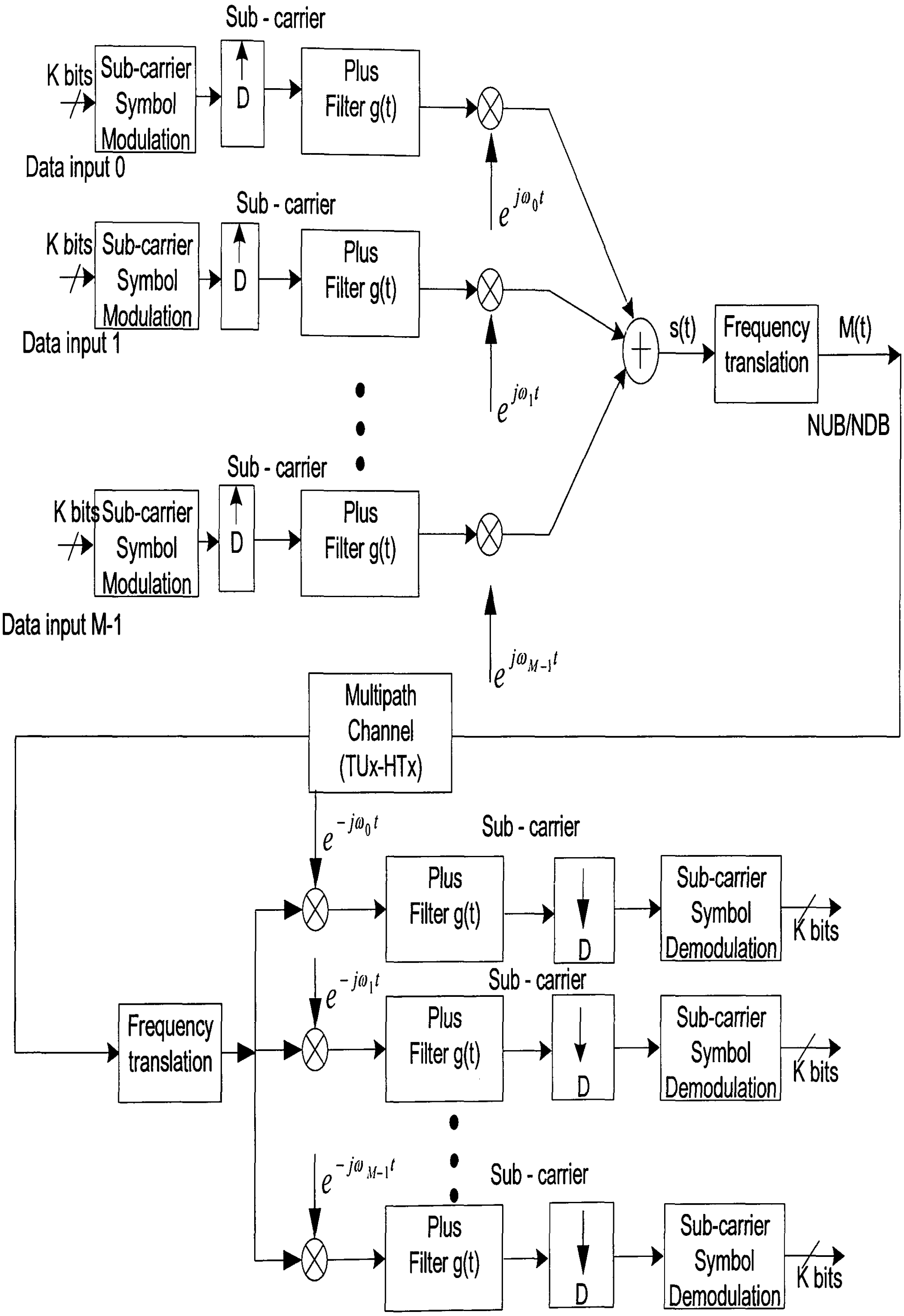


Figure 4.4: System architecture for subcarrier based QAM

The multicarrier modulated signal is transmitted through the six tap multi-path fading channel i.e. TU-50 or HT-200. Received signal is passed At the receiver, the received composite sequence frequency down-converted to base-band and passed through RRC filter. Impulse response of the receive filter is matched to the transmission filter g(t). The parallel outputs of the matched filters are then down sampled by a factor of D which is demodulated to recover the transmitted data bits. For higher order modulation estimation is applied before demodulation of the symbols.

4.5 PERFORMANCE RESULTS

Performance comparison of phase modulation schemes π/4-DQPSK, π/8-D8PSK and 16-DPSK over TU-5, TU-50 and HT 200 channels at TETRA frequency band of 400 MHz are presented along with the performance of QAM-4 over TU-50 and HT-200 channels. Message error rate is plotted against the Es/No. The message is the data burst (NUB or NDB) transmitted in one time slot, as defined in Figure 4.1 . A MER is defined as, a single NUB or NDB is received with at least one error bit in it. The NDB message is referred to as "erroneous" if the MS detects one error bit in the NDB transmitted from the BS. The number of slots used for retransmitting will limit the system throughput. Effective throughput for π/4-DQPSK, π/8-D8PSK and 16-DPSK is 30kbps, 45kbps and 60kbps based on the bits shown in table 2 transmitted in 1 timeslot duration of 14.1667ms.

In the TU-5 propagation environment, shown in Figure 4.5, the probability of error for π/4-DQPSK has a gain of 4dB over π/8-D8PSK and 8dB over 16-PSK at $10^{-1.}$ At 10^{-2} the difference of gain among the phase modulation schemes remains constant at 4dB. MER for π/4-DQPSK starts decreasing by 5dB for TU-50 channel conditions at the 400MHz frequency. While MER for π/8-D8PSK and 16-PSK decreased by 6dB and 10dB respectively in the TU-50 propagation environment. Figure 4.6 shows the performance of phase modulation schemes over TU-50 channel. It can be observed that, π/4- QPSK has a 5 dB gain over π/8-D8PSK and 10 dB over 16-DPSK in TU-50 channel at $10^{-2.}$ 16-DPSK does not require a channel estimator at the receiver, which makes it much simpler and faster compared with the 16 QAM defined in the standard of TEDS.

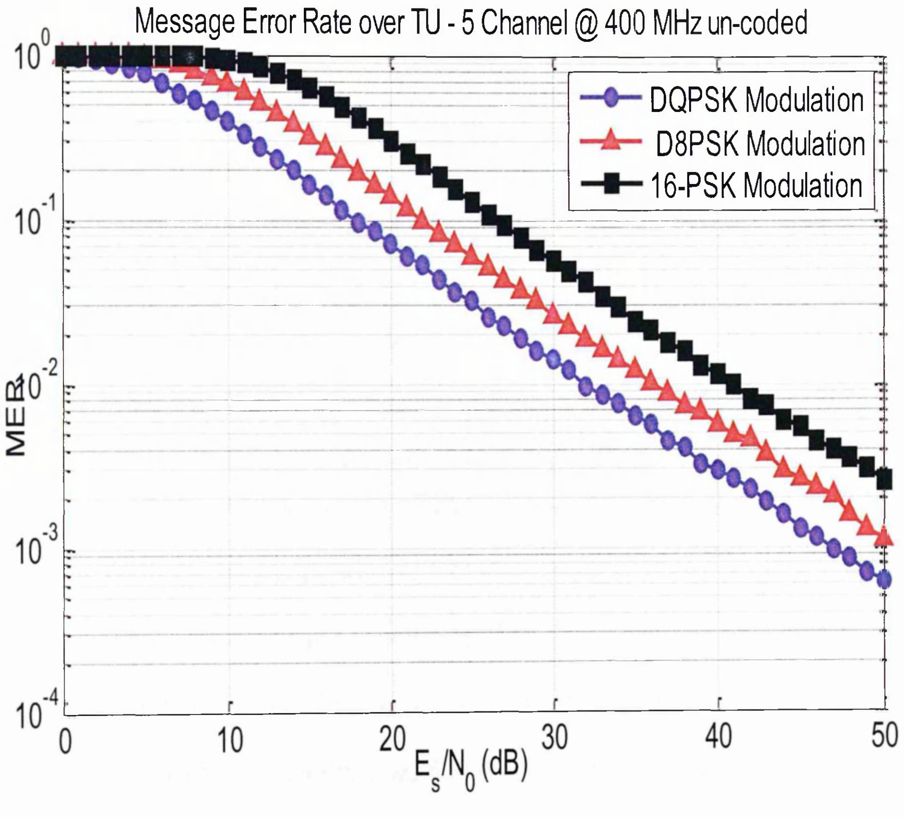


Figure 4.5: MER of un-coded Phase Modulation Schemes over TU-5 Channel at 400 MHz

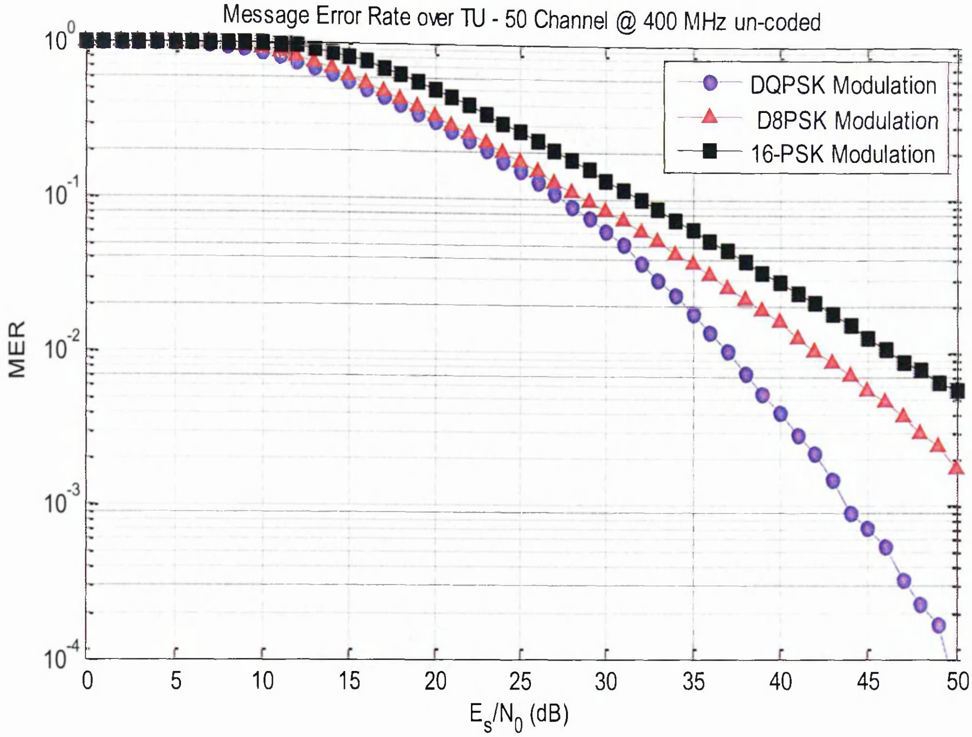


Figure 4.6: MER of un-coded Phase Modulation Schemes over TU-50 Channel at 400 MHz

For a HT channel, it can be observed in Figure 4.7 that π/4-DQPSK MER decreases by 13dB at the 400MHz frequency while π/8-D8PSK MER tends to drop by 15dB in same propagation conditions. In the region of 10^{-1} to 10^{-2} the probability of error for π/4-DQPSK decreases faster with increasing Es/No as compared to π/8-D8PSK. At a probability of error of 10^{-2}, π/4-DQPSK has 6 dB gain over π/8-D8PSK and 12dB gain over 16-PSK at the 400MHz frequency.

The performance of phase modulation schemes for the propagation channels is less complex than that of QAM for TETRA. For the TU-5 channel model, the performance of the modulation schemes is better than for the other propagation channels such as TU-50 and HT-200. The probability of error decreases with low values of Es/No as compared with other channels but, with higher values of Es/No the decrease in probability of message error is less than that for TU-50 and HT-200.

