QUATERNION MODEL OF ENHANCED ROTATING POLARIZATION WAVE FOR ROBUST HIGHER ORDER MODULATION LOW POWER WIDE AREA NETWORK WIRELESS COMMUNICATION

By

ZAID AHMAD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

June 2022

FK 2022 104

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairperson : Professor Shaiful Jahari bin Hashim, PhD
Faculty : Engineering

The growing interest in Industry 4.0 has spurred the demand for reliable wireless communication. Low-Power Wide-Area Networks (LPWANs) have pivotal role in emerging applications such as Internet of Things (IoT) and Machine-to-machine (M2M) communication wherein massive number of sparsely located machines and sensor nodes are connected. Reliability and robustness are compromised when LPWANs are deployed to support industrial grade communication. Moreover, critical IoT applications have pressing demands for high data rate and extended coverage with minimal information loss. The design requirements of wireless M2M systems influence the choice of modulation and diversity techniques, and the selection of spectrum. Rotating Polarization Wave (RPW) is an LPWAN technology tested for highly reliable M2M communication. It is a hybrid polarization-based modulation that exploits Binary Phase Shift Keying (BPSK) and Polarization Diversity (PD) to provide robust wireless connectivity. In this thesis, an enhanced RPW modulation is proposed whereby a novel pair of complementary Multilevel PSK (MPSK) modulators successfully generates an RPW waveform with multiple phase shifts, hence termed as Rotating Polarization Multilevel Phase-Shift Keying (RP-MPSK). A novel channel model is also proposed that exploits quaternions to account for the impact of multipath fading and channel depolarization on RPW transmission. The model is referred to as Quaternion RPW (Q-RPW) model in this thesis. Q-RPW simplifies computation involved in modeling and simulation of RPW that is otherwise complex if classical dual-polarized channel models are employed. Performance of RP-MPSK over multipath fading channel under noise and interference conditions has been evaluated in terms of Bit Error Rate BER using the proposed Q-RPW model. The results show that uncoded RP-MPSK

modulation with the smallest sampling ratio of 3 attains BER profile similar to that of BPSK system with second-order space diversity. Further improvement in BER performance can be achieved provided higher sampling ratios are maintained. Therefore, sampling ratio on RP-MPSK receiver is a practical trade-off between reliability and data rate. RPW with RP-MPSK also outperforms all other forms of polarization in terms of BER. A comprehensive link budget analysis is performed to demonstrate the potential of RPW as an enabling technology for LPWAN. Sensitivity, Received Signal Strength (RSS), and maximum range of RPW is determined. Results show that RP-MPSK exhibits an excellent sensitivity level of -114 dBm under multipath conditions. The minimum RSS in urban settings is -85 dBm while the maximum range achieved by RP-MPSK in rural areas is 15 km despite shadowing and multipath fading. RPW with proposed RP-MPSK modulation offers transmission rate of up to 500 kbps with a channel bandwidth of 125 kHz. However, in ISM band, channel bandwidth can be increased to 500 kHz. Consequently, potential transmission rates of up to 2 Mbps are feasible. Higher data rates translate to increased energy efficiency as more data is transmitted in shorter time intervals to counterpoise duty cycle limitations of ISM band.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan ijazah Doktoran Falsafah

MODEL QUATERNION GELOMBANG POLARIZASI BERPUTAR YANG DIPERTINGKATKAN UNTUK PEMODULASI ORDER TINGGI KUAT RENDAH KUASA RENDAH RANGKAIAN LUAS RANGKAIAN KOMUNIKASI TANPA WAYAR

