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Cognitive Radio based Carrier Adaptation to the Doppler Spread of NB-IoT using performance analysis.

A Dissertation Submitted in Partial Fulfillment of Requirement for the Degree of Bachelor of Science in Electrical and Electronic Engineering

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Declaration of Candidate

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any Degree or Diploma.

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Abstract

In this book we aimed to integrate cognitive radio with narrow band internet of things (NB IoT). The popularity of IoT devices have led to the invention of many popular machine-to-machine (m2m) communication. NB IoT is one of the most powerful candidates fulfilling the fundamental targets of low power wide area networks technologies built for IoT devices. We have summarized the details of NB IoT and its eventual evolution. While much of the NB IoT are already well published so we focused on summarizing the entire technology and developing a performance analysis. Furthermore, we indulged ourselves in finding the relation of NB IoT with large doppler spread. Thus, we carried simulations for different fading environment and variable doppler frequencies. The performance was measured in terms of BLER and throughput and the results were plotted with respect to variable SNR or Doppler frequencies. Our study shows agrees with the commonly accepted relation of doppler spread with BLER and throughput. That is as doppler frequency increases the throughput decrease sand BLER increases. However, the performance analysis is implicating the underlying problem that is the degradation of NB IoT performance at higher speed or higher doppler spread. To solve this, we turned to cognitive radio which is a clever way of allocating resources or switching carrier frequency or even changing operation mode of NB IoT suitably to enhance the overall performance. The data simulated can be used as a basis for cognitive radio to properly acknowledge the extent of carrier frequency change required to significantly improve the network performance.

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Symbols and Acronyms:

3GPP	Third-generation partnership project
AAS	Active antenna systems
ACIR	Adjacent channel interference ratio
ACK	Acknowledgment (in ARQ protocols)
ACLR	Adjacent channel leakage ratio
ACS	Adjacent channel selectivity
AGC	Automatic gain control
AIFS	Arbitration interframe space
AM	Acknowledged mode (RLC configuration)
A-MPR	Additional maximum power reduction
APT	Asia-Pacific tele community
ARI	Acknowledgment resource indicator
ARIB	Association of radio industries and businesses
ARQ	Automatic repeat-request
AS	Access stratum
ATC	Ancillary terrestrial component
ATIS	Alliance for telecommunications industry solutions
AWGN	Additive white Gaussian noise
BC	Band category
BCCH	Broadcast control channel
BCH	Broadcast channel
BL	Bandwidth-reduced low complexity
BM-SC	Broadcast multicast service center
BPSK	Binary phase-shift keying
BS	Base station
BW	Bandwidth
CA	Carrier aggregation
CACLR	Cumulative adjacent channel leakage ratio

CC	Component carrier
CCA	Clear channel assessment
CCCH	Common control channel
CCE	Control channel element
CCSA	China Communications Standards Association
CDMA	Code-division multiple access
CITEL	Inter-American Telecommunication Commission
B-MTC	Critical MTC
C-CN	Core network
CoMP	Coordinated multi-point transmission/reception
CP	Cyclic prefix
CQI	Channel-quality indicator
CRC	Cyclic redundancy check
D-RNTI	Cell radio-network temporary identifier
CRS	Cell-specific reference signal
CS	Capability set (for MSR base stations)
CSA	Common subframe allocation
CSG	Closed Subscriber Group
CSI	Channel-state information
CSI-IM	CSI interference measurement
CSI-RS	CSI reference signals
CW	Continuous wave
D2D	Device-to-device
DAI	Downlink assignment index
DCCH	Dedicated control channel
DCH	Dedicated channel
DCI	Downlink control information
DCF	Distributed coordination function
DFS	Dynamic frequency selection
DFT	Discrete Fourier transform

DL	Downlink
DL-SCH	Downlink shared channel
DM-RS	Demodulation reference signal
DMTC	DRS measurements timing configuration
DRS	Discovery reference signal
DRX	Discontinuous reception
DTCH	Dedicated traffic channel
DTX	Discontinuous transmission
DwPTS	Downlink part of the special subframe (for TDD operation) ECCE
	Enhanced control channel element
EDCA	Enhanced distributed channel access
EDGE	Enhanced data rates for GSM evolution; enhanced data rates for global evolution
eIMTA	Enhanced Interference mitigation and traffic adaptation
EIRP	Effective isotropic radiated power
EIS	Equivalent isotropic sensitivity
EMBB	Enhanced MBB
eMTC	Enhanced machine-type communication
eNB	eNodeB
eNodeB	E-UTRAN NodeB
EPC	Evolved packet core
EPS	Evolved packet system
EREG	Enhanced resource-element group
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UTRA
UTRAN	Evolved UTRAN
EVM	Error vector magnitude
FDD	Frequency division duplex
FDMA	Frequency-division multiple access
FEC	Forward error correction
FFT	Fast Fourier transform

GP	Guard period (for TDD operation)
GPRS	General packet radio services
GPS	Global positioning system
GSM	Global system for mobile communications
GSMA	GSM Association
HARQ	Hybrid ARQ HII High-interference indicator
HSFN	Hyper system frame number
HSPA	High-speed packet access
IEEE	Institute of Electrical and Electronics Engineers
LAA	License-assisted access
LAN	Local area network
LBT	Listen before talk
LCID	Logical channel identifier
LDPC	Low-density parity check code
LTE	Long-term evolution
MAC	Medium access control
MAN	Metropolitan area network
MBB	Mobile broadband
MBMS	Multimedia broad cast multicast service
MC	Multi-carrier
MCCH	MBMS control channel
MCE	MBMS coordination entity
MCG	Master cell group
MCH	Multicast channel
MCS	Modulation and coding scheme
MIB	Master information block
MIMO	Multiple input multiple output
MLSE	Maximum-likelihood sequence estimation
MME	Mobility management entity
MPR	Maximum power reduction
MSA	MCH subframe allocation

MSI	MCH scheduling information
MSP	MCH scheduling period
MSR	Multi-standard radio
MSS	Mobile satellite service
MTC	Machine-type communication
MTCH	MBMS traffic channel
NAK	Negative acknowledgment (in ARQ protocols)
NAICS	Network-assisted interference cancelation and suppression
NAS	Non-access stratum (a functional layer between the core network and the terminal that supports signaling)
NB-IoT	Narrow-band internet of things
NPSS	Narrowband primary synchronization signal
NSSS	Narrowband secondary synchronization signal
NRS	Narrowband reference signal
NPBCH	Narrowband physical broadcast channel
NPDSCH	Narrowband physical downlink shared channel
NPDCCH	Narrowband physical downlink control channel
NPRACH	Narrowband physical random-access channel
NPUSCH	Narrowband physical uplink shared channel
OFDM	Orthogonal frequency-division multiplexing
OI	Overload indicator
OOB	Out-of-band (emissions)
OSDD	OTA sensitivity direction declarations
OTA	Over the air
PA	Power amplifier
PAPR	Peak-to-average power ratio
PAR	Peak-to-average ratio (same as PAPR)
PBCH	Physical broadcast channel
PCCH	Paging control channel
PCFICH	Physical control format indicator channel
PCG	Project Coordination Group (in 3GPP)

PCH	Paging channel
PCID	Physical cell identity
PCRF	Policy and charging rules function
PDC	Personal digital cellular
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PDN	Packet data network
PDU	Protocol data unit
P-GW	Packet-data network gateway (also PDN-GW)
PHY	Physical layer
PMCH	Physical multicast channel
PMI	Precoding-matrix indicator
PRACH	Physical random-access channel
PRB	Physical resource block
P-RNTI	Paging RNTI ProSe Proximity services
PSBCH	Physical sidelink broadcast channel
PSCCH	Physical sidelink control channel
PSD	Power spectral density
PSDCH	Physical sidelink discovery channel
PSLSS	Primary sidelink synchronization signal
PSM	Power-saving mode
PSS	Primary synchronization signal
PSSCH	Physical sidelink shared channel
PSTN	Public switched telephone networks
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QAM	Quadrature amplitude modulation
QCL	Quasi-colocation
QoS	Quality-of-service
QPP	Quadrature permutation polynomial

QPSK	Quadrature phase-shift keying
RAB	Radio-access bearer
RACH	Random-access channel
RAN	Radio-access network
RAT	Radio-access technology
RB	Resource block
RE	Resource element
REG	Resource-element group
RF	Radio frequency
RI	Rank indicator
RLAN	Radio local area networks
RLC	Radio link control
RNTI	Radio-network temporary identifier
RNTP	Relative narrowband transmit power
RoAoA	Range of angle of arrival
ROHC	Robust header compression
PDCCH	Relay physical downlink control channel
RRC	Radio-resource control
Q-RRM	Radio resource management
RS	Reference symbol
RSPC	Radio interface specifications
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RV	Redundancy version
RX	Receiver
SBCCH	Sidelink broadcast control channel
SCG	Secondary cell group
SCI	Sidelink control information
SC-PTM	Single-cell point to multipoint
SDMA	Spatial division multiple access
SDO	Standards developing organization