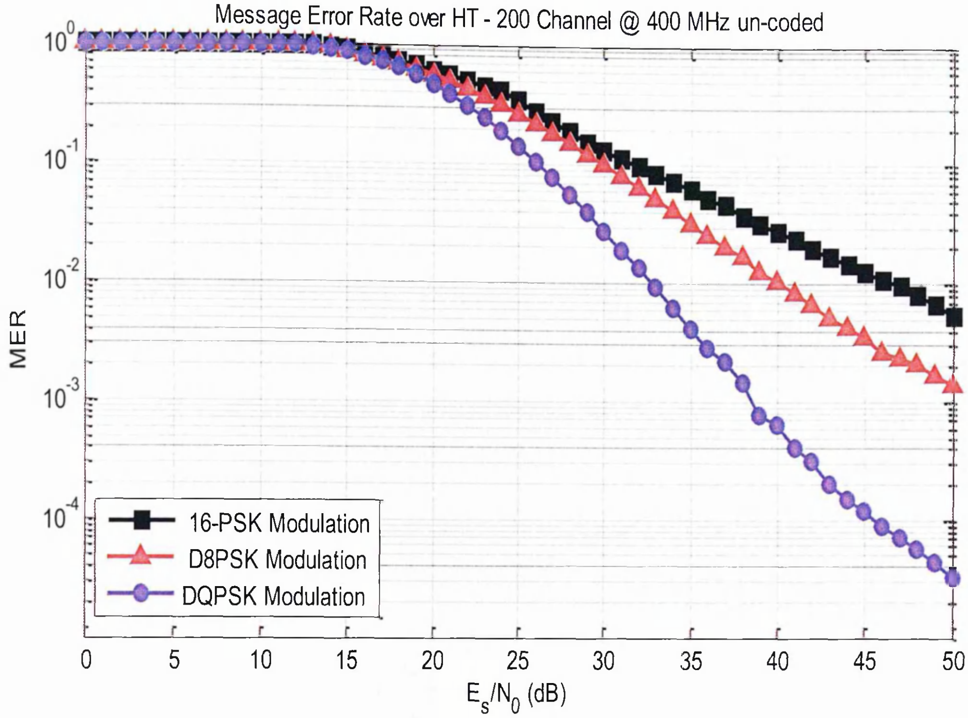


Figure 4.7: MER of un-coded Phase Modulation Schemes over HT-200 Channel at 400 MHz

This performance decrease is due to the fact that TU-5 channel behaves as slow fading channel. The results suggest that all the packets transmitted over TU-50 channel by using π/4-DQPSK will be retransmitted under 7dB. Likewise for HT-200 channel all the packets transmitted using π/4-DQPSK will be retransmitted under 14dB. Under better channel conditions higher order modulation schemes can help increase the system throughput. To support data extensive application like multimedia application, online video, CCTV or any TCP\UDP based high data rate application it is very important that system should support high order modulation with marginal performance compromise. 16-DPSK is one of the candidate schemes which can enable such application to operate for TETRA. Similar performance analysis can be drawn for 800 MHz frequency band for TETRA. TETRA standard spacify QAM modulation schemes in order to achive more throughput but induced sub-carrier based burst structure. Pilot sysmbol are spread across the burst for better channel estimation but long burst structure effects the MER. Higher order phase modulation schemes using the existing burst structure can help sending more information with higher order phase modulation schemes, while minimizing the MER.

Figure 4.8shows the performance of QAM – 4 over TU – 50 and HT – 200 channels. Structure of data burst for NDB given in figure 2 b is used for 25 kHz bandwidth only. Multi-carrier based modulation design discuss in Figure 4.4 is implemented over the TU – 50 and HT – 200 channels.

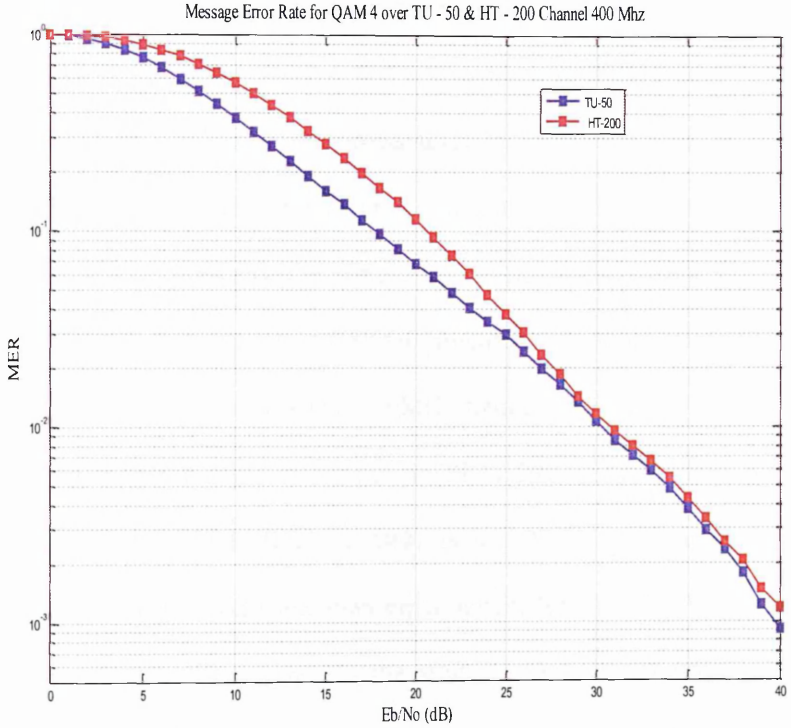


Figure 4.8: MER of un-coded QAM overTU-50 & HT-200 Channel at 400 MHz

Performance of QAM – 4 over TU – 50 propagation channel is better than the HT – 200 propagation channel with low E_b/N_o values. The difference of performance is due to high Doppler shift, however both channel have six tap delay lines as shown in table 3. There is small difference in performance of QAM – 4 over both channels at high E_b/N_o. All the tap delays are within the fraction of the symbol duration and with slight difference in average relative power. Performance of higher order QAM can also be simulated over same channel models.

4.6 CHARACTERISATION OF TETRA (Π/4-DQPSK) AT 138 MHZ

This section shows the results of the simulation to validate the performance of TETRA simulator at 430MHz and the proposed selection of the new parameters for operation of TETRA π/4-DQPSK at 138MHz. Validation of performance of TETRA with regard to π/4-DQPSK modulation at 430 MHz is done to establish a test bed for 138MHz simulations. The present TETRA standard [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] addresses the frequencies between 300MHz to 1 GHz. The TETRA standard illustrates the TETRA Protocol stack design and [ETSI TETRA ETR-300-1, 1997] presents the simulation results for π/4-DQPSK at 400MHz. Standard refers the simulation at 400MHz frequency while the actually value of the Doppler shift is calculated based on 430MHz frequency, for this reason we will refer all the standard simulation presented in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] and [ETSI TETRA ETR-300-1, 1997]as at 430MHz. This section presents the results for the verification simulation environment for π/4-DQPSK for TETRA at 430MHz, while next section presents the results at 138MHz. The results presented in both the sections follow the same protocol stack design as explained by [ETSI EN 300 392-2, 2007-09].

The study was carried out in three different stages, during the first stage BER/MER curve validation is carried out against the standard BER/MER curves and [ETSI TETRA ETR-300-1, 1997]. In the second stage, BER/MER performance curves are simulated at 138MHz for all logical channels. In the third stage of the study, shows the calculation of Static & Dynamic reference sensitivity values and reference interference ratios.

4.6.1 System Design

Transmission design characteristic for simulation results presented in the document are based on the parameters discussed in [ETSI TETRA ETR-300-1, 1997] where as receiver design characteristics are based on the transmission parameters and general system outline given in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] Error control coding for logical channels based on Rate-Compatible Punctured Convolutional Codes (RCPC) and Reed-Muller codes (RM) are based on section 8.2 of TETRA standard. The simulation system environment is based on the outline discussed in section 4.2, "Radio channels simulation description" of [ETSI TETRA ETR-300-1, 1997].

Burst structure and burst format for "Normal Downlink Burst", "Normal Continuous Down-link Burst", “Synchronisation Continuous Down-link Burst" and "Control Up-link Burst" for respective logical channels. Logical channels simulated are AACH, BSCH, SCH/F, SCH/HU, TCH/7.2, TCH/4,8 & TCH/2,4 for 430MHz and 138 MHz. TCH /4,8 and TCH/2,4 are also simulated with 2 special cases for each. In TCH/2,4 & TCH/4,8 N=4 case interleaving is carried over the 4 blocks n than within the block while In TCH/2,4 & TCH/4,8 N=8 case interleaving is carried over the 8 blocks and also within the block. Performance characteristics given as message error rate (MER) for AACH, BSCH, SCH/F and SCH/HU logical channel while BER plots for TCH/7.2 , TCH/2,4 , TCH/2,4 N=4 , TCH/2,4 N=8 , TCH/4,8 „ TCH/4,8 N=4 , TCH/4,8 N=8 logical channels over TU-50 and HT -200 propagation environments.

ETSI standard ETR 300-2 is referred for the evaluation and comparison of simulated results for 430MHz frequency for the respective channels, also by confirming the simulations matches with the standard results. Comparison of simulated results with the standard results as presented in ETR 300-2 is based on the simulation set-up guidelines discussed in section 3 of the mentioned document. However, the introduction of different filter parameters such as filter order, up-sampling or any other technique at receiver may impact the simulation results. Simulation parameters and receiver characteristics are configured based on the recommendation in the section 4.2 of ETR 300-2 while implementation for specific logical channels are based on the chapter 8 of ETS 300 392-2 and ETSI TS 100 392-2 V3.5.1.

Table 4-3 shows the Doppler values against the frequency and number of slots. The difference in Doppler shift value for 430MHz and 138MHz is major simulation difference between the performances presented. Doppler Shift at 430MHz is 20Hz for TU-50 and 80Hz for HT-200 propagation channel. The Doppler shift at 138MHz is calculated it to be around 6.38 for TU-50 and 25.48 for HT-200 propagation channel. Although there is not direct relation in the Doppler shift of TU-5 & HT-50 at 430 MHz and TU-50 & HT-200 at 138MHz, for comparison and analysis we can relate the performance of logical channels over TU-50 and HT-200 at 138MHz. Symbol duration for TETRA is 14.167ms while maximum relative delay for TU-50 channel is 5us and 15 us for HT-200 propagation channel. The Key characteristics due to change in Doppler shift as a result of change in frequency is given below. We can see the Doppler Shift for TU-50 at 430MHz and HT-200 at 138 MHz effects comparable number of slots in contrast to other channels, but due to difference in relative path delays for both channels, results behave differently.

Table 4-3 : Doppler Shift values against frequency and propagation channel

	Doppler Shift (Hz)	Time Period (ms)	Number of Slots
TU-50 430 MHz	20	50	3.52
TU-50 138 MHz	6.38	156.5	11.04
HT-200 430 MHz	80	12.5	0.88
HT-200 138 MHz	25.55	39.13	2.76

For TU -50 channel Doppler spread effects 12 slots in 138MHz as compared to 4 slots for TU-50 at 430 MHz, while for HT-200 channel Doppler spread is 3 slots as compared to 1 slot. Interleaving across 4 & 8 slots as in case of BER performance of TCH/2,4 and TCH/4,8 logical channels, it does improves the performance but due to larger Doppler spread in case of 138MHz there is a performance loss. The figures below show the Doppler spread for different propagation conditions and frequencies.

Figure 4.9 shows the Doppler shift propagation over number of slots, at TU-50 for 430MHz, Figure 4.10 shows the Doppler shift propagation over number of slots, at TU-50 for 138MHz,

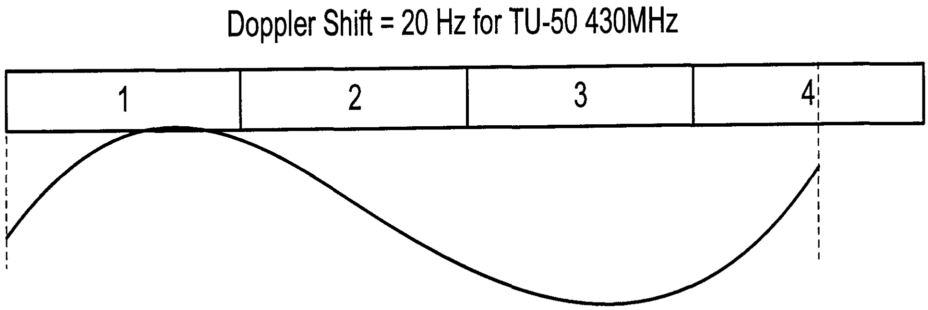


Figure 4.9 Doppler Shift = 20 Hz for TU-50 430MHz

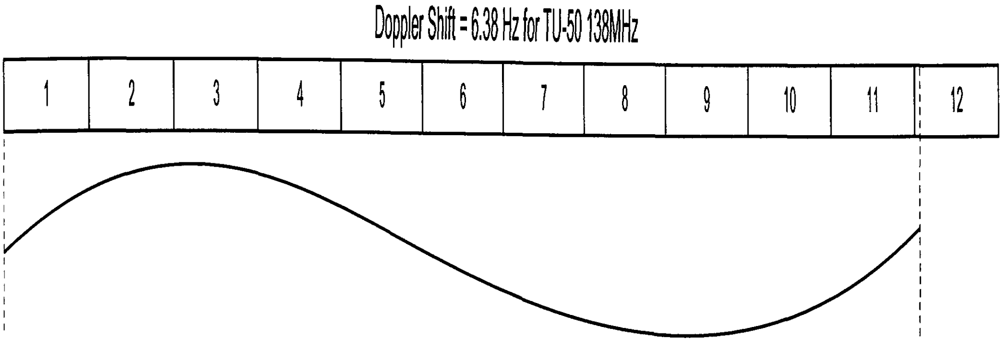


Figure 4.10: Doppler Shift = 6.38 Hz for TU-50 138MHz

Figure 4.11 shows the Doppler shift propagation over number of slots, at TU-50 for 430MHz, Figure 4.10 shows the Doppler shift propagation over number of slots, at TU-50 for 138MHz,

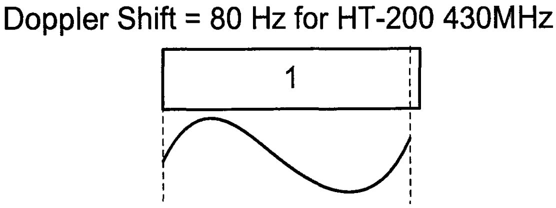


Figure 4.11 : Doppler Shift = 80 Hz for HT-200 430MHz

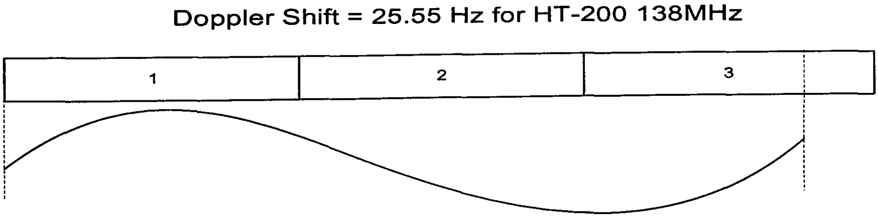


Figure 4.12 : Doppler Shift = 25.55 Hz for HT-200 138MHz

4.6.2 Simulator at 138MHz for TU-50 Channel

Bit Error Rate of TCH/7.2 channel as function of E_s/N_0 in TU50 propagation environments with ideal synchronization technique over 138MHz is shown in following figure, compared to the standard plots generated at 430Mhz ETR 300-2.