Oleh

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Minat yang semakin meningkat dalam Industri 4.0 telah mendorong permintaan untuk komunikasi tanpa wayar yang boleh dipercayai. Rangkaian Kawasan Luas Kuasa Rendah (LPWANs) mempunyai peranan penting dalam aplikasi baru yang sedang berkembang iaitu seperti Internet Benda (IoT) dan komunikasi Mesin-ke-mesin (M2M) di mana sebilangan besar mesin dan nod sensor yang jarang terletak, disambungkan. Kebolehpercayaan dan keteguhan dikompromi apabila LPWAN ditempatkan untuk menyokong komunikasi gred industri. Lebih-lebih lagi, aplikasi IoT kritikal mempunyai permintaan yang mendesak, untuk kadar data yang tinggi dan liputan luas dengan kehilangan data yang minimum. Reka bentuk yang diperlukan pada sistem M2M tanpa wayar mempengaruhi pilihan teknik modulasi dan kepelbagaian, dan pemilihan spektrum. Gelombang Polarisasi Berputar (RPW) adalah teknologi LPWAN yang telah diuji dan sangat cekap untuk komunikasi M2M. Ia adalah modulasi berasaskan polarisasi hibrid yang mengeksploitasi Kekunci Anjakan Fasa Perduaan (BPSK) dan Kepelbagaian Polarisasi (PD) untuk menyediakan sambungan tanpa wayar yang kukuh. Di dalam tesis ini, modulasi RPW yang intensif dicadangkan di mana sepasang pemodulat Pelbagai Peringkat Kekunci Anjakan Fasa (MPSK) pelengkap yang baru berjaya menjana bentuk gelombang RPW dengan peralihan pelbagai fasa, oleh itu disebut sebagai Polarisasi Berputar Pelbagai Peringkat Kekunci Anjakan Fasa (RP-MPSK). Model saluran baru juga dicadangkan iaitu yang dapat mengeksploitasi kuaternion serta mengambil kira kesan pudar multipath dan depolarisasi saluran pada penghantaran RPW. Model ini dirujuk sebagai model Quaternion RPW (Q-RPW) di dalam tesis ini. Q-RPW memudahkan pengiraan yang terlibat dalam

pemodelan dan simulasi RPW yang sebaliknya kompleks jika model saluran dwi-Polarisasi klasik digunakan. Prestasi RP-MPSK ke atas Berbilang Laluan saluran di bawah keadaan hingar dan gangguan telah dinilai dari segi Kadar Ralat Bit (BER) menggunakan model Q-RPW yang dicadangkan. Keputusan menunjukkan bahawa modulasi RP-MPSK yang tidak dikodkan dengan nisbah persampelan terkecil 3 mencapai profil BER yang sama dengan sistem BPSK dengan kepelbagaian ruang pesanan kedua. Penambahbaikan yang seterusnya dalam prestasi BER boleh dicapai dengan syarat nisbah persampelan yang lebih tinggi dikekalkan. Oleh itu, nisbah persampelan pada penerima RP-MPSK adalah pertukaran praktikal antara kebolehpercayaan dan kadar data. RPW dengan RP-MPSK juga telah mengatasi semua bentuk polarisasi lain dari segi BER. Analisis bajet pautan yang komprehensif dilakukan untuk menunjukkan potensi RPW sebagai teknologi yang berpotensi tinggi dengan LPWAN. Sensitiviti, Kekuatan Isyarat Diterima (RSS), dan julat maksimum RPW telah dapat ditentukan. Keputusan menunjukkan bahawa RP-MPSK menunjukkan tahap sensitiviti yang sangat baik -114 dBm di bawah keadaan MP. RSS minimum dalam persekitaran bandar ialah -85 dBm manakala julat maksimum yang dicapai oleh RP-MPSK di kawasan luar bandar ialah 15 km walaupun bayangan dan multipath pudar. RPW dengan modulasi RP-MPSK yang dicadangkan menawarkan kadar penghantaran sehingga 500 kbps dengan lebar jalur saluran 125 kHz. Walau bagaimanapun, dalam jalur ISM, lebar jalur saluran boleh ditingkatkan kepada 500 kHz. Oleh itu, kadar penghantaran yang berpotensi sehingga 2 Mbps boleh dilaksanakan. Kadar data yang lebih tinggi diterjemahkan kepada peningkatan kecekapan tenaga kerana lebih banyak data dihantar dalam selang masa yang lebih pendek untuk mengatasi batasan kitaran tugas kumpulan ISM.