SDU	Service data unit
SEM	Spectrum emissions mask
SF	Subframe
SFBC	Space frequency block coding
SFN	Single-frequency network (in general, see also MBSFN); system frame number (in 3GPP).
SGW	Serving gateway
SI	System information message
SIB	System information block
SIC	Successive interference combining
SIFS	Short interframe space
SIM	Subscriber identity module
SINR	Signal-to-interference-and-noise ratio
SIR	Signal-to-interference ratio
SL-DCH	Sidelink discovery channel
SLI	Sidelink identity
SL-SCH	Sidelink shared channel
SLSS	Sidelink synchronization signal
SNR	Signal-to-noise ratio
SORTD	Spatial orthogonal-resource transmit diversity
SR	Scheduling request
SRS	Sounding reference signal
R-SLSS	Secondary sidelink synchronization signal
S-SSS	Secondary synchronization signal
STCH	Sidelink traffic channel
STBC	Space time block coding
STC	Space time coding
STTD	Space time transmit diversity
TAB	Transceiver array boundary
TCP	Transmission control protocol

TDD	Time-division duplex
TDMA	Time-division multiple access
TF	Transport format
TPC	Transmit power control
TR	Technical report
TRP	Time repetition pattern; transmission reception point
TRPI	Time repetition pattern index
TS	Technical specification
TSDSI	Telecommunications Standards Development Society, India TSG
TTA	Telecommunications Technology Association
TTC	Telecommunications Technology Committee
TTI	Transmission time interval
TX	Transmitter
UCI	Uplink control information
UE	User equipment (the 3GPP name for the mobile terminal)
UL	Uplink
UL-SCH	Uplink shared channel
UM	Unacknowledged mode (RLC configuration)
UMTS	Universal mobile telecommunications system
URLLC	Ultra-reliable low-latency communication
UTRA	Universal terrestrial radio access
UTRAN	Universal terrestrial radio-access network
VoIP	Voice-over-IP
WCDMA	Wideband code-division multiple access
WCS	Wireless communications service
WG	Working group
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network
WMAN	Wireless metropolitan area network

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Chapter 1: Introduction

A network system that interconnects devices or any digital machines with each other with the ability to share data over the network without requiring any human interaction is termed as Internet of things, IOT and the devices are called IOT devices. These devices have certain requirement mainly wide network, low data rate, low energy consumption, and cost effectiveness. The application of IOT devices are diverse ranging from agriculture to smart homes. It is common knowledge that in the recent times the number of IOT devices is booming. It is estimated that by the year 2022 the number of IOT devices will reach approximately 22 billion. To accommodate such big number of devices in the limited spectrum is a major challenge for telecommunication engineers and one of the important features of 5G.

Statistically seen that 67% of the total IOT devices requires low data rate wide area network (WAN) technologies which is known in the industry as Low-Power Wide-Area Network (LPWAN) technology. Due to its greater popularity several industry grade LPWAN technology already exists namely Sigfox, Lora, NB-IOT. While Sigfox and LORA work in the unlicensed spectrum with a nonstandard and custom implemented network. NB-IOT, narrow-band Internet of Things, is a representative of mature cellular communication technology. The standard for this technology was developed by international standards organizations called 3GPP.

Numerous papers were published based on these machines to machine low powered wide area networks. However, the increased popularity and urgency to accommodate a huge amount of IOT devices with a highly efficient network has led us to further analyze the performance paradigm of one of these technologies called Narrow band Internet of things and introduce the idea of cognitive radio in NB- IOT. This proposal aims to solve the spectrum shortage and improve resource allocation for the huge data traffic.

In this book we will discuss elaborately the implication and challenges of NB-IOT and how the carrier adaptation can be manipulated effectively using cognitive radio which in turn is an isolated solution for increased global data traffic.

We have organized the book in the following way: first we discuss about NB-IOT and it evaluation, then we discuss its current challenges. Then we move on to the implications of doppler spread, and the section following holds our simulation results for performance of NB-IOT and finally cognitive radio.

1.1. Internet of Things (IoT)

The Internet of Things is an emerging topic of technical, social, and economic significance. Consumer products, durable goods, cars and trucks, industrial and utility components, sensors, and other everyday objects are being combined with Internet connectivity and powerful data analytic capabilities that promise to transform the way we work, live, and play. Projections for the impact of IoT on the Internet and economy are impressive, with some anticipating as many as 100 billion connected IoT devices and a global economic impact of more than $11 trillion by 2025.

At the same time, however, the Internet of Things raises significant challenges that could stand in the way of realizing its potential benefits. Attention-grabbing headlines about the hacking of Internet-connected devices, surveillance concerns, and privacy fears already have captured public attention. Technical challenges remain and new policy, legal and development challenges are emerging.

This overview document is designed to help the Internet Society community navigate the dialogue surrounding the Internet of Things in light of the competing predictions about its promises and perils. The Internet of Things engages a broad set of ideas that are complex and intertwined from different perspectives. Key concepts that serve as a foundation for exploring the opportunities and challenges of IoT include:

IoT Definitions: The term Internet of Things generally refers to scenarios where network connectivity and computing capability extends to objects, sensors and everyday items not normally considered computers, allowing these devices to generate, exchange and consume data with minimal human intervention. There is, however, no single, universal definition.
Enabling Technologies: The concept of combining computers, sensors, and networks to monitor and control devices has existed for decades. The recent confluence of several technology market

trends, however, is bringing the Internet of Things closer to widespread reality. These include Ubiquitous Connectivity, Widespread Adoption of IP-based Networking, Computing Economics, Miniaturization, Advances in Data Analytics, and the Rise of Cloud Computing.

Connectivity Models: IoT implementations use different technical communications models, each with its own characteristics. Four common communications models described by the Internet Architecture Board include: Device-to-Device, Device-to-Cloud, Device-to-Gateway, and Back-End Data-Sharing. These models highlight the flexibility in the ways that IoT devices can connect and provide value to the user.

Transformational Potential: If the projections and trends towards IoT become reality, it may force a shift in thinking about the implications and issues in a world where the most common interaction with the Internet comes from passive engagement with connected objects rather than active engagement with content. The potential realization of this outcome – a “hyperconnected world” — is testament to the general-purpose nature of the Internet architecture itself, which does not place inherent limitations on the applications or services that can make use of the technology.

Five key IoT issue areas are examined to explore some of the most pressing challenges and questions related to the technology. These include security; privacy; interoperability and standards; legal, regulatory, and rights; and emerging economies and development.

1.1.1. Security

While security considerations are not new in the context of information technology, the attributes of many IoT implementations present new and unique security challenges. Addressing these challenges and ensuring security in IoT products and services must be a fundamental priority. Users need to trust that IoT devices and related data services are secure from vulnerabilities, especially as this technology become more pervasive and integrated into our daily lives. Poorly secured IoT devices and services can serve as potential entry points for cyber-attack and expose user data to theft by leaving data streams inadequately protected.

The interconnected nature of IoT devices means that every poorly secured device that is connected online potentially affects the security and resilience of the Internet globally. This challenge is amplified by other considerations like the mass-scale deployment of homogenous IoT devices, the ability of some devices to automatically connect to other devices, and the likelihood of fielding these devices in unsecure environments.

As a matter of principle, developers and users of IoT devices and systems have a collective obligation to ensure they do not expose users and the Internet itself to potential harm. Accordingly, a collaborative approach to security will be needed to develop effective and appropriate solutions to IoT security challenges that are well suited to the scale and complexity of the issues.

1.1.2. Privacy

The full potential of the Internet of Things depends on strategies that respect individual privacy choices across a broad spectrum of expectations. The data streams and user specificity afforded by IoT devices can unlock incredible and unique value to IoT users, but concerns about privacy and potential harms might hold back full adoption of the Internet of Things. This means that privacy rights and respect for user privacy expectations are integral to ensuring user trust and confidence in the Internet, connected devices, and related services.

Indeed, the Internet of Things is redefining the debate about privacy issues, as many implementations can dramatically change the ways personal data is collected, analyzed, used, and protected. For example, IoT amplifies concerns about the potential for increased surveillance and tracking, difficulty in being able to opt out of certain data collection, and the strength of aggregating IoT data streams to paint detailed digital portraits of users. While these are important challenges, they are not insurmountable. In order to realize the opportunities, strategies will need to be developed to respect individual privacy choices across a broad spectrum of expectations, while still fostering innovation in new technology and services.

1.1.3. Interoperability and Standards

A fragmented environment of proprietary IoT technical implementations will inhibit value for users and industry. While full interoperability across products and services is not always feasible or necessary, purchasers may be hesitant to buy IoT products and services if there is integration inflexibility, high ownership complexity, and concern over vendor lock-in.

In addition, poorly designed and configured IoT devices may have negative consequences for the networking resources they connect to and the broader Internet. Appropriate standards, reference models, and best practices also will help curb the proliferation of devices that may act in disrupted ways to the Internet. The use of generic, open, and widely available standards as technical building blocks for IoT devices and services (such as the Internet Protocol) will support greater user benefits, innovation, and economic opportunity.