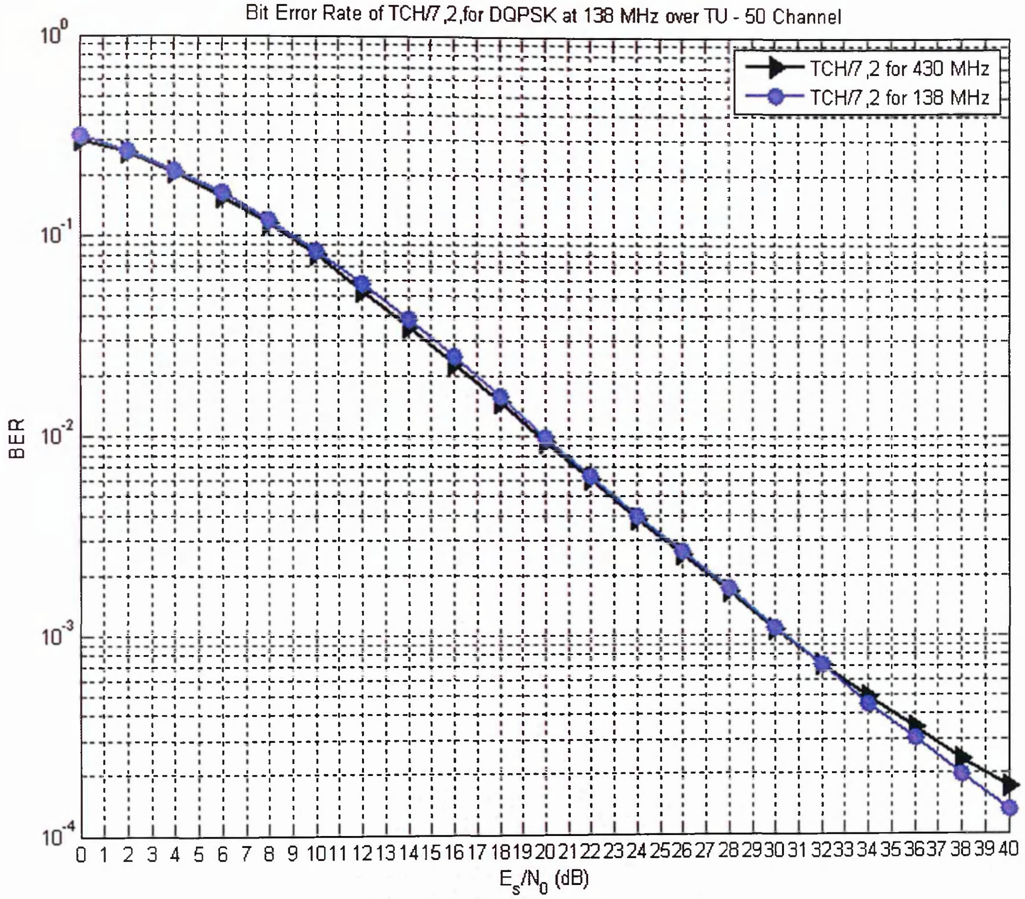


Figure 4.13: Bit Error Rate of TCH/7.2 over TU-50 Propagation Channel for 138 MHz

BER performance of TCH/7.2 for TU-50 channel over 138MHz exhibits a similar performance behaviour as TCH/7.2 for TU-5 over 430MHz. TCH/7.2 is un-coded channel with 432 type-1 bits. Relating the performance of TCH/7.2 in above Figure 4.13 Performance of TCH/7.2 over TU-5 channel at 430MHz is somewhat similar to the performance of TCH/7.2 over TU-50 channel at 430MHz. Performance of

TCH/7.2 over TU-50 channel at 138 MHz is performing slightly better in terms of BER due to reduced Doppler shift over un-coded channel.

Table 4-4: Simulation Parameters TCH /7.2 over TU-50 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	TCH
Propagation Channel	TU-50
Doppler Shift	6.38
Channel Encoding	Un-coded channel
Type-1 bits	432 bits

MER of SCH/F channel as function of E_s/N_0 in TU50 propagation environments with ideal synchronization technique over 138MHz is shown in following figure, compared to the standard plots generated at 430 MHz.

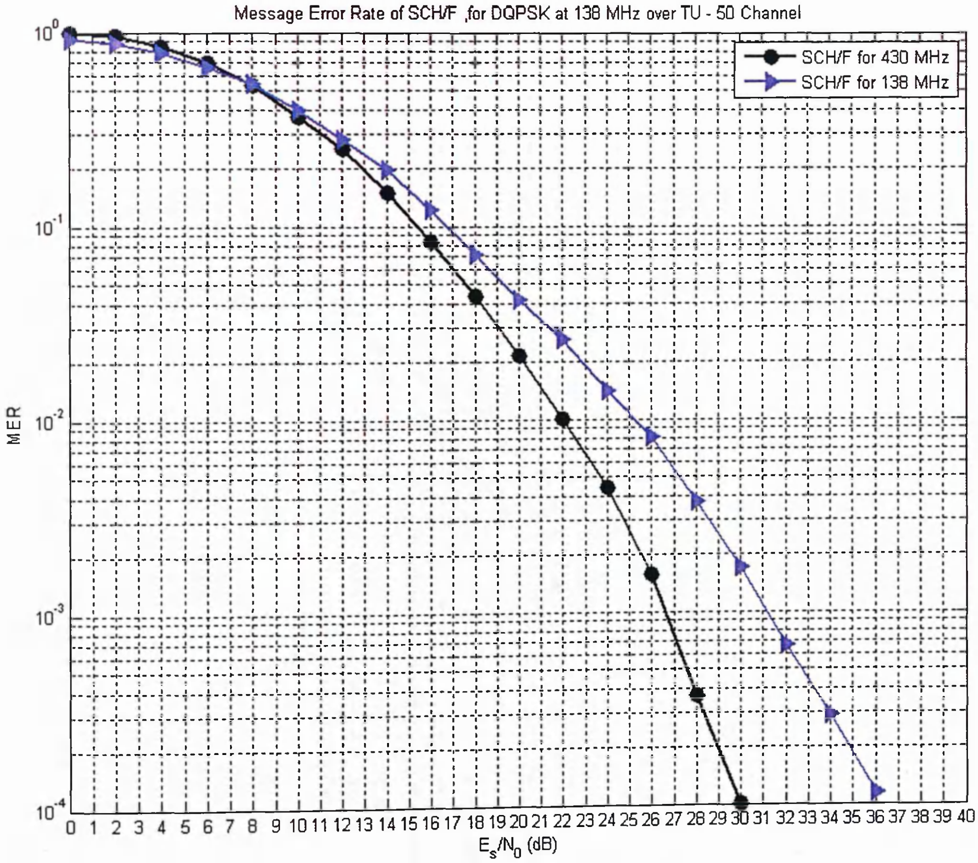


Figure 4.14: Message Error Rate of SCH/F over TU-50 Propagation Channel for 138 MHz

SCH/F is design as RCPC encoded, rate=2/3 with 268 type-1 bits. Performance of SCH/F over TU-5 channel at 430MHz is worse due to less Doppler shift which results in more slot errors and MER. The performance of SCH/F over TU-50 channel at 138MHz is ~4dB is worse than the performance of same system over 430MHz at 10e-3.

Table 4-5: Simulation Parameters SCH/F over TU-50 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	SCH/F
Propagation Channel	TU-50
Doppler Shift	6.38
Channel Encoding	RCPC code with rate 2/3
Type-1 bits	268 bits

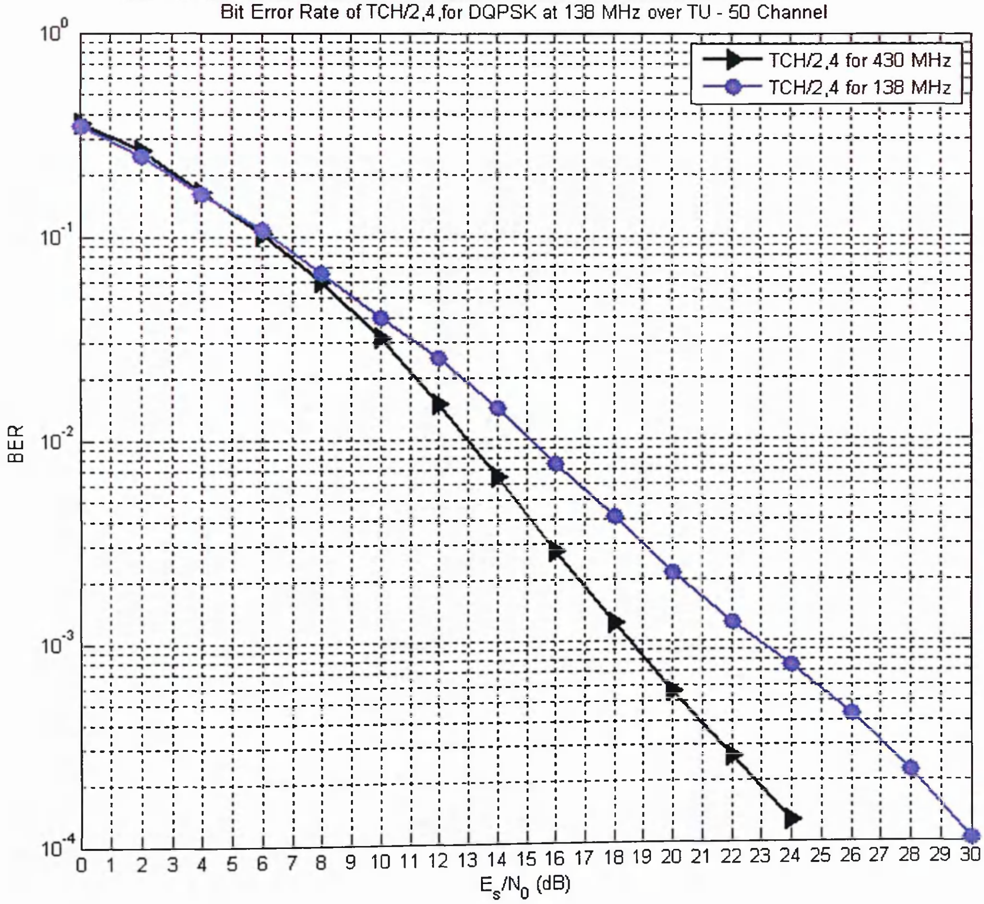


Figure 4.15: Bit Error Rate of TCH/2,4 over TU-50 Propagation Channel for 138 MHz

Bit Error Rate of TCH/2,4 channel as function of E_s/N_0 in TU50 propagation environments with ideal synchronization technique over 138MHz is shown in following figure,

BER performance of TCH/2,4 for TU-50 channel over 138MHz exhibits a similar performance behaviour as TCH/2,4 for TU-5 over 430MHz as compared to over TU-50. TCH/2,4 is RCPC encoded channel, rate=148/432 with 144 type-1 bits. Performance of TCH/2,4 over TU-5 channel at 430MHz is worse than the at TU-50 by around 10dB at 10e-3. Performance of the logical channel over TU-50 at 138 MHz is worse by 4dB at 10e-3. Doppler shift for TU-5 at 430MHz is about 10 times less than the Doppler shift for TU-50 at 430MHz while Doppler shift for TU-50 at 138MHz is about 3 times less than that Doppler shift for TU-50 at 430MHz.