ACKNOWLEDGEMENTS

I would like to express my profound gratitude to my supervisor and the Chairman of committee **Prof. Dr. Shaiful Jahari Hashim** for accomplishment of this research work under his visionary supervision. He has always enlightened and inspired me by inculcating the motivation and essence of research aimed for ultimate benefit of the society. His expertise in computer and communication engineering was a source of continuous insightfulness for me through the entire course of this research, in addition to his kindness that always encouraged me whenever I needed.

I also express my deepest regards to my **co-supervisors**:

Prof. Dr. Aduwati Sali
Prof. Dr. Syed Abdul Rahman Al-Haddad
Assoc. Prof. Dr. Fakhrul Zaman Rokhani.

for their kind mentorship, boosting up my confidence to accomplish my research and make it competitive in an era of rapid developments taking place globally. I also appreciate the generous support extended by the staff of Computer and Embedded Systems Lab at UPM.

It is a matter of immense pleasure and pride for me to have worked in close collaboration with the inventor of Rotating Polarization Wave (RPW) technology Mr. Ken Takei from Hitachi (Japan) and having necessary guidance from time to time. I am also thankful to Assoc. Prof. Dr. Guillaume Ferré from University of Bordeaux (France) for his valuable collaboration and suggestions on the comparative link budget analysis.

I am grateful to Government of Pakistan and my sponsor Higher Education Commission (HEC) of Pakistan on award of scholarship for PhD studies abroad. I am also thankful to my employer COMSATS University Islamabad (Pakistan) for allowing me to pursue PhD in Malaysia on study leave. Finally, I could not have accomplished this milestone in my life without consistent moral support from my family who suffered but always stood by me. My lovely and loving wife Maryam has always been patient and kind to me in spells of depression and anxiety. My daughters Nabiha Zahra, Hania Zainab and my son Muhtada Hussain have been eagerly waiting for my PhD to conclude so that I could give them quality time again and enjoy their sparkling faces. The prayers of my parents and the never-ending wishes of my brothers and sisters were always with me during my overseas stay to fulfil my dream.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

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ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BFSK	Binary Frequency-Shift Keying
BPSK	Binary Phase-Shift Keying
BS	Base Station
CAPEX	Capital Expenses
CIoT	Consumer Internet of Things
CNR	Carrier-to-Noise Ratio
CSS	Chirp Spread Spectrum
DoF	Degree of Freedom
DSSS	Direct Sequency Spread Spectrum
ECC	Error Control Coding
EC-GSM-IoT	Enhanced-Coverage GSM for IoT
ED	End Device
EGC	Equal-Gain Combining
ETSI	European Telecommunication Standard Institute
FDMA	Frequency-Division Multiple Access
FH	Frequency Hopping
FHSS	Frequency-Hopped Spread Spectrum
FSL	Free-Space Loss
GFSK	Gaussian Frequency-Shift Keying

GHGE	Green-House Gas Emission
GMSK	Gaussian Minimum Shift Keying
GW	Gateway
HP	Horizontally Polarized
ICS	Industrial Communication Systems
ICT	Information and Communication Technology
IIoT	Industrial Internet of Things
IoT	Internet of Things
ISM	Industrial, Scientific and Medical (band)
kbps	kilobits per second
LoRa	Long-Range
LoS	Line-of-Sight
LPWAN	Low-Power Wide-Area Network
LTE-M	Long Term Evolution for Machines
M2M	Machine-to-Machine (Communication)
MAC	Media Access Control Layer
Mbps	Megabits per second
MIMO	Multiple-Input Multiple Output
MLE	Maximum Likelihood
MLSE	Maximum Likelihood Sequence Estimation
MPSK	Multi-level Phase-Shift Keying
MQAM	Multi-level Quadrature Amplitude Multiplexing
Msps	Mega samples per second
NB	Narrowband