1.1.4. Legal, Regulatory and Rights

The use of IoT devices raises many new regulatory and legal questions as well as amplifies existing legal issues around the Internet. The questions are wide in scope, and the rapid rate of change in IoT technology frequently outpaces the ability of the associated policy, legal, and regulatory structures to adapt.

One set of issues surrounds cross border data flows, which occur when IoT devices collect data about people in one jurisdiction and transmit it to another jurisdiction with different data protection laws for processing. Further, data collected by IoT devices is sometimes susceptible to misuse, potentially causing discriminatory outcomes for some users. Other legal issues with IoT devices include the conflict between law enforcement surveillance and civil rights; data retention and destruction policies; and legal liability for unintended uses, security breaches or privacy lapses.

While the legal and regulatory challenges are broad and complex in scope, adopting the guiding Internet Society principles of promoting a user’s ability to connect, speak, innovate, share, choose, and trust are core considerations for evolving IoT laws and regulations that enable user rights.

1.1.5. Emerging Economy and Development Issues

The Internet of Things holds significant promise for delivering social and economic benefits to emerging and developing economies. This includes areas such as sustainable agriculture, water quality and use, healthcare, industrialization, and environmental management, among others. As such, IoT holds promise as a tool in achieving the United Nations Sustainable Development Goals.

The broad scope of IoT challenges will not be unique to industrialized countries. Developing regions also will need to respond to realize the potential benefits of IoT. In addition, the unique needs and challenges of implementation in less-developed regions will need to be addressed, including infrastructure readiness, market and investment incentives, technical skill requirements, and policy resources.

The Internet of Things is happening now. It promises to offer a revolutionary, fully connected “smart” world as the relationships between objects, their environment, and people become more tightly intertwined. Yet the issues and challenges associated with IoT need to be considered and addressed in order for the potential benefits for individuals, society, and the economy to be realized.

Ultimately, solutions for maximizing the benefits of the Internet of Things while minimizing the risks will not be found by engaging in a polarized debate that pits the promises of IoT against its possible perils. Rather, it will take informed engagement, dialogue, and collaboration across a range of stakeholders to plot the most effective ways forward.

1.1.6. Applications of IoT

The IoT can find its applications in almost every aspect of our daily life. Below are some of the examples.

Prediction of natural disasters: The combination of sensors and their autonomous coordination and simulation will help to predict the occurrence of land-slides or other natural disasters and to take appropriate actions in advance.

Industry applications: The IoT can find applications in industry e.g., managing a fleet of cars for an organization. The IoT helps to monitor their environmental performance and process the data to determine and pick the one that need maintenance.

Water Scarcity monitoring: The IoT can help to detect the water scarcity at different places. The networks of sensors, tied together with the relevant simulation activities might not only monitor long term water interventions such as catchment area management, but may even be used to alert users of a stream, for instance, if an upstream event, such as the accidental release of sewage into the stream, might have dangerous implications.

Design of smart homes: The IoT can help in the design of smart homes e.g., energy consumption management, interaction with appliances, detecting emergencies, home safety and finding things easily, home security etc.

Medical applications: The IoT can also find applications in medical sector for saving lives or improving the quality of life e.g., monitoring health parameters, monitoring activities, support for independent living, monitoring medicines intake etc.

Agriculture application: A network of different sensors can sense data, perform data processing and inform the farmer through communication infrastructure e.g., mobile phone text message about the portion of land that need particular attention. This may include smart packaging of seeds, fertilizer and pest control mechanisms that respond to specific local conditions and indicate actions. Intelligent farming system will help agronomists to have better understanding of the plant growth models and to have efficient farming practices by having the knowledge of land conditions and climate variability. This will significantly increase the agricultural productivity by avoiding the inappropriate farming conditions.

Intelligent transport system design: The Intelligent transportation system will provide efficient transportation control and management using advanced technology of sensors, information and network. The intelligent transportation can have many interesting features such as non-stop electronic highway toll, mobile emergency command and scheduling, transportation law enforcement, vehicle rules violation monitoring, reducing environmental pollution, anti-theft system, avoiding traffic jams, reporting traffic incidents, smart beaconing, minimizing arrival delays etc.

Design of smart cities: The IoT can help to design smart cities e.g., monitoring air quality, discovering emergency routes, efficient lighting up of the city, watering gardens etc.

Smart metering and monitoring: The IoT design for smart metering and monitoring will help to get accurate automated meter reading and issuance of invoice to the customers. The IoT can also be used to design such scheme for wind turbine maintenance and remote monitoring, gas, water as well as environmental metering and monitoring.

Smart Security: The IoT can also find applications in the field of security and surveillance e.g., surveillance of spaces, tracking of people and assets, infrastructure and equipment maintenance, alarming etc.

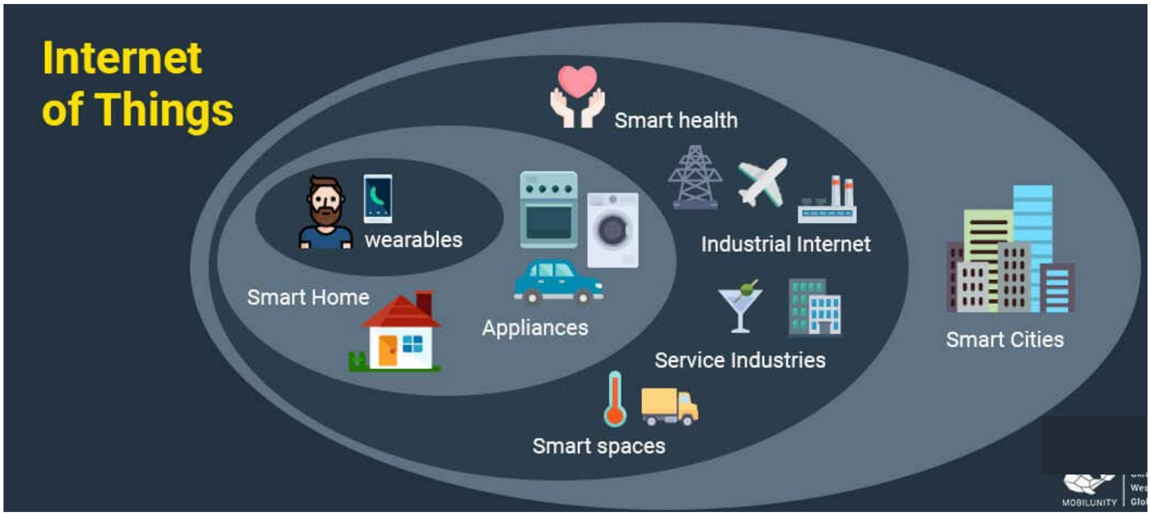


Figure 1: Applications of IoT devices.

The IoT is also getting increasing popularity for academia, industry as well as government. Many international organizations are involved in the development of IoT. Microsoft's Eye-On-Earth platform creates an environment where water and air quality of a large number of European countries can be viewed, thus aiding in climate change research [8]. The European Commission is also involved in the research and development related to IoT. The Cluster of European Research Projects on the Internet of Things (CERP-IoT) is one of their active research project. The CERP-IoT look for IoT applications in societal, industrial and environmental domains [8]. The European FP7 project ‘The Internet of Things Architecture’ (IoT-A) focuses on the possible standard architecture for the IoT. Some other currently active European FP7 research projects that focus on the development of IoT includes Io@Work, ‘The Internet of Things Initiative’ (IoT-i) and ‘European Research Cluster on the Internet of Things’ (IERC). HP is also researching IoT based infrastructure in their Central Nervous System for the Earth initiative. Their aim is to populate the planet with billions of small sensors aimed at detecting vibrations and motion.

The IoT applications will continuously evolve with the passage of time but it has also to face many challenges related to privacy, security, scale and complexity, sufficient spectrum for connecting huge number of tagged objects or sensors etc.

1.2. Low Power Wide Area Network (LPWAN)

Low-power WAN (LPWAN) is a wireless wide area network technology that interconnects low-bandwidth, battery-powered devices with low bit rates over long ranges. Created for machine-to-machine (M2M) and internet of things (IoT) networks, LPWANs operate at a lower cost with greater power efficiency than traditional mobile networks. They are also able to support a greater number of connected devices over a larger area.

LPWANs can accommodate packet sizes from 10 to 1,000 bytes at uplink speeds up to 200 Kbps. LPWAN's long range varies from 2 km to 1,000 km, depending on the technology. Most LPWANs have a star topology where, similar to Wi-Fi, each endpoint connects directly to common central access points.