Table 4-6: Simulation Parameters TCH/2,4 over TU-50 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	TCH/2,4
Propagation Channel	TU-50
Doppler Shift	6.38
Channel Encoding	RCPC code with rate 148/432
Type-1 bits	144 bits

4.6.3 Simulator at 138MHz for HT-200 Channel

Bit Error Rate of TCH/7.2 channel as function of E_s/N_0 in HT - 200 propagation environments with ideal synchronization technique over 138MHz is shown in following figure,

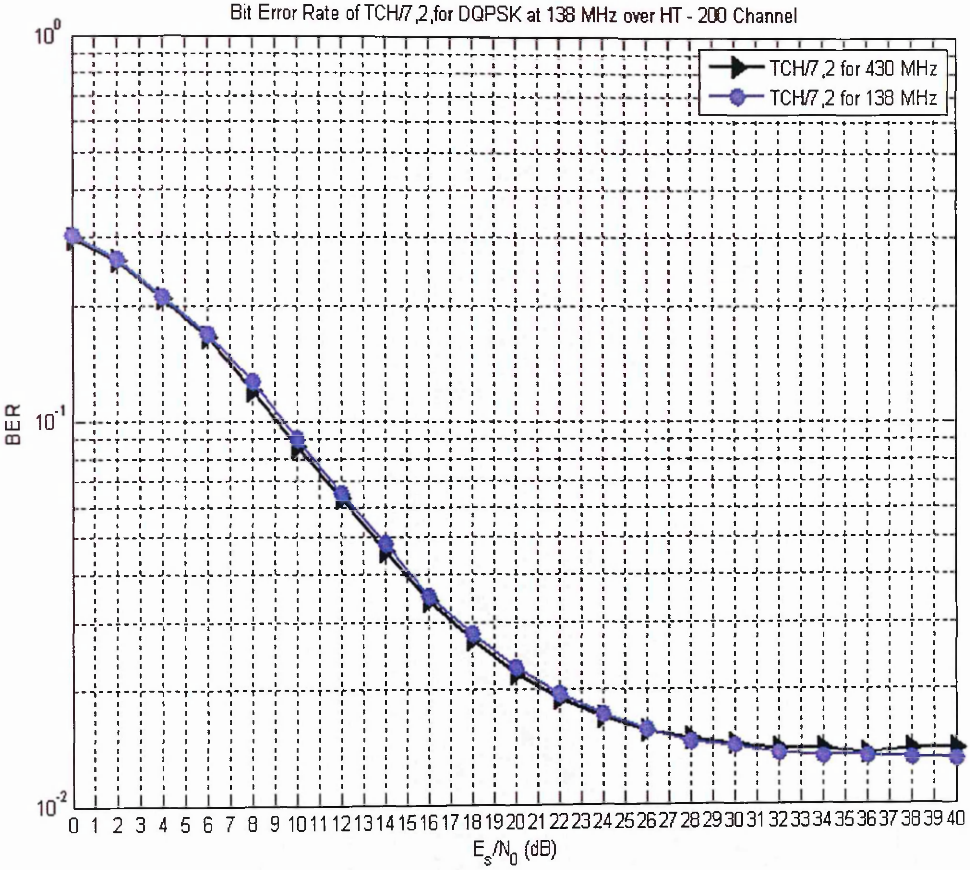


Figure 4.16: Bit Error Rate of TCH/7.2 over HT-200 Propagation Channel for 138 MHz

BER performance of TCH/7.2 for HT-200 channel over 138MHz exhibits a similar performance behaviour as TCH/7.2 for TU-50 over 138MHz. There is slight improvement in the performance of the system. TCH/7.2 is un-coded channel with 432 type-1 bits. We can observe the performance of TCH/7.2 logical channel over HT propagation channel in figure 29. Performance of TCH/7.2 over HT-200 channel at 138 MHz is performing slightly better in terms of BER due to reduced Doppler shift over un-coded channel.

Table 4-7 : Simulation Parameters TCH/7.2 over HT-200 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	TCH
Propagation Channel	HT-200
Doppler Shift	25.55
Channel Encoding	Un-coded channel
Type-1 bits	432 bits

MER of SCH/F channel as function of E_s/N_0 in HT - 200 propagation environments with ideal synchronization technique over 138MHz is shown in following figure,

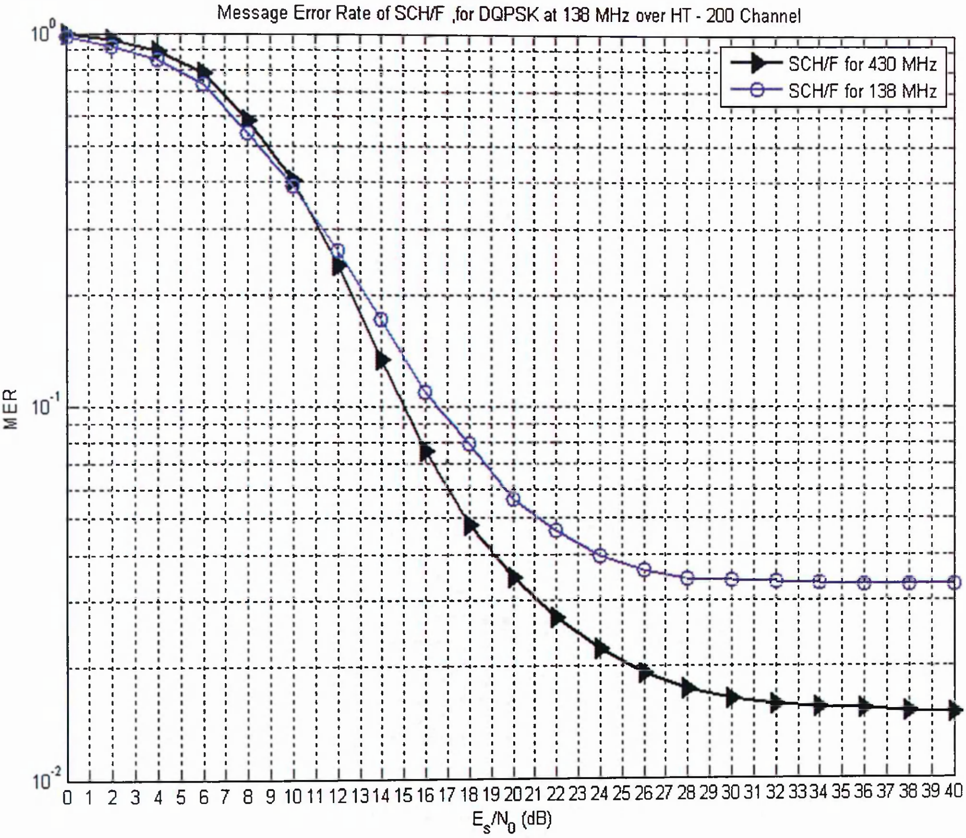


Figure 4.17: Message Error Rate of SCH/F over HT-200 Propagation Channel for 138 MHz

SCH/F is design as RCPC encoded, rate=2/3 with 268 type-1 bits. Performance of SCH/F over HT-50 channel at 430MHz is worst due to less Doppler shift which resultantly affects more slots, resultantly MER. Similarly performance of SCH/F over HT-200 channel at 138MHz.

Table 4-8: Simulation Parameters SCH/F over HT-200 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	SCH/F
Propagation Channel	HT-200
Doppler Shift	25.55
Channel Encoding	RCPC code with rate 2/3
Type-1 bits	268 bits

BER of TCH/2,4 channel as function of E_s/N_0 in HT - 200 propagation environments with ideal synchronization technique over 138MHz is shown in Figure 4.18.

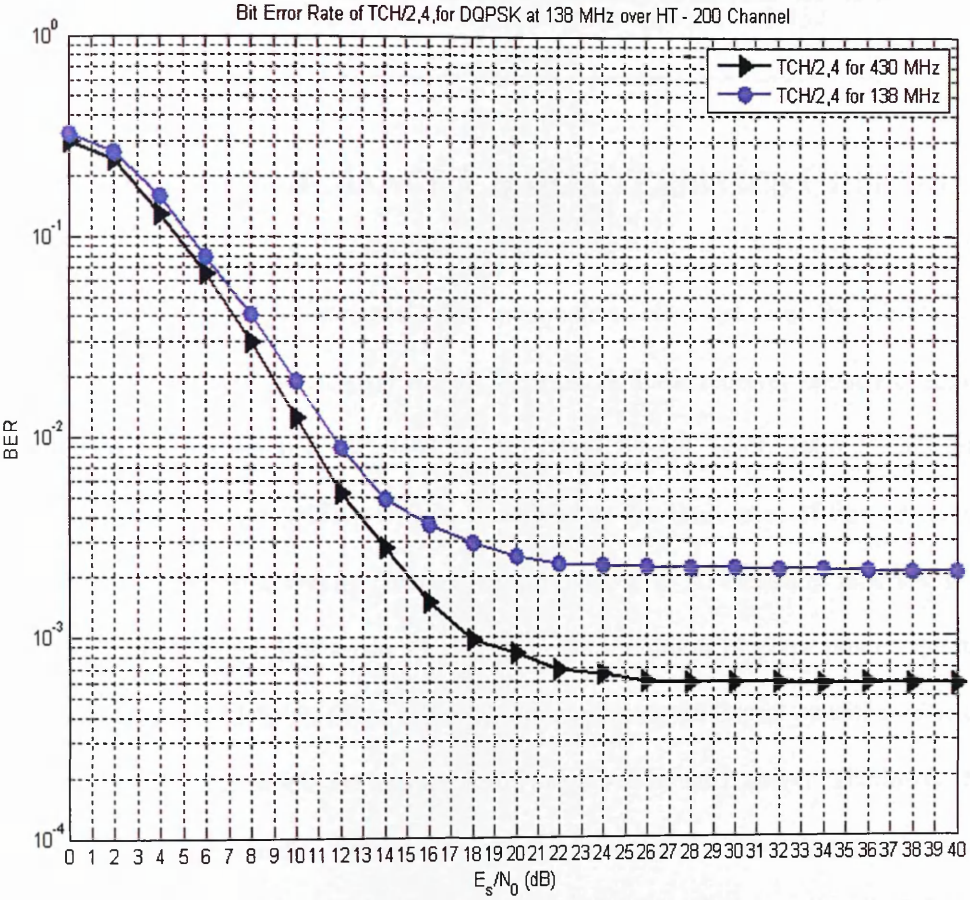


Figure 4.18 : Bit Error Rate of TCH/2,4 over HT-200 Propagation Channel for 138 MHz

BER performance of TCH/2,4 for HT-200 channel over 138MHz exhibits a similar performance behaviour as TCH/2,4 for HT-50 over 430MHz. TCH/2,4 is RCPC encoded channel, rate=148/432 with 144 type-1 bits. Performance of TCH/2,4 over HT-50 channel at 430MHz is worse than the at HT-200 and have a above the 10e-3.

while Performance of the logical channel over HT-200 at 138Mhz have an error floor above 10e-3 with reduced Doppler. Reason for which is reduce Doppler effects more slots resultantly MER.

Table 4-9 :Simulation Parameters TCH/2,4 over HT-200 Propagation Channel for 138 MHz

Channel Parameters	
Logical Channel	TCH/2,4
Propagation Channel	HT-200
Doppler Shift	25.55
Channel Encoding	RCPC code with rate 148/432
Type-1 bits	144 bits

4.7 PERFORMANCE CHARACTERISTICS CRITERIA

The receiver performance characteristics for phase modulation address the base station and mobile station performance. The parameters observed are Probability of Undetected Erroneous Message (PUEM), Dynamic & Static receiver sensitivity ratios and reference interference ratios which are based on Bit Error Ratio (BER) and Message Erasure Rate (MER). PUEM is defined as the limit ratio of the erroneous messages detected as correctly received by the receiver to all messages received in a given logical channel. Reference sensitivity is the minimum receiver power against which the specified BER/MER is achieved. This indicates the lowest possible value of the RF signal power which can be successfully received by the receiver. The lower the level of power on which a receiver can process successfully, the better the receiver sensitivity. The threshold for the BER/MER is specified based on the BER/MER simulation plots. Dynamic receiver sensitivity is calculated based on the dynamic channel i.e. multipath fading channel, TU-50 and HT - 200 in case of TETRA and static receiver sensitivity is calculated against the static channel performance. These sensitivity levels and the corresponding sensitivity performance specification are based on the calculations and the simulation of results at different noise figures for BS and MS. Nominal error rates for different propagation models are defined below.

Table 4-10 : Nominal error rates

Propagation model	BER	Equipment class
STATIC	0.01%	A, B, E
TU -50	0.4%	A, B, E
HT -200	3%	A

The sensitivity levels have been determined such that the TCH un-coded 7/2 BER does not exceed 0.4% in the most common propagation conditions considered in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09].

4.7.1 Dynamic Reference Sensitivity Performance for Phase Modulation

The present TETRA standard for π/4-DQPSK specifies dynamic reference sensitivities which were chosen where uncoded TCH channel BER does not exceed 4% in the most common propagation conditions. This is explained in [ETSI TETRA ETR-300-1, 1997] whereas Es/No of 17dB was found to provide the required 4%, which was then used for deriving the present full set of MERs and BERs. The power corresponding to Es/No represents the receiver sensitivity, and is calculated according to the following equation (in logarithmic notation):

Receiver Sensitivity =

$$E_s / N_o(dB) + NF(dB) - (k(dBJ/K) + T(dBK) + B(dBHz))$$

$k = 1.38 \times 10^{-23}$ J/K (-228.6 dBJ/K) ; Boltzmann's constant;

$T_0 = 290$ K (24.62 dBK) , reference temperature for receiver noise figure;

B = 18 kHz (42.6 dBHz) Channel Bandwidth, which is the effective bandwidth of the system after filtering.

NF = Noise Figure

= 6.4 + 2 = 8.4 dB for uplink (BS receiver)

= 9.4 + 2 = 11.4 dB for downlink (MS receiver).

The receiver noise figure is 6.4 dB for the uplink (BS receiver) and 9.4 dB for the downlink (MS receiver) and an additional 2dB margin is allowed for implementation losses [ETSI TETRA ETR-300-1, 1997]and [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09]

Dynamic reference sensitivity performance for π/4-DQPSK modulation, calculated for 430MHz simulation in [ETSI TETRA EN 300 392-2 V3.2.1, 2007-09] are calculated as:

- for BS π/4-DQPSK modulation: -106 dBm ; -136 dBW
- for MS π/4-DQPSK modulation: -103 dBm ; -133 dBW

Based on the function above, the signal to noise ratio for TETRA BS at reference sensitivity is calculated to be (16.98) 17 dB while Receiver sensitivity for TETRA MS is also (16.98) 17 dB.

4.7.2 Dynamic Reference Sensitivity Level at 138MHz

This section explains the evaluation of performance at 138MHz carrier frequency against dynamic reference sensitivity level. Performance of the system is shown in terms of maximum permissible MER/BER for MS/BS receiver at dynamic reference sensitivity level with π/4-DQPSK modulation at 138 MHz based on the description in previous section. Es/No for 138MHz is chosen as 17dB to match that used by the standard at 430MHz as described above. A different value of Es/No could be chosen for consideration at 138MHz if the MERs and BERs shown in the present document are thought to be unsatisfactory.