NB-IoT	Narrowband IoT
NLoS	Non-Line-of-Sight
N_p	Sampling Ratio
NS	Network Server
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operating Expense
OTA	Over-The-Air
PD	Polarization Diversity
PDF	Probability Distribution Function
PEL	Plane-Earth Loss
PHY	Physical Layer
QPSK	Quaternary Phase-Shift Keying
Q-RPW	Quaternion Model for RPW Communication
RF	Radio Frequency
RP-BPSK	Rotating Polarization Binary Phase-Shift Keying
RPMA	Random-Phase Multiple Access
RP-MPSK	Rotating Polarization Multilevel Phase-Shift Keying
RPW	Rotation Polarization Wave
RSS	Received Signal Strength
SC	Selection Combining
SDR	Software-Defined Radio
SF	Spreading Factor
SNR	Signal-to-Noise Ratio
SPC	Serial-to-Parallel Conversion

TDMA	Time-Division Multiple Access
TITO	Two-Input Two-Output
ToA	Time-on-Air
TSMA	Telegram-Splitting Multiple Access
TVWS	Television White Spaces
UNB	Ultra-Narrowband
UP	Uni-polarized
URLLC	Ultra-Reliable Low-Latency Communication
UWB	Ultra-Wideband
VP	Vertically Polarized
XPD	Cross-Polarization Discrimination
XPI	Cross-Polar Isolation
XPR	Cross-Polar Ratio

CHAPTER 1

INTRODUCTION

This first chapter of the thesis opens with a background of latest trends and developments in the domain of Information and Communication Technologies (ICT) and the rising significance of Wireless Communication in Internet of Things (IoT). The background of the thesis is described followed by the statement of underlying problem and its aim and objectives. The last section explains the organization of the thesis.

1.1 Background

The onset of the 21st century has pushed new terms into ICT domain with impending demands for robust and seamless wireless connectivity for billions rather trillions of end users, sensor nodes and machines. A few terms that have attracted worldwide attention of academia, industry and governments are IoT, Machine-to-Machine (M2M) communication, Industrial IoT (IIoT), Industrial Communication Systems (ICS), and Industry 4.0. These terms are related to each other and occasionally interchanged in context of digital revolution. IoT is the combination of physical devices with an ability to generate, process and exchange data with humans and machines (Montori et al., 2018). M2M is the exchange of data between the devices without human intervention (Montori et al., 2018). The exact origin of M2M is not known but it is widely believed to conceive as the first telemetry circuit in 1845 for an exchange of logistic information between two military locations in Russia (Mayo-Wells, 1963). The terms M2M and IoT were coined in 1990s and now IoT is seen as an evolution of M2M (Alam et al., 2013). IoT can be further divided into Consumer IoT (CIoT) and IIoT based on the type of services they provide (Sisinni et al., 2018). CIoT is human-centered to improve his awareness about the surrounding consumer electronic devices through Machine-to-Human (M2H) link. On the other hand, in IIoT, Information Technology (IT) is combined with Operating Technology (OT) to optimize industrial operations for smart manufacturing. A suitable ICS is used for this purpose so that the control systems and machines can be connected to the business processes and information systems (Vitturi et al., 2019). An ICS is a communication network adopted in factories to automate manufacturing and control processes. Industry 4.0 is a subset of IIoT that combines IoT with Internet technologies and Cyber-Physical Systems (CPS) to improve production efficiency (Sisinni et al., 2018). CPS provides a digital description of real-world physical objects.

Some IoT systems perform communication tasks on wired media while others can communicate wirelessly. Low-Power Wide-Area Networks (LPWAN) are wireless IoT systems that have been explored and deployed worldwide because of robust communication, broader coverage, and low power consumption.

Rotating Polarization Wave (RPW) is a new method for reliable wireless communication that is undergoing its embryonic stages (Takei & Yamada, 2018). It offers the advantage of high reliability that is of central interest to M2M and ICS. It can also offer data rates equivalent to or higher than most of the LPWANs. However, RPW has not been fully explored for its suitability to IoT applications. Detailed analysis of its performance in terms of reliability, link budget, power consumption, receiver sensitivity, and transmission delay is required to demonstrate its eligibility for LPWANs.