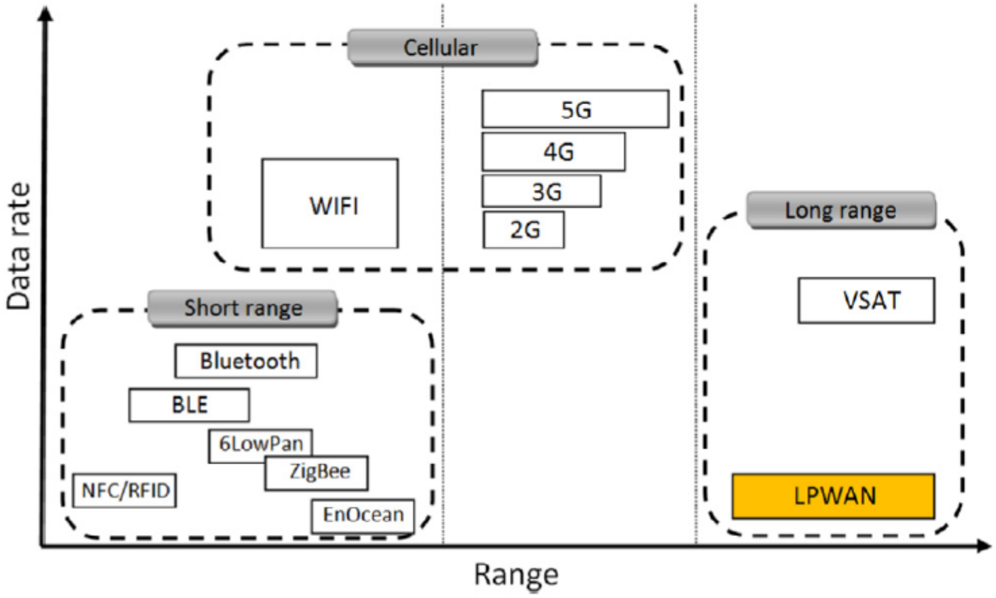


Figure 2: LPWAN positioning with respect to radio communication technology.

1.2.1. Types of LPWANs

LPWAN is not a single technology, but a group of various low-power, wide area network technologies that take many shapes and forms. LPWANs can use licensed or unlicensed frequencies and include proprietary or open standard options.

The proprietary, unlicensed Sigfox is one of the most widely deployed LPWANs today. Running over a public network in the 868 MHz or 902 MHz bands, the ultra-narrowband technology only allows a single operator per country. While it can deliver messages over distances of 30-50 km in rural areas, 3-10 km in urban settings and up to 1,000 km in line-of-site applications, its packet size is limited to 150 messages of 12 bytes per day. Downlink packets are smaller, limited to four messages of 8 bytes per day. Sending data back to endpoints can also be prone to interference.

Random phase multiple access, or RPMA, is a proprietary LPWAN from Ingenu Inc. Though it has a shorter range (up to 50 km line of sight and with 5-10 km nonline of sight), it offers better bidirectional communication than Sigfox. However, because it runs in the 2.4 GHz spectrum, it is prone to interference from Wi-Fi, Bluetooth and physical structures. It also typically has higher power consumption than other LPWAN options.

The unlicensed LoRa, specified and backed by the LoRa Alliance, transmits in several sub-gigahertz frequencies, making it less prone to interference. A derivative of chirp spread spectrum (CSS) modulation, LoRa allows users to define packet size. While open source, the underlying transceiver chip used to implement LoRa is only available from Semtech Corporation, the company behind the technology. LoRaWAN is the media access control (MAC) layer protocol that manages communication between LPWAN devices and gateways.

Weightless SIG has developed three LPWAN standards: The unidirectional Weightless-N, bidirectional Weightless-P and Weightless-W, which is also bidirectional and runs off of unused TV spectrum. Weightless-N and Weightless-P are often more popular options due to Weightless-W's shorter battery life. Weightless-N and Weightless-P run in the sub-1 GHz unlicensed spectrum but also support licensed spectrum operation using 12.5 kHz narrowband technology.

Narrowband-IoT (NB-IoT) and LTE-M are both 3rd Generation Partnership Project (3GPP) standards that operate on the licensed spectrum. While they have similar performance to other standards, they operate on existing cellular infrastructure, allowing service providers to quickly add cellular IoT connectivity to their service portfolios.

NB-IoT, also known as CAT-NB1, operates on existing LTE and Global System for Mobile (GSM) infrastructure. It offers uplink and downlink rates of around 200 Kbps, using only 200 kHz of available bandwidth.

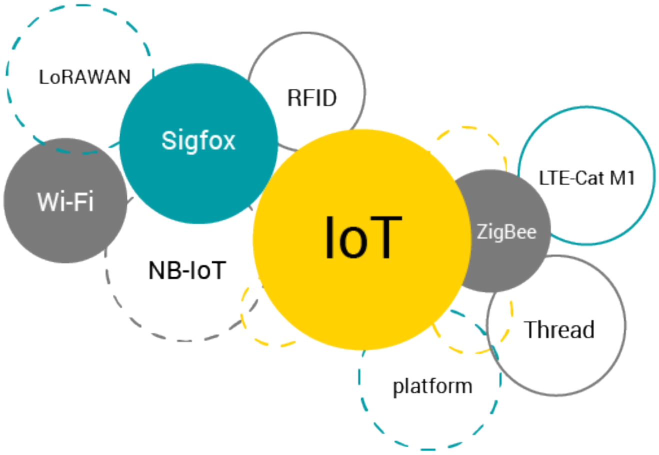


Figure 3: Types of LPWAN

LTE-M, also known as CAT-M1, offers higher bandwidth than NB-IoT, and the highest bandwidth of any LPWAN technology.

Some vendors, including Orange and SK Telecom, are deploying both licensed and unlicensed technologies to capture both markets.

Other LPWAN technologies include:

- GreenOFDM from GreenWaves Technologies
- DASH7 from Haystack Technologies Inc.

- Symphony Link from Link Labs Inc.
- ThingPark Wireless from Actility
- Ultra-Narrow Band from various companies including Telensa, Nwave and Sigfox
- WAVIoT

1.2.2. LPWAN vs. cellular, RF, mesh

While Bluetooth, Zigbee and Wi-Fi are adequate for consumer-level IoT connectivity, many IoT applications -- particularly in industrial, civic and commercial deployments -- benefit from an LPWAN where large numbers of low-power devices in a wide area range can be supported cost-effectively.

Unlike prior wireless technologies, LPWAN provides battery-efficient, ubiquitous wide-area connectivity, enabling more M2M and IoT applications that were previously prohibitive due to cost. However, a major tradeoff is the amount of data that can be transmitted. Yet, according to James Brehm & Associates, 86% of all IoT devices use less than 3 MB of data per month, and 3GPP estimates that 99.9% of LPWAN devices will use less than 150 KB of data per month.

Cellular networks often suffer from poor battery life and may have gaps in coverage. Cellular technologies are also frequently sunset. As many IoT devices are deployed for 10 years or longer, sunsetting cellular coverage isn't a feasible option.

Radio frequency (RF) technologies, such as Bluetooth and near-field communications (NFC), don't have the range many IoT applications require.

Mesh technologies, such as Zigbee, are better suited for medium-distance IoT applications such as smart homes or smart buildings. They have high data rates and are far less battery-efficient than LPWAN.

1.2.3. LPWAN applications

With decreased power requirements, longer ranges and lower costs than traditional mobile networks, LPWANs enable a number of M2M and IoT applications, many of which were previously constrained by budgets and power issues.

Choosing an LPWAN depends on the specific application, namely the desired speed, data amounts and area covered. LPWANs are best suited for applications requiring infrequent uplink message delivery of smaller messages. Most LPWAN technologies also have downlink capabilities.

LPWANs are commonly used in applications including smart metering, smart lighting, asset monitoring and tracking, smart cities, precision agriculture, livestock monitoring, energy management, manufacturing, and industrial IoT deployments.

1.2.4. LPWAN security

Different LPWAN technologies offer varying levels of security. Most include device or subscriber authentication, network authentication, identity protection, advanced standard encryption (AES), message confidentiality and key provisioning.

1.2.5. The future of LPWAN

As a fairly new technology, the LPWAN landscape is constantly changing and far from mature. With many players in the market, it is unclear who the winner(s) will be, especially as the speed of market expansion is also unknown. Long-term performance of each LPWAN variation is also uncertain, as many are still in their initial rollouts and real-world testing at scale has not yet been completed.

1.3. SigFox

SigFox is a cellular style, long range, low power, low data rate form of wireless communications that has been developed to provide wireless connectivity for devices like remote sensors, actuators and other M2M and IoT devices.

The SigFox wireless interface has been developed to enable any communications that take place to consume a minimum amount of power. In this way the remote devices can run on battery power for very extended periods without the need for any battery changes or maintenance.

In addition to this, M2M and IoT communications will communications over extended distances and the SigFox system has been designed to enable the transmissions to cover long distances, enabling a limited number of base stations to be used.

Using a cellular style approach, the remote SigFox nodes are able to communicate with base stations which have Internet connectivity, thereby enabling remote control and data collection from anywhere with Internet connectivity.

In this way, SigFox is able to provide a low data rate connection to anywhere that is covered by a network at very low cost for many M2M and IoT applications.