Table 4-11 shows the recommended maximum permissible BS receiver MER or BER at dynamic reference sensitivity level for BS at 138 MHz. Table 4-12 shows the recommended maximum permissible BS receiver MER or BER at dynamic reference sensitivity level for MS at 138 MHz.

Table 4-11 shows the recommended maximum permissible BS BER/MER at the dynamic reference sensitivity level with π/4-DQPSK modulation at 138 MHz. Values given in brackets represent the values for 430MHz

Table 4-11 : Recommended Maximum permissible BS receiver MER or BER at dynamic reference sensitivity level with π/4-DQPSK modulation at 138 MHz, based upon Es/No=17dB

Logical Channel	**Error Count Type**	**Propagation Condition**	
		TU-50	**HT 200**
SCH /HU	MER	10.5% (8%)	11% (9.5%)
SCH/F	MER	9.2% (11%)	9.5% (11%)
TCH/7.2	BER	2% (2.5%)	3.1% (4%)
TCH/4,8 N=1	BER	2.2% (4%)	3.1% (4%)
TCH/4,8 N=4	BER	1.1% (1.2%)	0.95% (4%)
TCH/4,8 N=8	BER	0.04% (0.4%)	0.04% (4%)
TCH/2,4 N=1	BER	0.55% (1.2%)	0.35% (1.3%)
TCH/2,4 N=4	BER	0.08 (0.02%)	0.006 (0.3%)
TCH/2,4 N=8	BER	0.015% (0.01%)	0.001% (0.15%)
STCH	MER	10.5% (9%)	11% (11%)

Table 4-12 shows the recommended maximum permissible MS BER/MER at the dynamic reference sensitivity level for π/4-DQPSK modulation at 138 MHz. Figures given in brackets represent the figures for 430MHz

Table 4-12 : Recommended Maximum permissible MS receiver MER or BER at dynamic reference sensitivity level with π/4-DQPSK modulation at 138 MHz, based upon Es/No=17dB

Logical Channel	**Error Count Type**	**Propagation Condition**	
		TU-50	**HT 200**
AACH	MER	9.5% (10%)	16.5% (17%)
BSCH	MER	6.7% (8%)	13% (11%)
SCH/HD	MER	10.5% (8%)	11% (11%)
BNCH	MER	10.5% (8%)	11% (11%)
SCH/F	MER	9.2% (8%)	9.5% (11%)
TCH/7.2	BER	2% (2.5%)	3.1% (4%)
TCH/4,8 N=1	BER	2.2% (2%)	3.1% (4%)
TCH/4,8 N=4	BER	1.1% (0.4%)	0.95% (3.3%)
TCH/4,8 N=8	BER	0.4% (0.06%)	0.4% (3%)
TCH/2,4 N=1	BER	0.55% (0.35%)	0.35% (1.1%)
TCH/2,4 N=4	BER	0.08% (0.01%)	0.006% (0.4%)
TCH/2,4 N=8	BER	0.015% (0.01%)	0.001% (0.13%)
STCH	MER	10.5% (8%)	11% (11%)

4.8 SUMMARY

This study shows a performance comparison of the single carrier based phase modulation schemes π/4-DQPSK, π/8-D8PSK and 16 –DPSK with multi-carrier based QAM – 4 over TU-5, TU-50 and HT 200 channels in the TETRA at 400 MHz frequency band. The probability of message error for π/4-DQPSK is better than the π/8-D8PSK and 16-DPSK.Single carrier based design is easy to implement however multicarrier based system is more resistant to ISI due to sub-carrier based FMT modulation. For the TU-5 channel environment which is mostly used by the mobile user, the performances of π/4-DQPSK and π/8-D8PSK are better than 16-DPSK. MER suggest the performance threshold for packet drop ratio for various phase modulation schemes, As result of packet or slot error retransmissions system throughput can degrade. The performance of QAM – 4 is shown over TU-50 and HT-200 channels. Performance of QAM – 4 shows that MER over wider E_b/N_o range as compared to results given in TEDS standard. Performance of real-time class application under bad channel conditions can introduce significant delay. Choosing suitable modulation scheme for given channel conditions can guarantee defined throughput. Higher order phase modulations are simpler to implement than QAM and the receiver is also less complex. To achieve higher data rate QAM modulation schemes uses complex sub-carrier based burst structure while burst structure for phase modulation schemes is simple to implement. Increased bandwidth helps to support great variety of multimedia services and extends the support for broadband. Characterisation of TETRA (π/4-DQPSK) at 138 MHz is also presented.

5. IPv6 Support & Application of RoHC for PLC

This chapter presents a novel Internet Protocol (IPv6) system based on Power Line Communication (PLC) that delivers high resilience communication solution in order to achieve a smart grid purposes. We begin by introducing the communication problems to be tackled, including the demands made by the applications which enable the smart grid. Based on these requirements, the architecture of the communication system developed in the DLC+VIT4IP is presented. New techniques for integrating IPv6, IPSec Security, Robust Header Compression (RoHC) and End-to-End QoS are also described, demonstrating PLC as an important candidate for the fulfilment of the smart grid. Contributions in this chapter are also presented at [Shan R. , et al., 2011] and [Adebisi, 2011]

5.1 INTRODUCTION

Traditionally, electricity network management involves loads, fed by generators which are designed and operated to match those loads. Generation is generally based on easily controllable large centralised power stations with electricity flowing in one direction from high to low voltage level of the network. Consequently, communication required for controlling the grid is in one direction. Such a grid is characterised by high line loss, i.e. the amount of power leaving the generation plant which is lost on its journey to homes and businesses. Losses of up to 8 percent are typical and could even be higher in the most advanced countries [ABB, 2009]

Smart grid is a combination of modern information and communication technologies working together with existing network assets in order to enable the power grid to transfer energy and information in all directions. In effect, it

- Integrates intermittent energy sources such as renewable as wind or solar power
- Integrates distributed generation (DG),
- Enables load management,
- Promotes more local demand response,
- Reduces energy consumption, and subsequently CO_2 emissions.

A smart grid is characterised by its functionalities and not necessarily by the set of individual appliances of which it is comprised of [D. Balmert, 2010].

Communication is a key ingredient of the smart grid vision providing bidirectional flow of information across the energy networks. This could be achieved via different media and technologies including wireless, coaxial, PLC, or a hybrid combination of these technologies. The choice of technology is based on factors like cost, integration with legacy technologies, electrical distribution system arrangements, etc.

There are currently a number of research activities and pilot projects with the specific aims of investigating and developing communication platforms for smart grid applications. One of these projects is "Distribution Line Carrier: Verification, Integration and Test of PLC Technologies and IP Communication for Utilities (DLC+VIT4IP[1])", which aim to use the existing electric grid network for communication. The communication system to be developed in this project operates in the frequency range between 1 and 500 kHz. By operating under 1MHz, it avoids electromagnetic interference (EMI) problems associated with broadband PLC

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[1] DLC-VIT4IP Project funded by the European Commission under FP7 Ref.: 247750. http://www.dlc-vit4ip.org.

(BPLC). In addition, it is able to achieve higher bit rate in comparison to the traditional narrowband PLC which operates in a much narrower frequency band. On the application side, the system is based on the Internet Protocol (IPv6). IP is an increasingly used protocol stack in many supervisory and control application fields, including the energy sector, and has been predicted to take a prominent role in future smart grid communication solutions [F. Baker, 2011] . With IPv6, future smart grid applications, such as asset control/management, can be supported, and a flexible communication platform with improved interoperability is available. A major benefit is given by the common protocol independent of the used network technology. This allows end-to-end delivery of application data within all parts of the utility network including the PLC network.

In [A. Haidine, 2011], the authors discuss the state-of-the-art of narrowband high-speed PLC and introduce a general overview of DLC+VIT4IP project. In the following sections in depth analysis of this communication solution is presented including the unique advantages of each communication layer, i.e. access Power Line Communication, the convergence and security layers.

5.2 PLC FOR THE DISTRIBUTION GRID: APPLICATIONS AND REQUIREMENTS

Results of a recent survey in Germany show that of the 24 existing smart metering projects the majority (13) use PLC. Only five projects uses Digital Subscriber Line (DSL) and six are based on the General Packet Radio Service (GPRS). The dominance of PLC in the smart metering projects can also be observed in other European countries, e.g., Spain, Italy, and the Netherlands [A. Haidine, 2011]. Apparently, PLC technology is the favourite solution from the power utilities perspective [A. Haidine, 2011]. Since PLC infrastructure is owned by utilities, they have complete access and control. PLC is also an inexpensive means of providing new and intelligent applications to and from the last mile of the distribution grid, because it uses existing (cabling) infrastructure that covers a wider area than any other traditional communication network.

Electrical distribution systems can be arranged in varieties of ways, including radial, looped, or meshed topologies. Typically Europe has a density that ranges around 50 - 300 meters attached to a medium voltage (MV)/low voltage (LV) substation, and the average distance between MV/LV transformer and the consumer meters is about 465m. DLC+VIT4IP is an access communication technology that provides a communication solution for the whole collection of distribution smart grid applications in both MV and LV networks. It will enable the utility companies to gather more detailed information about how energy is consumed by end users and about the status of the power grid. In addition, it will equip them with means to remotely control the grid, e.g., control the Supervisory Control and Data Acquisition (SCADA) equipments, or terminate supply of energy in pre-paid systems.

According to the latest survey made by the council on large electric systems, Conseil International des Grands Reseaux Électriques (CIGRE) in [CIGRE Working Group, 2008], there are 12 key application services for automating the MV and LV Distribution Grid. Those that will especially benefit from PLC and are targeted by DLC+VIT4IP are described below:

Metering Service: Automatic Meter Reading (AMR) implies the remote reading of the measurement registers of a meter without physical access to the meter

Telecontrol (Remote Control and Monitoring Service): This is the control of operational equipment at a distance using the transmission of information by telecommunication techniques. Telecontrol may comprise of any combination of commands, alarm, indication, metering, protection and tripping facilities. Tele-measurement and power quality measurement are part of the predictive and diagnostic tools necessary for self-healing solutions

Video Surveillance: A digital utility video surveillance system enhances security of MV/LV sites and equipment by remotely monitoring the video sequences captured in the areas covered by it. Due to limited network bandwidth, the video surveillance mentioned in this paper is event-triggered (alarm indication, door opening); Frame rate and video resolution will be limited

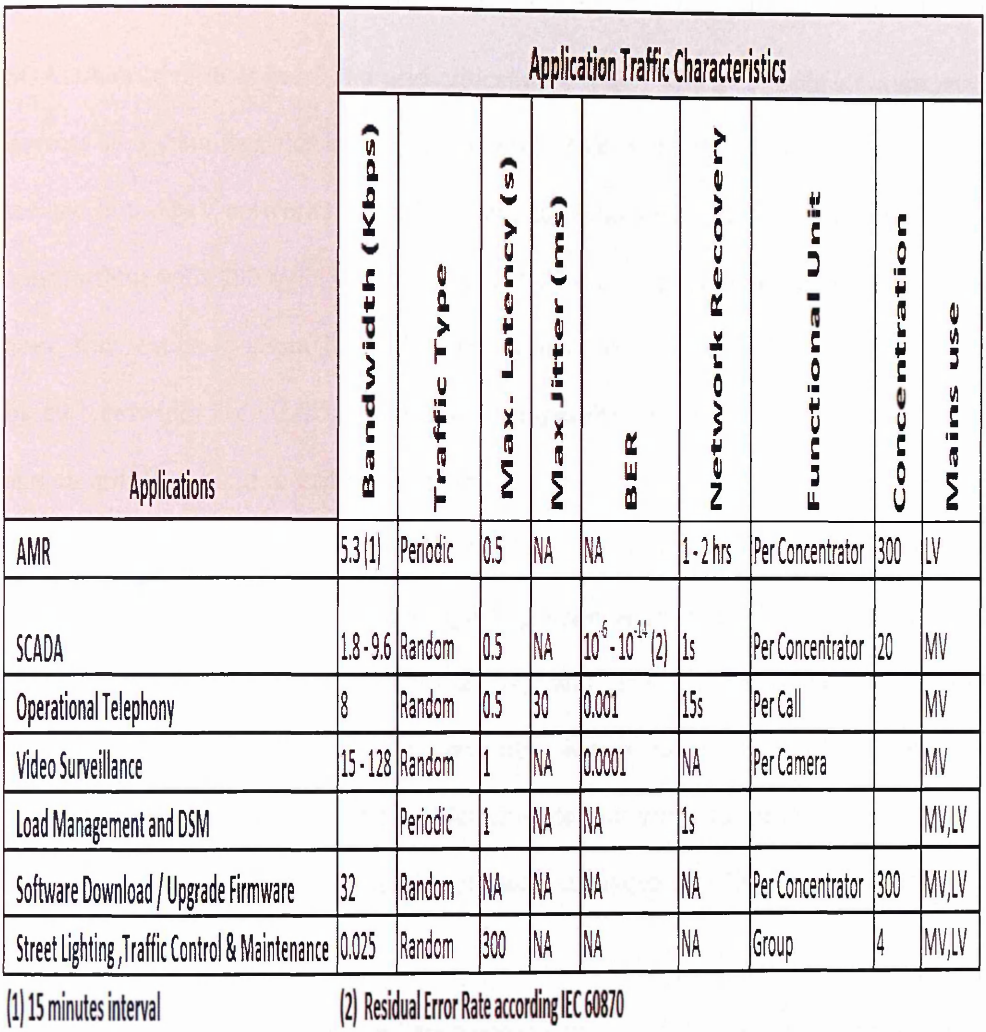
Operational Telephony: Operational telephony provides personnel at LV/MV sites a direct bidirectional audio connection to the network operation center. Voice over IP (VoIP) connections over DLC network is targeted.