1.2 Motivation

The IoT market is growing exponentially in terms of number of market shares, size of data traffic, number of connections, and number of subscriptions. One of the factors is the rapid growth of M2M subscriptions. The estimated global subscriptions of M2M are 97 billion by 2030, approximately five times the number of mobile subscriptions (International Telecommunications Union, 2015). Existing M2M deployments mostly use LPWANs. In their LPWAN market report, IoT Analytics have shown that LPWAN landscape was dominated by four technologies namely Long Range (LoRa), Sigfox, Narrowband IoT (NB-IoT) and Long-Term Evolution for Machines (LTE-M) in 2019, projecting 92% share among all LPWAN connections (*LPWAN Market Report 2018-2023*, 2018). In 2023, this share is expected to reach 97%. Therefore, a contribution to LPWAN research has a discernable impact on IoT research and industry.

Exponential Roadmap Initiative has highlighted 36 solutions to exponentially scale Green-House Gas Emissions (GHGE) to halve by 2030 (J. Falk et al., 2019). ICT is one of the key sectors that can contribute to achieving this goal. The projected share of GHGE from ICT has been forecasted to exceed 4% and 6% of the global GHGE in 2025 and 2030, respectively (Belkhir & Elmeligi, 2018). IoT could help reduce this percentage globally by up to 15% by 2030, which is equivalent to 10 gigatons of GHGE (*ICT's Potential to Reduce Greenhouse Gas Emissions in 2030*, n.d.). With a large number of LPWAN connections in future, use of energy efficient LPWANs is indispensable to converge the amount of GHGE.

The purpose of this research is therefore to propose an affordable and environment-friendly solution for dependable wireless connectivity that can bridge digital divide in the era of IoT.

1.3 Problem Statement

In wireless communication systems, the reliability and data rate are affected by the modulation technique being used (Buurman et al., 2020b). Simple modulations like BPSK and Binary Frequency-Shift Keying (BFSK) are reliable but provide low data rates. To achieve higher data rates, higher order or multilevel modulation schemes such as Multilevel Phase Shift Keying (MPSK) and Multilevel Quadrature Amplitude Modulation (MQAM) are required, but they increase complexity resulting in reduced reliability and increased power consumption. This complexity can be reduced by combining a diversity technique with a multilevel modulation scheme. Polarization Diversity (PD) with MPSK modulation can provide higher data rate and reliability, while reducing the overall complexity.

Based on design requirements, IoT systems are sometimes classified as critical and non-critical IoT systems (Buurman et al., 2020b). Critical systems are intended for high data rate and high reliability real-time communication such as cellular LPWANs, whereas moderate reliability and data rates are sufficient for non-critical systems. LPWANs operating on Industrial, Scientific, and Medical (ISM) band such as LoRa and Sigfox can be used in this case. However, they compromise link reliability in harsh multipath environments with elevated perturbations and provide low data rates not exceeding a few kilobits per second (kbps). On the other hand, cellular LPWANs like LTE-M and NB-IoT are reliable and provide data rates up to a few hundred kbps (Buurman et al., 2020b), but they necessitate cellular infrastructure that is often limited or not available in rural and remote areas. Therefore, a reliable LPWAN is the need of the hour to minimize dependency of IoT on infrastructure but offer the benefits of cellular LPWAN connectivity. RPW system can offer a high data rate and reliable communication by employing MPSK modulation.

An accurate performance analysis of a wireless system depends on the system model being used. Channel models for PD systems are either physical or analytical, both having their own limitations (Guo et al., 2017). The physical models are more scenario-specific and cannot be generalized for all PD systems. On the other hand, analytical models are appropriate for Rayleigh fading but they do not address some of the crucial propagation aspects such as scattering and depolarization. A quaternion analytical model was proposed for PD systems with an advantage to include depolarization and scattering effects and thus provides polarization as an additional degree of freedom for signal detection

(Wysocki et al., 2006). The model also reduces the complexity of the classical channel models (Wysocki et al., 2006). RPW transmitter and receiver can also be modelled in terms of quaternions to exploit quaternion channel model for a realistic performance analysis of RPW system.