Thus, SigFox provides a cellular style network operator that provides a tailor-made solution for low-throughput Internet of Things and M2M applications.

For a host of applications from smart meters to control nodes that need connectivity over long ranges the only option until recently has been to use a cellular connection. This option has several disadvantages because cellular phone systems are focussed on voice and high data rates. They are not suited to low data rate connections as the radio interface is complex and this adds cost and power consumption - too much for most M2M / IoT applications.

The SigFox network is aimed at providing connectivity for a variety of applications and users. It is not aimed at one area, but at being for general use by a variety of different types of users. The SIGFOX network performance is characterised by the following:

- Up to 140 messages per object per day

- Payload size for each message is 12 bytes
- Wireless throughput up to 100 bits per second

1.3.1. SigFox M2M application areas

The SigFox network and technology is aimed at the low-cost machine to machine application areas where wide area coverage is required. There are a number of applications that need this form of low-cost wireless communications technology. Areas where the SigFox network may be used include:

- Home and consumer goods
- Energy related communications - in particular smart metering
- Healthcare - in particular the mHealth applications that are starting to be developed
- Transportation - this can include the automotive management
- Remote monitoring and control
- Retail including point of sale, shelf updating, etc
- Security

1.3.2. SigFox radio access network

In view of the low data rates used for IoT connections, the SIGFOX network employs Ultra-Narrow Band, UNB technology. This enables very low transmitter power levels to be used while still being able to maintain a robust data connection.

The SigFox radio link uses unlicensed ISM radio bands. The exact frequencies can vary according to national regulations, but in Europe the 868MHz band is used; in the US it is 915MHz; and 433MHz in Asia.

The density of the cells in the SigFox network is based on an average range of about 30-50km in rural areas and in urban areas where there are usually more obstructions and noise is greater the range may be reduced to between 3 and 10km. Distances can be much higher for outdoor nodes where SIGFOX states line of sight messages could travel over 1000km, although more usual figures will be much less than this.

The overall SigFox network topology has been designed to provide a scalable, high-capacity network, with very low energy consumption, while maintaining a simple and easy to rollout star-based cell infrastructure.

SigFox operation is based around the use of very narrow bandwidths. The uplink and downlink have different characteristics:

- ***Uplink:*** The uplink bandwidth is just 100 Hz in the European area, although 600 Hz is allowed in the USA, and the modulation scheme is DBPSK, differential binary phase shift keying.

  In Europe the uplink frequency availability is limited to frequencies between 868.00 and 868.60 MHz and the maximum power is limited to 25 mW. Also the European Union has limited the maximum duty cycle to a maximum mean transmission time of 1% to fairly share the spectrum usage between all users of this and other similar communications systems.
- ***Downlink:*** For the downlink the channel bandwidth is 1.5 kHz and GFSK, Gaussian frequency shift keying is used as the modulation format. This provides a data rate of 600 bps.

  The downlink frequency band is limited to frequencies between 869.40 and 869.65 MHz. In the case of the downlink, the power output is limited to a maximum of 500mW with 10% duty cycle. Again this duty cycle is limited by Eu regulations.

Although the duty cycle limitations affect all IoT / M2M type applications using the 868MHz band, it limits the Sigfox data transmission. It means that the maximum length of a SigFox packet is 24 bytes, and of this, the payload data may occupy a maximum of 12 bytes. Accordingly it can be seen that with the data rate of 100bps each packet transmission takes about 2 seconds. Also each transmission from a SigFox device consists of three packets transmitted each transmitted on three different frequencies chosen from a pseudorandom sequence. The multiple transmission of the data is sued to ensure the integrity of the data received.

Early versions of SigFox only supported uplink transmissions, but later the system evolved to support bi-directional communication, even though there is significant link asymmetry as seen from the details of the uplink and downlink.

In terms of the system protocol, the downlink communication, i.e., data from the base stations to the end devices can only occur following an uplink communication.

Also, the number of messages sent each day is limited, making the system ideal for low data rate remote monitoring nodes, etc. In view of this acknowledgements are not set, but the uplink communication reliability is provided by the use of time and frequency diversity as well as the duplication of transmissions.

As SigFox is a proprietary standard different number of messages are allowed each day according to the plan which has been selected.

1.3.3. SigFox system parameters summary

The key figures for the SigFox radio interface are summarized in the table below:

PARAMETERS FOR SIGFOX SYSTEM	
PARAMETER	**SIGFOX FIGURES**
Signal format	Ultra-narrowband, UNB
Modulation	Downlink: GFSK Uplink DBPSK
Downlink channel bandwidth	100 / 600 Hz (Eu / USA)
Uplink channel bandwidth	1.5 kHz
Uplink data rate	Eu: 100 bps USA 600 bps
Downlink data rate	600 bps
Efficiency (b/s.Hz)	0.05
Doppler sensitivity	Unconstrained
Link budget	156dB

Table 1: Parameters for SigFox Systems

SIGFOX is one of a number of systems that is being deployed to meet the growing demand for M2M and IoT applications. Each of the different systems has its own characteristics and the size of the market will mean that there is space for several different competing systems.

1.4. LoRa

LoRa is a '**Lo**ng **Ra**nge' low power wireless standard intended for providing a cellular style low data rate communications network.
Aimed at the M2M and IoT market, LoRa is ideal for providing intermittent low data rate connectivity over significant distances. The radio interface has been designed to enable extremely low signal levels to be received, and as a result even low power transmissions can be received at significant ranges.

The LoRa modulation and radio interface has been designed and optimized to provide exactly the type of communications needed for remote IoT and M2M nodes.

1.4.1. LoRa Alliance

As with many other systems, an industry body was set up develop and promote the LoRa wireless system across the industry. Called the LoRa Alliance, the body was launched at Mobile World Congress in March 2015. As the Alliance states, it was set up to provide an open global standard for secure, carrier-grade IoT LPWAN connectivity.

Although LoRa had been fundamentally developed by Semtech, opening he standard out enabled it to be adopted by a wide number of companies, thereby growing he ecosystem and gaining significantly greater engagement, a wider variety of products and an overall increase in usage and acceptance.

The founding members of the LoRa Alliance include Actility, Cisco, Eolane, IBM, Kerlink, IMST, MultiTech, Sagemcom, Semtech, and Microchip Technology, as well as lead telecom operators: Bouygues Telecom, KPN, SingTel, Proximus, Swisscom, and FastNet (part of Telkom South Africa).

1.4.2. LoRa technology basics

There are several key elements of LoRa technology. Some of its key features include the following:

- Long range: 15 - 20 km.

- Millions of nodes
- Long battery life: in excess of ten years

There are various elements to LoRa technology that provide the overall functionality and connectivity for the system:

- *LoRa PHY / RF interface:* The LoRa physical layer or PHY is key to the operation of the system. It governs the aspects of the RF signal that is transmitted between the nodes or endpoints, i.e. the sensors and the LoRa gateway where signals are received. The physical layer or radio interface governs aspects of the signal including the frequencies, modulation format, power levels, signaling between the transmitting and receiving elements, and other related topics.

- *LoRa network architecture (LoRa WAN):* Apart from the RF elements of the LoRa wireless system, there are other elements of the network architecture, including the overall system architecture, backhaul, server and the application computers. The overall architecture is often referred to as LoRa WAN.

- *LoRa protocol stack:* In addition to the LoRa physical layer, the LoRa Alliance has also defined an open protocol stack. The creation of the open source stack has enabled the concept of LoRa to grow because all the different types of companies involved in LoRa development, use and deployment have been able to come together to create an easy to use, low cost solution for connectivity all manner of connected IoT devices.

1.4.3. Typical applications

LoRa wireless technology is ideally placed to be used in a wide variety of applications. The low power and long-range capabilities mean that end points can be deployed in a wide variety of places, in buildings and outside and still have the capability of being able to communicate with the gateway.

As such the system is easy to deploy and it can be used for a large number of Internet of Things, IoT and machine to machine, M2M, applications.

Applications for LoRa wireless technology include: smart metering; inventory tracking, vending machine data and monitoring; automotive industry; utility applications . . . in fact anywhere where data reporting and control may be needed.

LoRa technology is particularly attractive for many applications because of its long-range capability. New nodes can easily be connected and activated and coverage is easy to provide.