Demand Side Management (DSM): The purpose of DSM programs is to influence the behaviour of electrical loads of different customers (e.g. residential, commercial or industrial facilities) in order to optimise energy production costs, enhance energy utilisation or system reliability, or to match utilisation to environmental factors. When planned accordingly, they can also contribute to defer investment in new infrastructure by diminishing the peak capacity requirements of the system. Active Demand (AD), Demand Response (DR) or Demand Side Response (DSR) are newer terms describing the market based approach to DSM.

Table 5-1 presents a summary of traffic characteristics to the above application services and are key requirements for the DLC+VIT4IP solutions. Some of these traffic profiles were simulated over DLC simulator. DLC simulation environment was implemented in NS-3 based on the design discussed in next section.

Table 5-1: Applications and Application Traffic Characteristics

[DLC+VIT4IP Project, 2010]



Applications	Application Traffic Characteristics								
	Bandwidth (Kbps)	Traffic Type	Max. Latency (s)	Max Jitter (ms)	BER	Network Recovery	Functional Unit	Concentration	Mains use
AMR	5.3 (1)	Periodic	0.5	NA	NA	1 - 2 hrs	Per Concentrator	300	LV
SCADA	1.8 - 9.6	Random	0.5	NA	10^{-6} - 10^{-14} (2)	1s	Per Concentrator	20	MV
Operational Telephony	8	Random	0.5	30	0.001	15s	Per Call		MV
Video Surveillance	15 - 128	Random	1	NA	0.0001	NA	Per Camera		MV
Load Management and DSM		Periodic	1	NA	NA	1s			MV,LV
Software Download / Upgrade Firmware	32	Random	NA	NA	NA	NA	Per Concentrator	300	MV,LV
Street Lighting ,Traffic Control & Maintenance	0.025	Random	300	NA	NA	NA	Group	4	MV,LV

(1) 15 minutes interval (2) Residual Error Rate according IEC 60870

Requirements differ from one application to another, for instance, AMR is a non - time critical application where the meters in the LV network can be read periodically. A subsystem on one transformer station contains on average, 50 to 300 metering points. As meter data is collected for back office, applications like billing latency and variation of delay (jitter) at the PLC are not practically relevant. E.g., If we assume 300 meters and that all meters are read every 15 minutes having a net data volume of

2Kbytes, a speed of 5.33 Kbps is required per transformer station, since the transfer can be spread over the complete day. In [Engage Consulting Ltd, 2010] a detailed data traffic evaluation based on sets of assumptions on data transfer over smart metering system has been carried out.

SCADA on the other hand is a grid-critical application which controls all automated devices and monitors the electrical network. Most of these automated devices are located in the MV network. Assuming about 20 devices have to be controlled per data concentrator with 200 bytes per message with 200 messages (request and response) an hour, this results in about 1800 bits/s (based upon real live trace by utility). CIGRE based bandwidth for SCADA applications ranges from 9.6 to 64 kbit/s. Since control and monitoring is time critical, requirements for latency and error rate values are completely different. According to IEC 60870, the requirements for residual error rate are, 10^{-6}, 10^{-10} and 10^{-14} for cyclic updating systems (telemetering), event initiated transmission (teleindication & telecounting), and critical information transmission (telecommands) respectively. The maximum latency ranges are: 0.5 seconds for telecontrol, 1 to 5 seconds for fault detection telecontrol, and up to 30 seconds for (temperature, gas, flood, and humidity) alarm management. Jitter is in general not relevant.

The requirements for video surveillance depend on the video resolution, the number of captured and sent frames, the codec and whether the video capturing is event based or continuous. For instance, in Common Intermediate Format (CIF; 352 x 288), at 1 frame per second a rate of about 15 kbps is required upstream, at 4 frames per second, 36 kbps are required while 128 kbps are required at 10 frames per second. Latency should be less than 1 second and a maximum bit error should be better than 10^{-4}.

Other requirements such as load management and software download follow similar assumptions as shown in Table 5-1 above.

Another critical requirement in the development and deployment of a viable smart grid is security. Therefore security has a high priority in communications design of the DLC+VIT4IP system. Different access rights to the connected entities must be foreseen. Unlike the other requirements, security is not precisely measurable. But generally, it is essential that any security mechanism should guarantee five features: confidentiality, integrity, availability, authentication and authorisation. This is the only way a reliable authentication and privacy can be guaranteed.

5.3 IPV6 FOR PLC PROTOCOL ARCHITECTURE

Energy management applications in LV and MV power distribution require integration with other network technologies, applications and services through defined communication protocols and topologies. DLC+VIT4IP is based on common standards with IP based network technologies. Figure 5.1 presents a general overview of the DLC+VIT4IP network architecture which is built on the various components including; (a) The LV level connecting the consumer premises, especially smart meters, to a collecting node/data concentrator at the LV/MV substation. Repeaters are installed when the distance is above a certain threshold. (b) The MV level connecting a cluster of MV/LV substations and ends at High Voltage (HV)/MV substations. (c) Access point at the HV substation side builds the access to the wide area network (IP network) or to the private utility network, to reach the control centre or the Metering Data Management System (MDMS). (d) Bridging points enable the extraction of the signal from the LV level and the injection in the MV level and vice versa. This is necessary, because the information signal cannot propagate through the substation without strong attenuation. Bridges can also directly connect the consumer premises to the Access point.

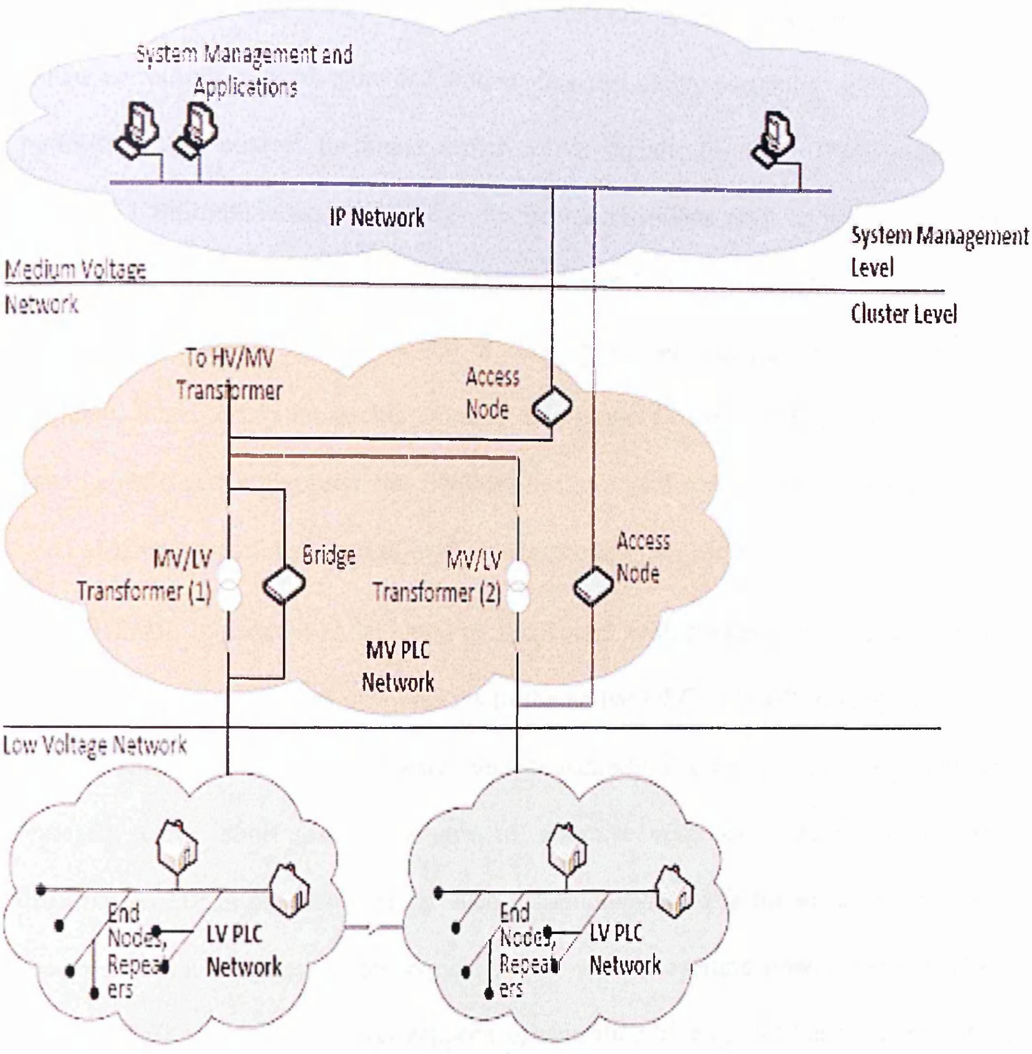


Figure 5.1: Overview of IPv6 centric PLC Network Architecture

IP support for PLC network enables it to support existing applications and extend to new application areas [C. Chauvenet, 2010]. This allows support for applications and services across network borders in wired backbones, wireless networks and access PLC networks. IPv6 offers considerable advantages over IPv4. It provides improved packet format designed for packet header processing by routers and offers much larger address space than IPv4. Improvement in address space makes it possible for PLC based applications to allocate IP address to all electrical equipment and thereby provide control and connectivity. Furthermore, advantages of IPv6 may include improved multicasting facility, support for network layer security through IPsec, enhanced routing support, extended unique identifier, global portability and flexibility, optimisation of control functions, better native support for QoS. IPv6 is seen as enabling (communication) technology for new applications such as management of renewable energies, DSM, management of distribution channels and advance customer services [S. Deering, 1998]. Similar studies such as [Bauer M., 2009] and [Pujante, et al., 2005] for packet oriented data services over the smart grid and QoS management and integration for IPv6 applications and services also suggested the need of IPv6 support and need of QoS management.

DLC+VIT4IP introduces an IP based protocol stack with convergence and adaptation layers to help deliver IPv6 data packets to the native DLC+VIT4IP modem and help achieve reliable, secure and efficient data transmission. Existing PLC technologies typically carry short data messages to optimise response times and prevent disturbances. IP is not designed for such extremely short data frames as a single IP header is often longer than the typical packet size in existing power line systems. DLC+VIT4IP convergence layer supports optimisation of lengthy IP headers by using header compression. The convergence layer provides critical control, suited to address the individual application requirements shown in Table 5-1. It ensures transparent data flow, cross layer QoS, end-to-end QoS and security.

5.3.1 A Convergence Layer

One of the primary functions of the Convergence Layer is to communicate with the native modem on behalf of applications through designated interfaces to ensure the required QoS. Figure 5.2 shows the structure and position of the Convergence Layer as mediator between IPv6 stack and the modem. In order to ensure smooth and transparent data transmission between applications, the convergence layer defines a Service Access Points (SAPs). Each layer outlines its own set of interfaces which are visible only within the allowed SAPs. Different types of SAPs are defined to ensure reliable data delivery for the respective layer. Figure 5.2 shows the SAPs for the DLC+VIT4IP protocol stack. The management plane allows for configuration and control of parameters at each layer. The context plane manages the context of IPv6 PDUs travelling over the signalling plane in terms of security and QoS. Several contexts may be realised from source to intended destination across the power line network. Each context is specified before data transfer and may be re-negotiated during a data transfer. The signalling plane carries IPv6 Protocol Data Units (PDUs), which are destined to be transferred or have been received from the power line physical layer. Signalling will include PDUs, which represent both application data and context negotiation information. Defined SAP interface planes ensure that application gets maximum access to the DLC network resources and use these resources to ensure secure, reliable and efficient data transmission.