Link budget analysis is of crucial importance to validate a wireless network in various terrains. Previous works on LPWANs have either ignored fast fading margin or have used empirical values for shadowing and fast fading margins (Ikpehai et al., 2019b; Lauridsen et al., 2017). In practice, the fast-fading margin depends on the type of modulation being used, because different modulations respond differently to multipath conditions. Therefore, a propagation model should consider all propagation effects such as large-scale path loss, shadowing, multipath fading, fixed losses and indoor losses for link budget estimates. Link budget performance of RPW system can be appropriately evaluated as an LPWAN using a propagation model that takes all these factors into account.

In view of the research gap stated above, this thesis has proposed a reliable high-data rate RPW system that employs Rotating Polarization Multilevel Phase-Shift Keying (RP-MPSK) modulation by combining RPW with MPSK modulation. A novel Quaternion RPW (Q-RPW) model has also been proposed for performance analysis of RP-MPSK modulation. A comprehensive link budget analysis is carried out to investigate its performance as an LPWAN in terms of enhanced coverage, low power, and improved reliability. The system exploits sub-GHz ISM band and requires minimal infrastructure.

1.4 Aims and Objectives

The aim of this thesis is to enhance and evaluate the performance of RPW and validate its use as an LPWAN for critical IoT applications The objectives of this thesis are:

1. To propose and design a novel RP-MPSK modulator and demodulator and analyze the Bit Error Rate (BER) of RPW system under noise, multipath and interference conditions.

2. To propose novel Q-RPW model for RPW system with RP-MPSK modulation.

3. To analyze link budget performance of RPW with RP-MPSK modulation considering large scale path loss, shadowing and multipath fading to determine Received Signal Strength (RSS) and maximum range in urban, suburban and rural areas.

1.5 Scope of Research

Research topic is selected by narrowing down the broader perspectives of IoT to performance characteristics and factors, enabling technologies, PHY techniques, channel models and link budget **(**Figure 1.1**)**. Only ISM band LPWAN is considered for performance comparison. For the simulation purpose, information symbols are taken to be uniformly distributed while channel coefficients follow normal distribution to introduce Rayleigh fading. Flat fading with single-tap impulse response in the absence of Line-of-Sight (LoS) is assumed and the receiver has perfect knowledge of the wireless channel. Known values of the fixed obstacle loss and indoor propagation loss are considered. Communication performance is evaluated for a point-to-point Physical Layer (PHY). To validate the performance analysis, only 868 MHz ISM carrier frequency with a channel bandwidth of 125 kHz is considered unless otherwise specified. A BER of 10^{-5} for uncoded modulation is considered under multipath conditions to limit the time of simulation and comparison with available BERs of other LPWANs. The probability of edge user or fringe coverage is 0.95. No preamble is considered and no error detection and correction is employed.