1.4.4. LoRa system parameters summary

The key figures for the LoRa radio interface are summarized in the table below:

PARAMETERS FOR LORA SYSTEM	
PARAMETER	**LORA FIGURES**
Signal format	CSS
Spreading factor	2^7 to 2^{12}
Channel bandwidth	125 to 500 kHz
Uplink data rate	29 - 50 kbps
Downlink data rate	27 - 50 kbps
Efficiency (b/s.Hz)	0.12
Doppler sensitivity	Up to 40 ppm
Link budget	156dB

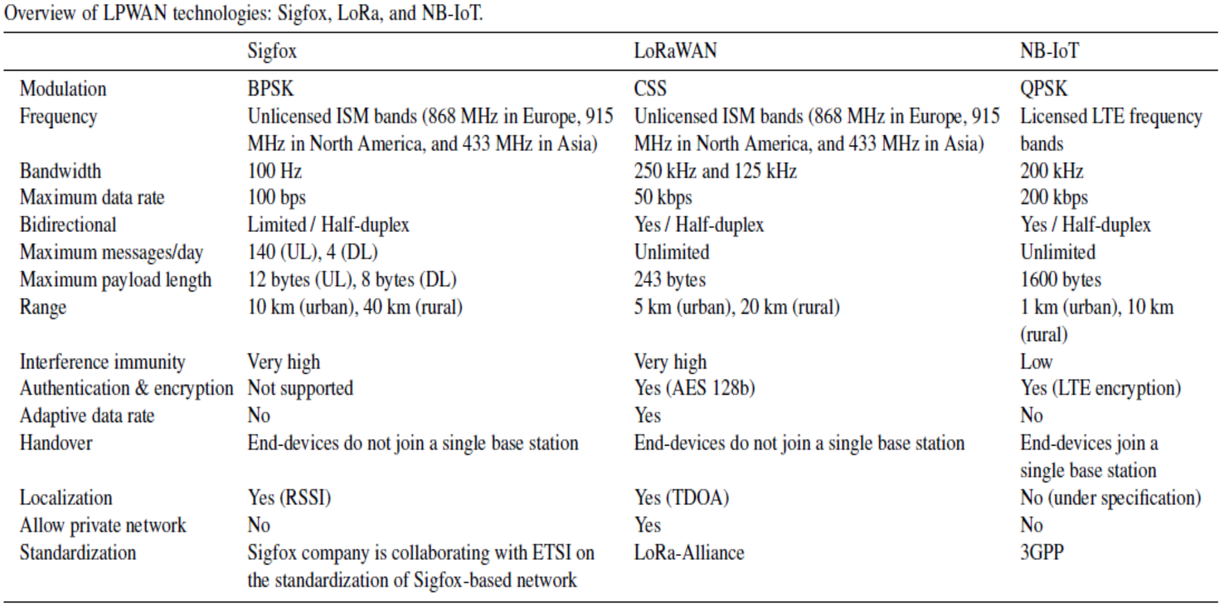
Table 2: Parameter of LORA

LoRa technology is now being widely deployed. It is being incorporated into many systems, and even the small maker-style computers like Arduino have LoRa options. Accordingly, it is very easy to develop applications for LoRa for both large scale manufacture or the more specialist applications.

1.5. NB IoT

Over the last 20 years, the IoT technologies have developed significantly and they have been incorporated in various fields. Namely, almost everything can be connected through IoT network. IoT has achieved significant improvement in big data processing, heterogeneity, and performance. From the perspective of transmission rate, the communication services of IoT can be coarsely classified into two categories: high-data-rate services (such as video service) and low-data rate services (such as meter reading service). According to statistics by ATECH in 2017, the low-data-rate services represent more than 67% of total IoT services, which indicates that the low-data-rate WAN technologies are really desirable. Recently, due to the development of IoT, the IoT communication technologies have become mature and widespread. From the perspective of transmission distance, IoT communication technologies can be categorized into short-distance communication technologies and WAN communication technologies. The former are represented by Zigbee, Wi-Fi, Bluetooth, Z-wave and etc. Their typical application is smart home. The latter are desired in low-data-rate. Services like smart parking mentioned above, which is generally defined by industry as the Low-Power Wide-Area Network (LPWAN) technology. There into, the development of LPWAN communication technology is especially obvious. From the perspective of frequency spectrum licensing, LPWAN technologies can be classified into two categories, technologies that work in unauthorized spectrum and technologies that work in authorized spectrum. The first category is represented by Lora, SigFox and etc., of which most are nonstandard and custom implemented. The second category is generally represented by some relatively mature 2G/3G cellular communication technologies (such as GSM, CDMA, WCDMA and etc.), LTE technology and evolved LTE technology, which support different categories of terminals. The standards for these authorized-spectrum communication technologies are basically developed by international standards organizations such as 3GPP (GSM, WCDMA, LTE and evolved LTE technology, etc.) and 3GPP2 (CDMA, etc.). The Narrow-Band Internet of Things (NB-IoT) is a massive Low Power Wide Area (LPWA) technology proposed by 3GPP for data perception and acquisition intended for intelligent low-data-rate applications. The typical applications are smart metering and intelligent environment monitoring. The NB-IoT supports massive connections, ultra-low power consumption, wide area coverage and bidirectional triggering between signaling plane and data plane. Besides, it is supported by an excellent cellular communication network. Therefore, NB-IoT is a promising technology.

1.6. Comparative analysis between SigFox, Lora, and NB IoT



Overview of LPWAN technologies: Sigfox, LoRa, and NB-IoT.

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

Table 3 Comparative analysis of LPWAN

Each technology will have its place in the IoT market. Sigfox and LoRa will serve as the lower-cost device, with very long range (high coverage), infrequent communication rate, and very long battery lifetime. Unlike Sigfox, LoRa will also serve the local network deployment and the reliable communication when devices move at high speeds. By contrast, NB-IoT will serve the higher-value IoT markets that are willing to pay for very low latency and high quality of service. Despite the cellular companies' tests, the lack of NB-IoT commercial deployments currently leaves open questions on the actual battery lifetime and the performance attainable by this technology in real-world conditions. Finally, it is expected that 5th generation (5G) wireless mobile communication will provide the means to allow an all-connected world of humans and devices by the year 2020, which would lead to a global LPWAN solution for IoT applications.

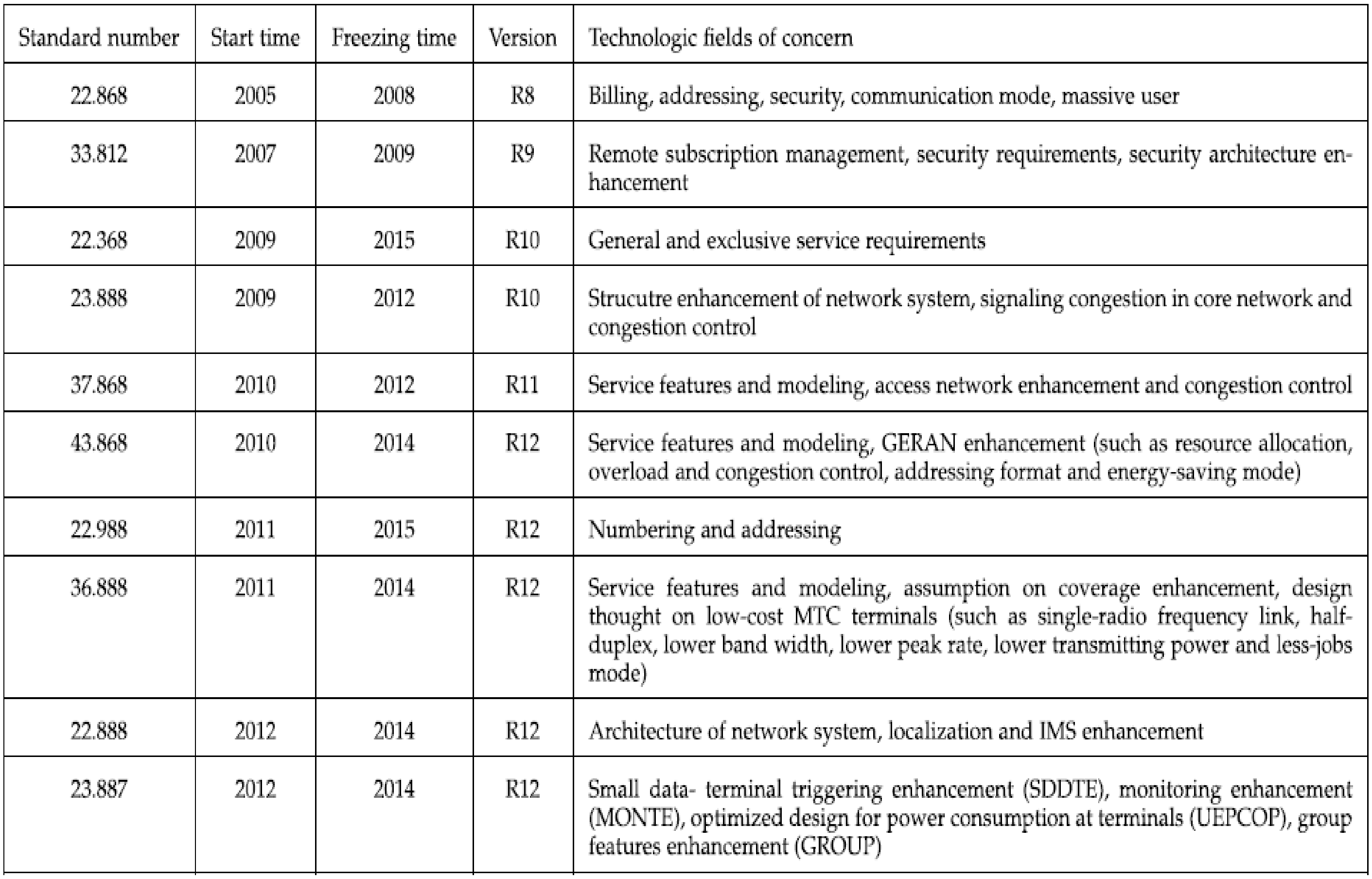
Chapter 2: Narrow Band Internet of Things

Voice services and mobile broadband services have been the sole focus of cellular broadband networks for years. Over the years, thorough research and extensive studies has led to Machine-Type Communication to become an integral part of the modern 5G network.