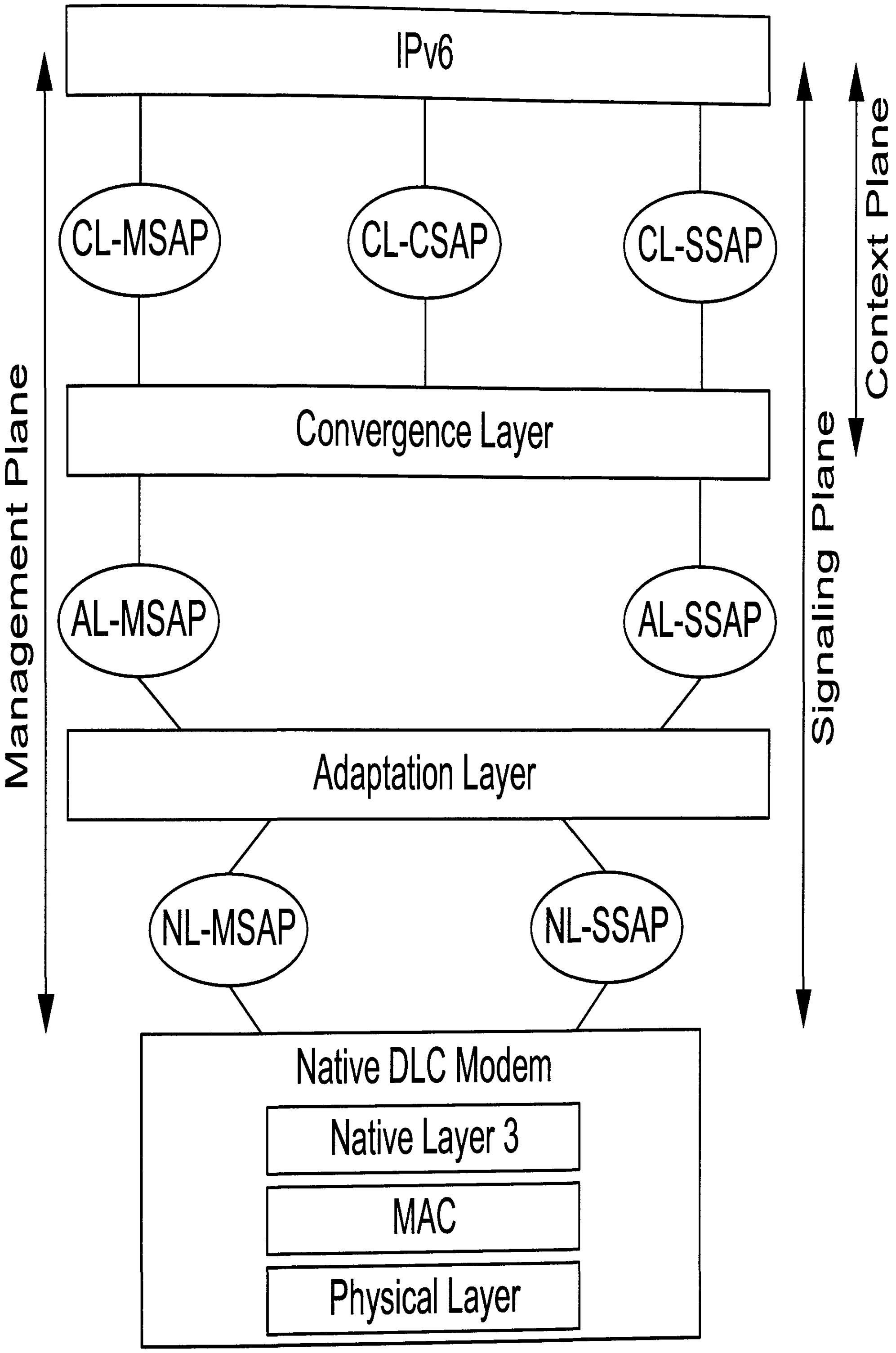


Figure 5.2: Service Access Points for DLC Protocol Stack

Current PLC systems only provide basic point to point QoS due to the continuously changing nature of available bandwidth and channel quality. In DLC+VIT4IP, the convergence layer provides a QoS negotiation platform for applications to request communication resources and then receive notification from PLC layers with regard to available resource both prior to communication and most importantly during communication. Such negotiation allows an application to modify its requirements to the available communication resources and to 'gracefully degrade' a service rather than completely cease to communicate should a node on the communication path experience a poor channel. End-to-End QoS are managed through static and dynamic QoS "traffic classes".

It contains the core functionality for:

- Cross Layer QoS to offer the necessary transmission guarantees and map between IPv6 QoS and the QoS functionality of the underlying PLC system.
- Header (and payload) compression to reduce the transmission of unnecessary data on the bandwidth limited PLC.
- Secrurity to protect data communication.
- packet fragmentation and reassembly to accommodate large IP packets into the small PLC payloads.
- Address mapping to PLC MAC addresses and adaptation to specific PLC service calls to offer the possibility to seamlessly use multiple PLC systems[2].

Additionally, support functionality for transport of IPv4 and auto configuration is foreseen to facility the intended seamless operation.

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[2] Within the project DLC+VIT4IP two systems are supported: the iAd DLC2000 and the Yitran IT900 chipset.

Prior to data transmission the application may make a request to the convergence layer to perform a negotiation across the nodes in order to determine whether the available communication resources are able to support the application's requested requirements. The application will receive a report from the convergence layer, which will indicate approval or rejection of the application's resource request. Where it is impossible to meet the application's request, a report is made of the best fitting capability set for which the application may choose to accept or reject. Upon acceptance, the application negotiation may conclude the operational parameters of the source application performance parameters, e.g. adjust the audio/video codec rate. At this point a context is created at all the nodes within the network. During transmission, the communication capability of the power line network may vary depending on the point where one or more 'hops' between application source and sink may not be able to provide the agreed QoS. In this case, the convergence layer informs the application and this may trigger a renegotiation of application QoS. The processes described above seek to negotiate and agree the QoS requirements of applications. Once agreed, a context is formed on which IPv6 fields can be used to identify the membership of each IP packet to a particular context for which a QoS has been agreed.

Using the IPv6 protocol carries a significant overhead which must be managed in order to retain its benefits. The application profiles mentioned in Table 5-1 (periodic or random traffic) use transport protocols such as RTP and UDP together with IPv6 for end-to-end connectivity and payload delivery. Headers are appended to the payload resulting in increased packet size. The frame sizes of audio, SCADA, and other data application presented in Table 5-1 varies from under tens of bytes to few hundred bytes. For effective bandwidth usage and data reliability, DLC+VIT4IP network proposes shorter maximum transmission unit (MTU) size. As shown in Table

5-2 applications with high packets rate send more data units to the RTP/UDP/IPv6 layer than lower rate applications thus resulting in more header contribution.

Table 5-2 : Header size contribution to VoIP packets

Protocol	Header Size (bits)	Rate (kbit/s) at period 20ms	Rate kbit/s at period 30ms
RTP	96	4.69	3.13
UDP/IPv6	384	18.75	12.50
TCP/IPv6	480	23.44	15.63
RTP/UDP/IPv6	480	23.44	15.63

Since header size of DLC+VIT4IP applications profiles, especially with TCP/IPv6 and RTP/UDP/IPv6 based applications, is significantly high, it is beneficial to use header compression. Here, Robust Header Compression (RoHC) has been employed to compress the header and minimise the control information flow over the band limited network without compromising on the reliability and QoS. RoHC and decompression is integrated within the DLC+VIT4IP convergence layer to allow maximum control of the Convergence layer over QoS. In order to test the gain obtained as a result of RoHC, we simulated a system using RoHC. Headers are typically compressed;

- For RTP/UDP/IPv4 from 40 bytes to 3 bytes,
- For UDP/IPv6 from 48 bytes to 4 bytes,
- For RTP/UDP/IPv6 from 60 bytes to 5 bytes, and
- For TCP/IPv6 from 60 bytes to 4 bytes [EFFNET Lab, 2007] and [Wang, et al., 2004].

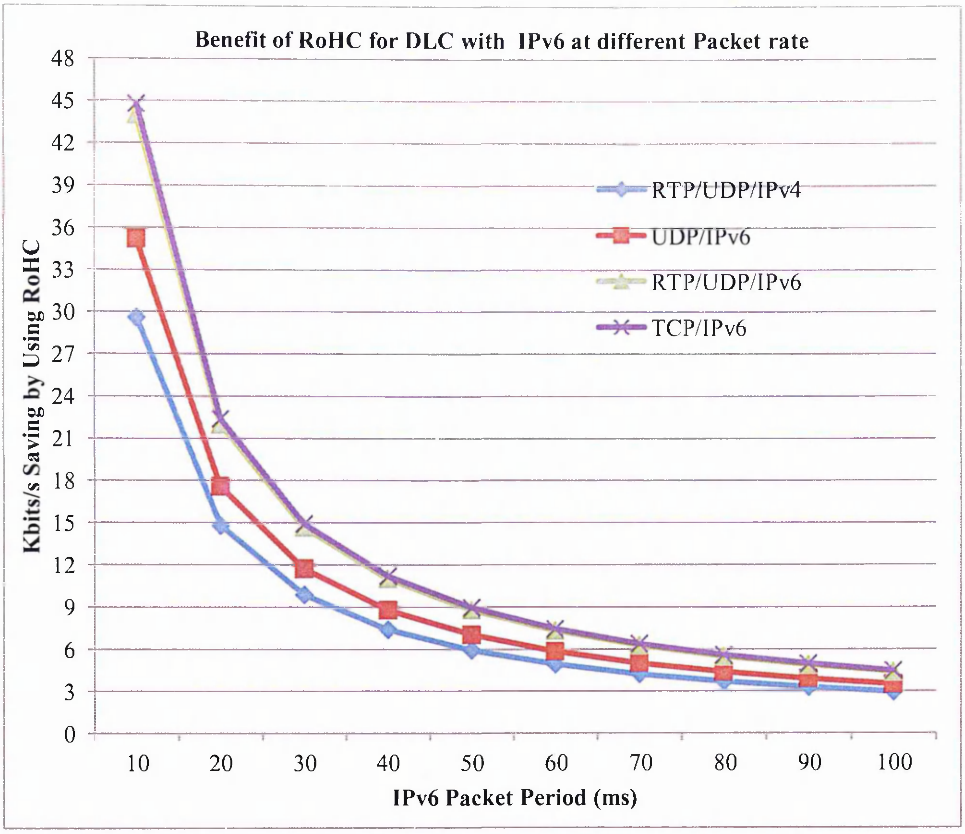

Figure 5.3: Bandwidth saved by using RoHC for DLC+VIT4IP System with IPv6.

Figure 5.3 shows the overall gain in bandwidth due to header compression. For RTP/UDP/IPv6 which are typical protocols for voice applications the gain is around 44 kbits/s. Similarly, gain for other periodic applications like load managements and DSM applications is around 36 kbits/s. Applications where connection orientation and acknowledgement based packet delivery is required, i.e, traffic control and management applications follow TCP/IPv6 protocols, while RoHC offers over 40 kbits/s bandwidth gain. It is clear that high rate applications benefits more from the header compression introduced.

5.3.2 The Network Topology

Figure 5.4 shows typical scenarios for smart grid utility communication: Multiple utilities data sources and sinks in the grid are connected by PLC network.

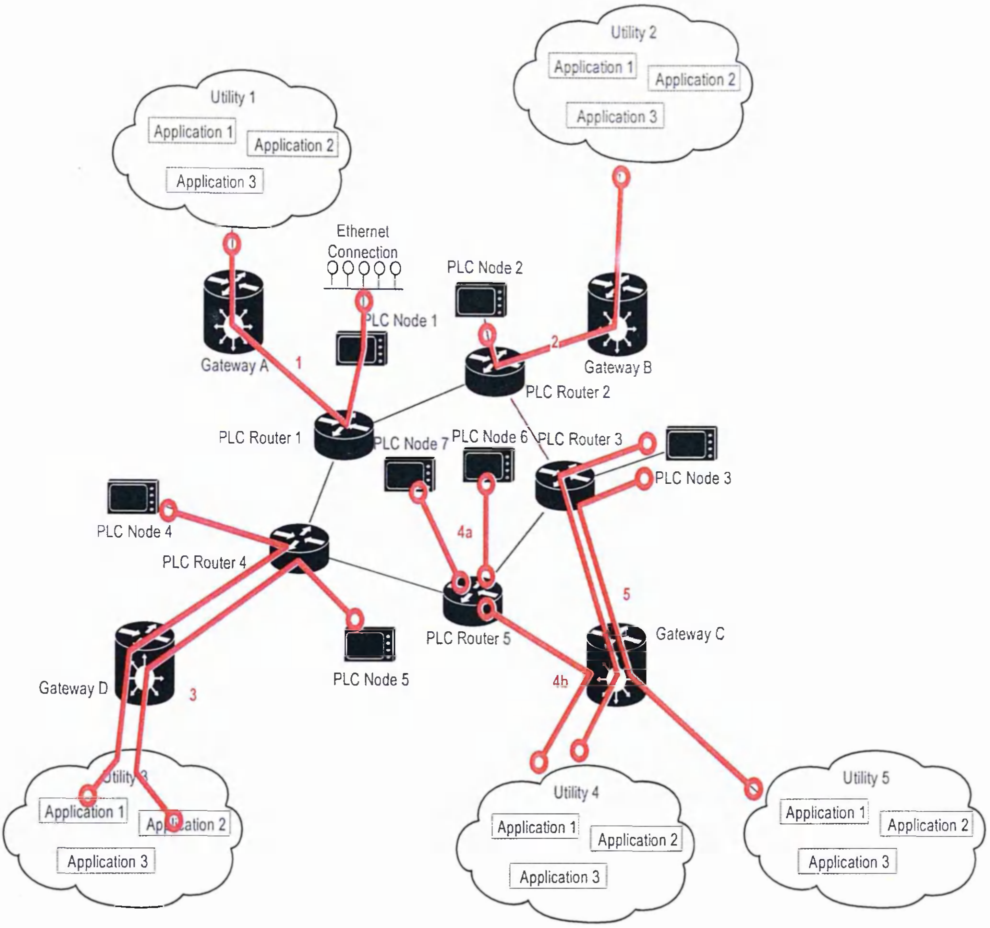

Figure 5.4: Communication scenarios in DLC+VIT4IP

The security requirements for this traffic can be divided into five key scenarios covering most utility field level communication requirements. Within Figure 5.4 these security associations are indicated by red lines, where the ends of these lines indicate the security boundary:

1. Tunneling: In this scenario the communication system establishes a secure tunnel between the utility Intranet and a field site such as a substation hosting multiple devices. The two networks are connected transparently as though they are a single logical network. The tunnel must guarantee proper integrity, authentication and authorization of the gateways. Confidentiality can also be

offered, although proper operation of the smart grid can be guaranteed without it.