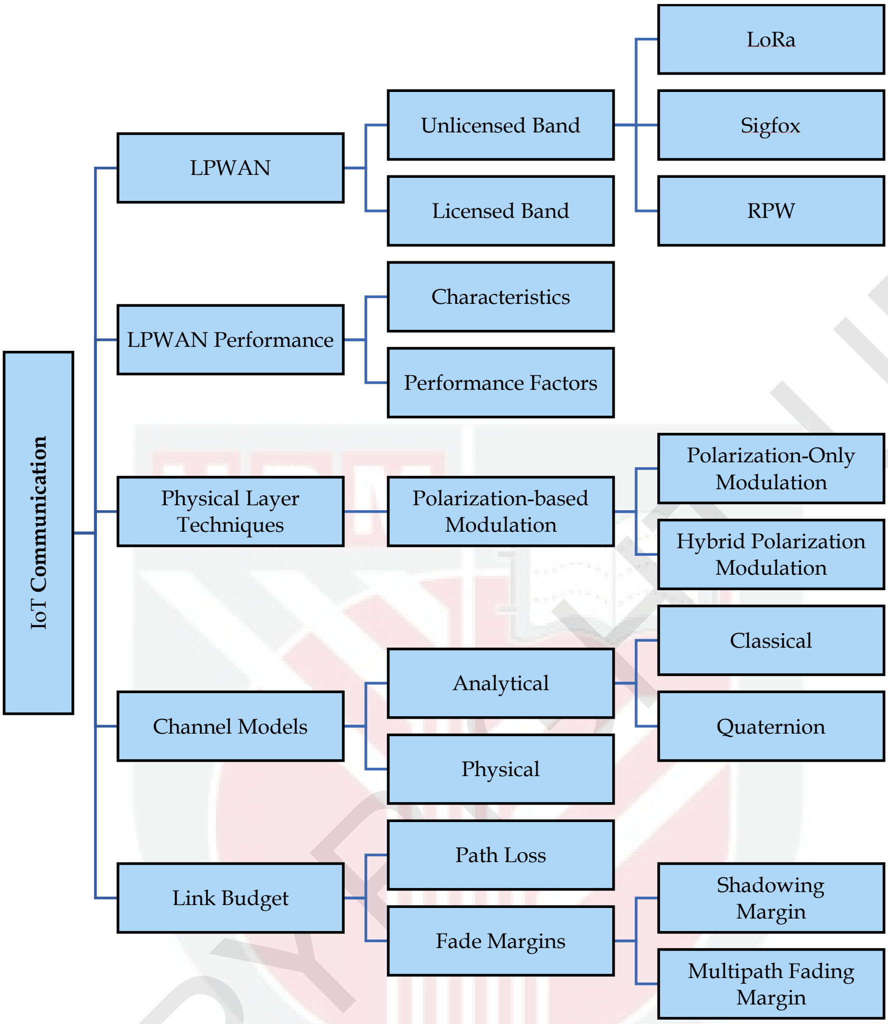

Figure 1.1: Outlines of research topic

1.6 Novelty and Contributions

A novel pair of Quaternary Phase-Shift Keying (QPSK) modulators has been proposed to be specifically used in RPW communication. This was inspired by the fundamental idea of RPW where two BPSK modulations with orthogonal carriers were used. Extending it to QPSK multi-level modulation was a challenge as the simple RPW modulation already employs quadrature carriers. Therefore, two non-identical QPSK modulators with complementary constellations are proposed such that the two carriers being used are orthogonal in phase. Another aspect of novelty is the proposed efficient Q-RPW model as it successfully exploits quaternion model for dual-polarized systems to bring an incremental rotation in the linear polarization over a symbol period.

This thesis has made three contributions to RPW technology. First, an RP-MPSK modulator and demodulator is proposed and designed based on the novel complementary QPSK modulators. Secondly, Q-RPW is proposed, and its mathematical treatment is provided for simulation of RP-MPSK transmission. Finally, a generalized approach for link budget analysis is also provided to incorporate shadowing and multipath fading margins in LPWAN systems.

1.7 Thesis Organization

The remaining part of thesis is organized as follows:

Chapter 2 is a comprehensive literature review on leading LPWAN solutions, their PHY technologies, polarization-based modulations, and link budget analysis of LPWANs. The existing RPW system is also completely described.

Chapter 3 elaborates the methods applied in this thesis. System modeling and simulation method is illustrated. Methodology is explained from three aspects: RP-MPSK modulation, Q-RPW model and link budget analysis. The proposed novel pair of QPSK modulators and its extension to RP-MPSK is described. The chapter also covers the proposed Q-RPW model for RP-MPSK transmission, comprising transmitter model and receiver model. Link budget analysis has also been discussed based on large-scale path loss, shadowing and multipath fading. To support the proposed solution, a comprehensive mathematical treatment is provided.

Chapter 4 is dedicated for results and discussion. It comprises three sections. The first two sections present the results of error performance of RP-MPSK modulation using Q-RPW model and its link budget analysis, respectively. In the last section, the results have been discussed to highlight the significance of proposed solution, especially in the context of LPWANs.

Chapter 5 concludes the thesis with recommendations for future work and the research directions.

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