Initial works constituting from Release 8 to Release 11 dealt with numbering and addressing of resource shortage during synchronous access of numerous terminals to the network, the signaling planes as well as the dilemmas faced with the overload and congestion of data. Following up in Release 12 improvements were made in the network system architecture that enhanced the security as well as further improved the quality of low-cost MTC terminals. Release 13 of 3GPP brought forward 3 new kind of NB air interfaces including GSM-compatible EC-GSM-IoT, LTE-compatible eMTC and brand-new NB-IoT technology. Moreover, Release 13 focused on some core properties of the MTC and these included improved indoor coverage, support for a massive number of low throughput devices, low delay sensitivity, ultra-low device cost, low device power consumption, optimized network architecture. Release 13 has laid the foundation ascertaining the scopes for long-term works of improvement of NB-IoT. Crafted to the needs of using small powered batteries, Release 14 has introduced a lower power class of 14 dBm instead of 23 dBm used previously for NB-IoT. devices. New specifications also increase the size of the transport blocks allowing the data to be broken into larger data packages reducing the time needed, directly affecting the power consumption. 3GPP Release 14 brings enhancements in the cell capacity and usage of NB-IoT network resources via two features called Non-Anchor Paging and Non-Anchor Random Access Procedure (RACH), increasing the number of devices to be operated in a single network, like smart homes and connected building applications. LTE-M significantly increases data rates by expanding data packet sizes almost threefold. With peak data rates around 4 Mbps in DL and 7 Mbps in UL at a bandwidth of 5 MHz, LTE-M becomes an interesting technology for a greater range of applications that require greater data throughput or lower latency, like in smart cities and remote monitoring devices. RRC connection reestablishment allows modems to move from one network cell to another without requiring to renegotiate a new connection.

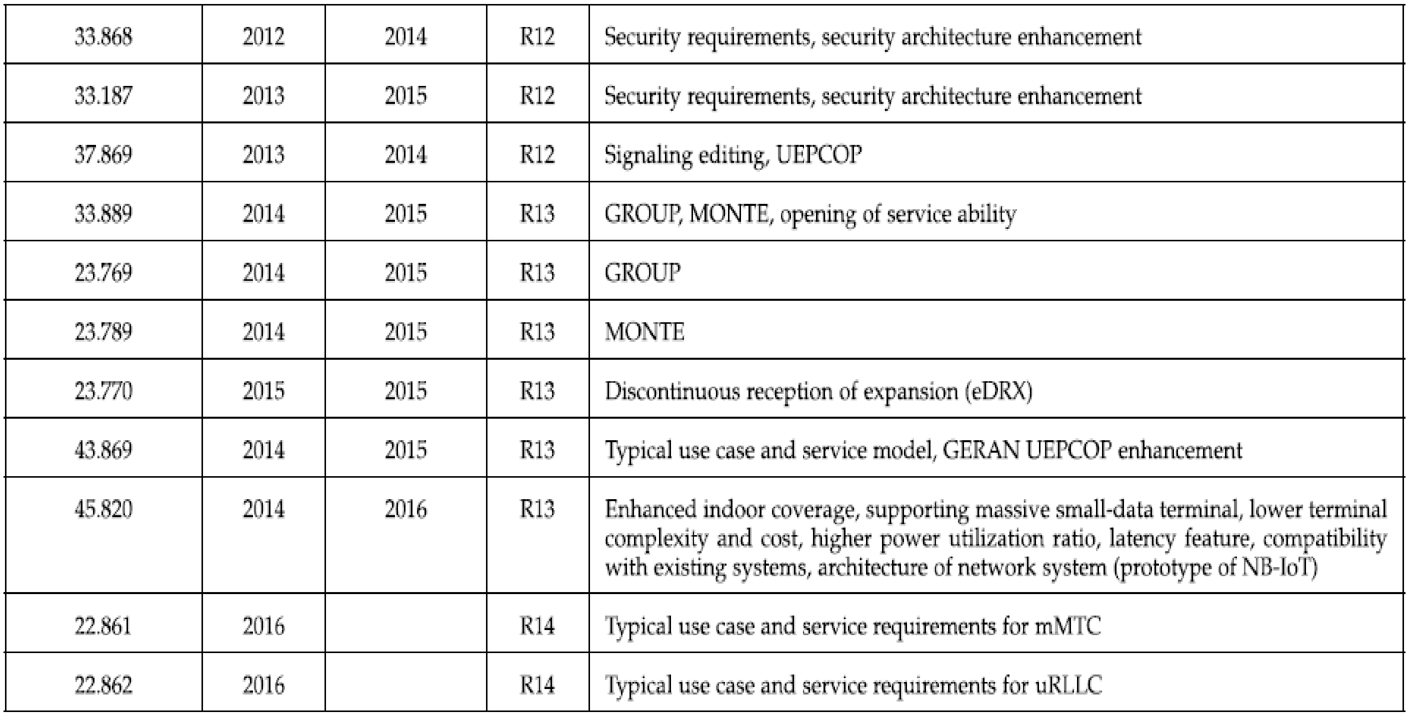
3GPP Release 15 performed 5G self-evaluation of LTE-M and NB-IoT performance that showed

5G connection density requirement of a million devices per square kilometer with a service latency of at most 10 seconds. Extremely low SNR levels can be sustained, a coupling loss of 164 dB between the base station and the device is found which matches the 5G coverage requirements. Massive IoT performance combination with eMBB and Critical IoT use cases must be supported by mobile operators and consequently, R15 supports a close coexistence between NR, LTE-M and NB-IoT allowing them to operate in the same frequency band, configure the same physical layer numerology, align the uplink and downlink transmissions in time and frequency and reserve NR time-frequency resources dedicated for LTE-M and NB-IoT transmissions.



Standard number	Start time	Freezing time	Version	Technologic fields of concern
22.868	2005	2008	R8	Billing, addressing, security, communication mode, massive user
33.812	2007	2009	R9	Remote subscription management, security requirements, security architecture enhancement
22.368	2009	2015	R10	General and exclusive service requirements
23.888	2009	2012	R10	Strucutre enhancement of network system, signaling congestion in core network and congestion control
37.868	2010	2012	R11	Service features and modeling, access network enhancement and congestion control
43.868	2010	2014	R12	Service features and modeling, GERAN enhancement (such as resource allocation, overload and congestion control, addressing format and energy-saving mode)
22.988	2011	2015	R12	Numbering and addressing
36.888	2011	2014	R12	Service features and modeling, assumption on coverage enhancement, design thought on low-cost MTC terminals (such as single-radio frequency link, half-duplex, lower band width, lower peak rate, lower transmitting power and less-jobs mode)
22.888	2012	2014	R12	Architecture of network system, localization and IMS enhancement
23.887	2012	2014	R12	Small data- terminal triggering enhancement (SDDTE), monitoring enhancement (MONTE), optimized design for power consumption at terminals (UEPCOP), group features enhancement (GROUP)