2. Transport: The communication system protects the traffic from a gateway directly to the addressed node, e.g. a switch gear or SCADA component. Security requirements are equivalent to the tunnelling scenario (1). Authorization is done between the utility intranet as a whole and the individual nodes.
3. Protection of application to node communication: In this scenario the security association directly links a field device with an application offering the finest grained security. This is for example required for AMR-based billing additionally raising the requirement of non-repudiation.
4. Data concentration: The difference of this protection scenario is given in the interruption of the security connection at the data concentrator (Router). The data concentrator acts as a client to both the application and the field level equipment.
5. Multi-utility Communication: Within the deregulated market multiple utilities can use the same grid and may even address identical nodes. Traffic separation between different users is required allowing multi-utility use of this communication infrastructure. Additional to the requirements of the individual security connections confidentiality becomes a strong requirement.

Furthermore, the utility intranet might be setup by multiple security domains not shown Figure 5.4. Often there is a gap between the security measures in the intranet and the PLC network. PLC networks if at all often only have individual security highly optimised to the bandwidth limitations or different applications protocols, which differ to the ones used in the intranet. Essentially, DLC+VIT4IP is expected to have transparent communication and to be compatible with other communication means in the utility IT infrastructure the security system of DLC+VIT4IP is based on fully standardised protocols.

5.4 ROHC INTEGRATION AT CONVERGENCE LAYER

RoHC compression and decompression is integrated with the DLC convergence layer to allow maximum control for Convergence layer over QoS. The convergence layer can manage the compression gain of the RoHC based on channel conditions and QoS parameters requested by the DLC application. This adaptive control for convergence layer will ensure maximum reliability and efficiency for DLC applications over the network. Currently RoHCv1 is implemented for DLC network with profile support for Uncompressed, IPv6-only, IPv6/UDP, IPv6/UDP-Lite and IPv6/UDP/RTP. Traffic generated from mentioned profiles will be passed to the RoHCv1 compression at DLC Convergence layer. Data will be travelling through signalling plane through the CL-SSAP. At Implementation level, RoHC compression and decompression code needed to fit into the function where DLC convergence layer separates the IPv6 packet from the Ethernet frame and already done any of the QoS and pre compression functions.

CL-SSAP enables IPv6 PDU to be transmitted between IPv6 and DLC Convergence layer. CLS-DATA PDU is “Ethernet Frame” which is carried from the TAP device to the convergence layer. Convergence layer will receive the “CLS-DATA” PDU as “Ethernet Frame”. Convergence layer will process the Ethernet frame information by separating the Ethernet frame from the IPv6 PDU. RoHC compression is implemented over the IPv6 PDU after it is separated from “Ethernet Frame”. RoHC compression will take IPv6 PDU as input, separate IPv6, UDP and RTP headers from the DLC application payload. RoHC header is computed over the filtered fields and appended with the DLC application payload, resultant PDU is treated as ALS-Data within the DLC Convergence layer. Only the DLC application payload type data within CLS-DATA will be passed to RoHC compression at DLC Convergence layer, as a result ALS-DATA will only be carrying RoHC compressed packets if data payload was carried by CL-SSAP as application payload type. Ethernet header is appended back to the RoHC packet. RoHC compression works in stages and can switch among the stages resulting in variable RoHC header size, thus the size of ALS-DATA will also vary with the variable RoHC header. RoHC decompression will separate the RoHC header from the payload and tries to recalculate the original header. On successful recalculation, RTP/UDP/IPv6 header is appended back to the payload. At this stage packet should ideally be the same as the transmitter DLC convergence layer received from through the CL-SSAP as CLS-DATA. RoHC decompression works on variable size input and tries to recalculate the original IPv6 header based on the context information it have from the DLC RoHC compression. In case of failure to compute the original header RoHC decompression will tend to drop any erroneous packets at convergence layer. RoHC performance at the Convergence layer can be calculated based on the header compression gain, Compression efficiency in terms of bandwidth saved due to compression gain and error propagation to the application layer due to error in recalculated header on DLC RoHC decompression.

5.4.1 RoHC Performance Evaluation for DLC

Performance of RoHC can be illustrated with robustness, compression transparency and most importantly compression efficiency. RoHC compression efficiency can be established from size of the header compressed by RoHC. Header Compression gain percentage is calculated based on reduced header size against the actual header size.

RoHC transparency is established from the degree to which RoHC ensures that decompressed headers are semantically identical to the original headers. Damaged headers from the decompression propagate errors while high compression transparency states low damage propagation. Robustness is established from the loss propagation and residual errors from the decompression. In case of lost context on the decompression, efficiency of recovery of decompression ascertains the RoHC robustness. RoHC Compression gain and Damage Propagation are two basic parameters for numeric evaluation of RoHC performance for DLC.

Selected traffic profiles are tested for RoHC performance over DLC network. Average header size of RoHC send over the interval is monitored. RoHC header compression gain is calculated by computing size of compressed header against the size of actual IPv6 header carried by CL-SSAP. Header compression gain will answer the compression efficiency of the RoHC over DLC. Header compression gain is expected to drop with high channel errors. To calculate damage propagation the application packet error rate at receiver needed to be computed with and without RoHC activated at DLC convergence layer.

Impact of RoHC performance for applications in the small LV+MV network, payload size for traffic types against the header contributions and estimated RoHC compression gain is given below.

Table 5-3: Average RoHC Compression gain for DLC Network, based on selected traffic profiles

Application	**Average RoHC Header for IPv6 (Bytes)**	**RoHC Compression Gain**	**% of IPv6 uncompressed Header**	**% of RoHC Header**
Tele-Control	4	93.33%	37.50%	3.85%
Video Surveillance	4	94.29%	4.46%	0.27%
AMR/AMM	4	93.33%	37.50%	3.85%
Load Management	4	91.67%	60.00%	11.11%

AMR Codec	4	93.33%	70.59%	13.79%

It is expected that RoHC should be able to compress IPv6 header down to 4 bytes, which is supported by different simulations available in literature. Based on that, Compression gain for RoHC is up to 93%. Column four suggests the percentage of uncompressed header in IPv6 packet received by the Convergence layer. Last column shows the expected percentage of header in a packet transmitted over DLC network.

5.5 PERFORMANCE OF ROHCV2 AGAINST ROHCV1

RoHCv1 [C. Bormann et al, 2001] implemented for DLC network supports traffic profiles for Uncompressed, IPv6-only, IPv6/UDP, IPv6/UDP-Lite and IPv6/UDP/RTP, RoHCv2 [G. Pelletier, 2008] support some of the additional feature which are mentioned below, however RoHCv2 suggest that if implemented under similar conditions performance is RoHCv2 is equivalent to RoHCv1 for unidirectional mode.

ROHCv2 is the newest standardized protocol in Header Compression that allows the compression of a large number of protocols (RTP, UDP, IP, ESP and UDP-Lite). It is a second definition of the profiles used in ROHC, and introduces some simplifications and improvements on reordering links. Several features of ROHCv2 are the shared with ROHCv1, like the description language of the compressed packets. However, ***both versions are incompatible***. In addition, the three-state machine defined in ROHCv1 is replaced by a two-state model in ROHCv2. Like the IR state in ROHC, the first state corresponds to the transmission of uncompressed headers (NC). The second state is a generic compression state (CO). In this state, packets are compressed dynamically. The compressor assumes the decompressor state based on the packets ahead sent and encodes the packet with the appropriate compression scheme. Moreover, the compressor uses an optimistic approach, quite similar to the ROHC approach. Requirements for ROHC are based upon avoidance of damage propagation. For that, ROHC requires a mechanism that cancels the effects of damage propagation by an efficient error detection mechanism. Hence, the observed channel can be considered as an erasure channel. Some of the additional features supported by the RoHCv2 are given below.

- Tolerance to reordering
- Operational logic
- IP extension header
- IP encapsulation
- Robustness and repairs
- Feedback

Summary of the feature of RoHCv1 against the newly added features of RoHCv2 over narrowband systems such as TETRA and DLC is illustrated below in Table 5-4

Table 5-4 : Feature comparison of RoHCv1 & RoHCv2 over Narrowband systems

Features of RoHCv1 [C. Bormann et al, 2001]	**Features of RoHCv2** [G. Pelletier, 2008]	**Effect over Narrowband Systems (TETRA/ DLC)**
Three stage compression -- Initialization and Refresh (IR) -- First Order compression(FO) -- Second Order compression(SO)	Two stage compression -- Initialization and Refresh (IR) -- Compressed(CO)	RoHCv1 is gradual compression from IR to SO, RoHCv2 behaves more optimistic. Average RoHC header size may very maximum up to 1 byte over approx. 10,000 packets. This may increase with noisy channel where we have more lost context and switching between

		the states.
Doesn't support reordering of packet	Support Reordering and out of order packet arrivals	Does affect the performance if we have significant out of order packet arrivals. With current node to node delivery, it is less probable to happen
U-Mode,O-Mode and R-Mode with explicit profile modes	Enhanced operational Logic, support all previous modes	Under unidirectional mode [RFC 5225] suggest that performance of both versions are similar. Under bi-directional O and R mode, RoHCv2 is more robust and have better context management system. Can affect performance only under bi-direction mode if we have frequent lost context.
Up to two level of IP encapsulation supported	Arbitrary number of IP encapsulation is supported	In case of tunneling, two level encapsulation may be implemented in case of DLC, it is less probable to happen
Use list compression to compress IP extension headers	ROHCv2 profiles instead treat extension headers in the same manner as other protocol headers	With static extension headers it is less probable to affect DLC.
Static Context repair strategy and use three state logic	More robust context repair mechanism and use two state logic	In case of more context lost, due to high errors can effect performance but on average 1 up to one byte of RoHC header over the interval.
Support list compression	Doesn't support list compression	Doesn't affect DLC

5.6 SUMMARY

Important services based on the DLC+VIT4IP project has been discussed, which further strengthen PLC as a suitable technology for providing the much needed communication solution for the smart grid vision. Through the use of a future proof

IPv6 protocol, PLC communication may not be limited to any individual device, application, nor the changing face of the rapidly developing internet and smart grid application space. It can support the complete bundle of utility applications, both current and future. Finally, such a system can only work – technically as well as from an economic point of view – with adequate end-to-end QoS management, flexible and accessible security and versatile generic communication services; all of which are presented in the chapter. The DLC+VIT4IP approach aims to offer such a system and defines the necessary technical requirements by defining a modular IP-to-PLC convergence layer.

6. CONCLUSION AND FURTHER WORK

6.1 CONCLUSION

It is important to investigate the type of information processed at the physical layer of the communication system. Communication systems with limited bandwidth, both wired and wireless, need more control at the physical layer for the analysis of the information flow. Throughput optimization techniques applied above logical link control and medium access control layers, enables the system to control and analyse the information type and rate at the physical layer. A header compression technique such as RoHC greatly benefits the communication systems especially with traffic profiles where the application payload size is significantly smaller than the combined header contributions above the LLC/MAC layers. RoHC can be easily integrated into the communication protocol stack without significant changes at the LLC/MAC layer. RoHC is very adaptive to the propagation channel conditions and can be adjusted according to the error rate.

PMR systems such as TETRA greatly benefit from the application of RoHC, by compressing the large headers and saving the number of slot capacities. Integration of RoHC into the TETRA protocol is simple and does not affect the reliability of the PMR system. As a result of the study, performance of RoHC over different traffic profiles such as VoIP, video, medical data and HTTP were analysed and the threshold for performance critical factors such as delay and packet drop rate were outlined. Apart from the application of RoHC over TEDS, a simulation of the TEDS physical layer, for the purpose of performance analysis over different modulation schemes, was also carried out. The study helped in providing BER/MER performance curves against E_s/N_o for different higher order modulation schemes. Current TEDS standards are based on the transmission frequencies above 400MHz range, however with delays in broadband TETRA, it is important to explore all possible avenues to extend the capacity of the system. For this purpose, an investigation of TETRA performance below 200 MHz was carried out. To investigate the performance of header compression over a narrowband wired communication system, RoHC has been integrated into the IPv6 enabled PLC system. In case of application of RoHC over band limited communication systems, it is evident that fast rate RTP applications have high gain in terms of bandwidth than the slow rate RTP application. It is clear from the study that the performance of high data rate multimedia applications over band limited communication systems suffers from delay and a huge packet drop. Multimedia application with fast rate packet generation and significant packet/frame sizes suffers more application packet drop than channel errors. This problem is overcome by introducing a buffer at Layer 2 or controlling the packet generation rate. RoHC helps to reduce the header percentage in the overall packet, and then can achieve up to 94% header compression gain under 1-5% message error rate conditions. In one of the examples, it was shown that RoHC is capable of compressing the header size of 40 bytes down to 3-4 bytes (i.e. 86% reduction). By reducing the frame rate, the packet drop can also be reduced. New receiver sensitivity parameters below 200MHz are outlined in the study.

6.2 RECOMMENDATION FOR FURTHER WORK

Broadband TETRA may not be available till 2020; however it is vital to explore all possible avenues to extend the current support system. Due to the huge market surge of multimedia based applications and services for commercial mobile systems and limitation of PMR, it is imperative to investigate homogeneous and heterogeneous solutions for TETRA systems. Integration of TETRA with 4G mobile communication technologies is one such avenue which requires extensive investigation, due to the fundamental differences in the objectives of both systems. Studies carried out for the integration could not impress the market due to limitation of scope and rapidly evolving commercial mobile market.

The bandwidth optimization in the current 25 kHz band systems is an important research area, which can be addressed by exploring adaptive QoS techniques at Layer 2. Such applications are more software oriented and can be easily adapted with the existing system. The Federal Communications Commission – US is pushing the industry to adapt 12.5 kHz band for all narrowband PMR systems, the application of such a change for TETRA would be an exciting research area. Current UHF and VHF bands are congested and a very limited spectrum is available for the extension or implementation of new communication systems. Such migration will help in creating more channels, hence accommodating more users within the same spectrum.

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