Table 4 Part 1 of the 3GPP release summary of NB IoT



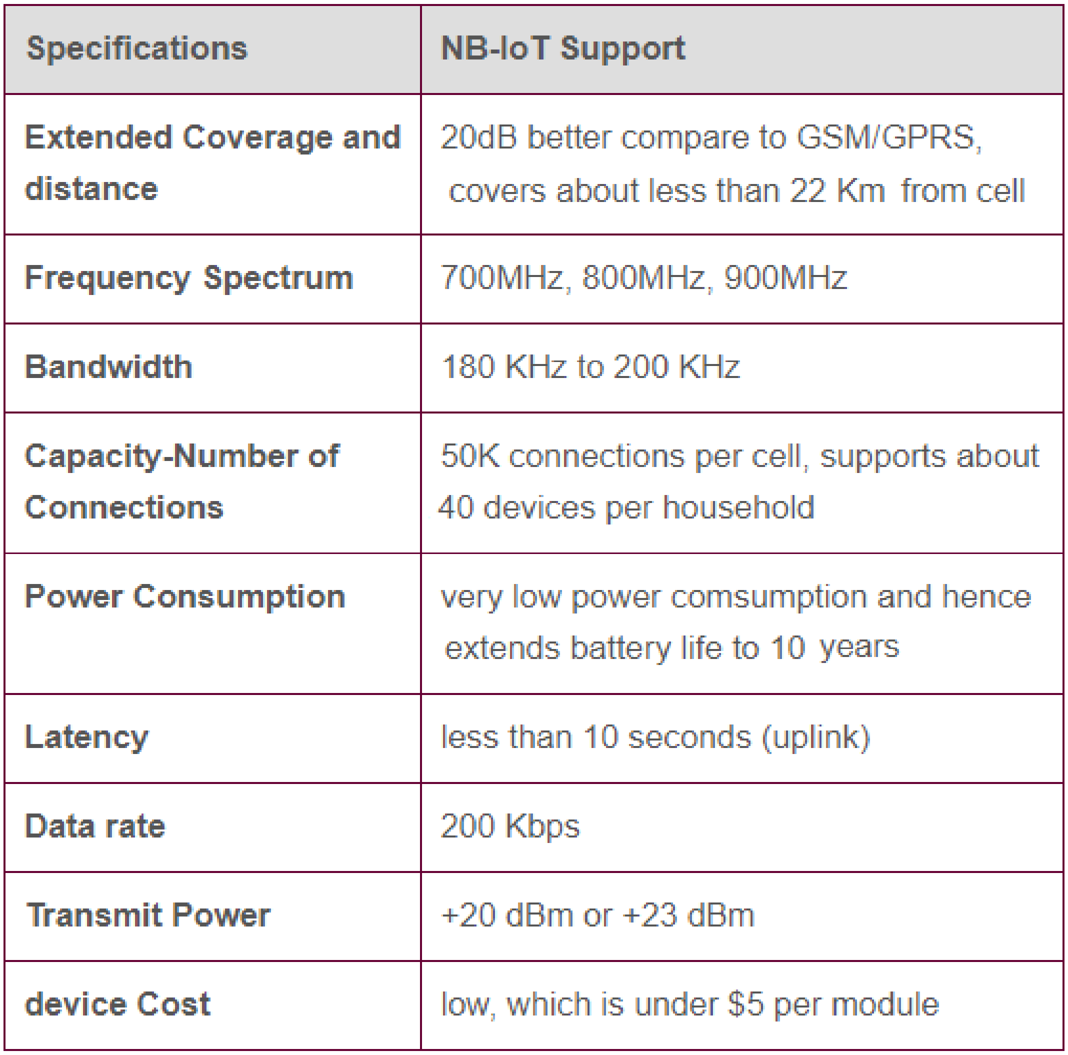
33.868	2012	2014	R12	Security requirements, security architecture enhancement
33.187	2013	2015	R12	Security requirements, security architecture enhancement
37.869	2013	2014	R12	Signaling editing, UEPCOP
33.889	2014	2015	R13	GROUP, MONTE, opening of service ability
23.769	2014	2015	R13	GROUP
23.789	2014	2015	R13	MONTE
23.770	2015	2015	R13	Discontinuous reception of expansion (eDRX)
43.869	2014	2015	R13	Typical use case and service model, GERAN UEPCOP enhancement
45.820	2014	2016	R13	Enhanced indoor coverage, supporting massive small-data terminal, lower terminal complexity and cost, higher power utilization ratio, latency feature, compatibility with existing systems, architecture of network system (prototype of NB-IoT)
22.861	2016		R14	Typical use case and service requirements for mMTC
22.862	2016		R14	Typical use case and service requirements for uRLLC

Table 5; Part 2 of the 3GPP release summary of NB IoT

2.1. LOW POWER CONSUMPTION

Using the power saving mode (PSM) and expanded discontinuous reception (eDRX), longer standby time can be realized in NB-IoT. Thereinto, PSM technology is newly added in Rel-12, where in the power saving mode the terminal is still registered online but cannot be reached by signaling in order to make the terminal deep sleep for a longer time to achieve the power saving. On the other hand, the eDRX is newly added in Rel-13, which further extends sleep cycle of terminal in idle mode and reduces unnecessary startup of receiving cell. Compared to PSM, eDRX promotes downlink accessibility significantly.

NB-IoT requires that the terminal service life of a constant- volume battery is 10 years for typical low-rate low-frequency service. According to simulated data of TR45.820, for coupling loss of 164 dB and using both PSM and eDRX, the ser- vice life of 5-Wh battery can be 12.8 years if a message of 200 byte is sent once per day by terminal.



Specifications	NB-IoT Support
Extended Coverage and distance	20dB better compare to GSM/GPRS, covers about less than 22 Km from cell
Frequency Spectrum	700MHz, 800MHz, 900MHz
Bandwidth	180 KHz to 200 KHz
Capacity-Number of Connections	50K connections per cell, supports about 40 devices per household
Power Consumption	very low power comsumption and hence extends battery life to 10 years
Latency	less than 10 seconds (uplink)
Data rate	200 Kbps
Transmit Power	+20 dBm or +23 dBm
device Cost	low, which is under $5 per module

Table 6: Specifications of NB IoT

2.2. ENHANCED COVERAGE AND LOW LATENCY SENSITIVITY

According to simulated data of TR45.820, it can be con- firmed that the covering power of NB-IoT can reach 164 dB in independent deployment mode. The simulation test was conducted for both in-band deployment and guard band deployment. In order to realize coverage enhancement, mechanisms such as retransmission (200 times) and low frequency modulation are adopted by NB-IoT. At present, the NB-IoT support for 16QAM is still in discussion. For coupling loss of 164 dB, if a reliable data transmission is provided the latency increases due to retransmission of mass data. Simulations for TR45.820 show the latency for irregular reporting service scenario and different coupling losses (header compressing or not) with reliability of 99%. Currently, the tolerable latency in 3GPP IoT is 10 s. In fact, lower latency of about 6 s for maximal coupling losses can be also supported. For more details, please refer to simulation results of NB-IoT for TR45.820.

2.3. TRANSMISSION MODE

The development of NB-IoT is based on LTE. The modification is mainly made on relevant technologies of LTE according to NB-IoT unique features. The RF bandwidth of NB-IoT physical layer is 200 kHz. In downlink, NB-IoT adopts QPSK modem and OFDMA technology with sub-carrier spacing of 15 KHz [32]. In uplink, BPSK or QPSK modem and SC-FDMA technology including single sub-carrier and multiple subcarrier are adopted. A single sub-carrier technology with sub-carrier spacing of 3.75 kHz and 15 kHz is applicable to IoT terminal with ultra-low rate and ultra-low power consumption.

For sub-carrier spacing of 15 kHz, 12 continuous sub- carriers are defined. Accordingly, 48 continuous sub-carriers are defined for sub-carrier spacing of 3.75 kHz. Multiple sub- carrier transmission supports sub-carrier spacing of 15 kHz and defines 12 continuous sub-carriers which are combined into 3, 6, or 12 continuous sub-carriers. The coverage abiliity for 3.75-kHz spacing is higher than for 15-kHz spacing because of higher power spectral density. The cell capacity for 15-kHz spacing is 92% of that for 3.75-kHz spacing, but the dispatching efficiency and dispatching complexity are superior. Since the Narrow Physical Random-Access Channel (NPRACH) has to adopt single sub-carrier transmission with spacing of 3.75 kHz, most of equipment preferentially supports single sub-carrier transmission with spacing of 3.75 kHz for uplink. After introducing single sub- carrier transmission with spacing of 15 kHz and multiple sub- carrier transmission, choice is made adaptively according to channel quality at terminal. The minimal dispatching unit for the Narrow Physical Downlink Shared Channel (NPDSCH) transmission is the resource block (RB), and the minimal dis- patching unit for the Narrow Physical Uplink Shared Channel (NPUSCH) transmission is the resource unit (RU). In the aspect of time domain, for single sub-carrier transmission, the resource unit is 32 ms for sub-carrier spacing of 3.75 kHz and 8 ms for sub-carrier spacing of 15 kHz, and for multiple sub-carrier transmission, the resource unit is 4 ms for spacing with 3 sub-carriers, 2 ms for spacing with 6 sub-carriers, and 1 ms for spacing with 12 sub-carriers.

The protocol of NB-IoT high layer (the layer above physical layer) is formulated through modification of some LTE features, such as multi-connection, low power consumption and few data. The core network of NB-IoT is connected through S1 interface.

2.4. SPECTRUM RESOURCE

The IoT is the core service that will attract larger user group on communication service market in the future, therefore the development of NB-IoT has a great support from four largest telecom operators in China, who own respective spectrum resource for NB-IoT.

2.5. WORKING MODE OF NB-IOT

According to stipulations in RP-151621 of NB-IoT, NB-IoT currently supports only FDD transmission mode with bandwidth of 180 kHz and 3 following types of deployment scenes.

- Independent deployment (Stand-alone mode), which utilizes independent frequency band that does not over- lap with the frequency band of LTE;

- Guard-band deployment (Guard-band mode), which utilizes edge frequency band of LTE;

- In-band deployment (In-band mode), which utilizes LTE frequency band for deployment, and it takes 1 PRB of LTE frequency band resource for deployment

Chapter 3: Doppler Spread

3.1. What is Doppler Effect?

The Doppler effect (or Doppler shift), named after Austrian physicist Christian Doppler who proposed it in 1842 in Prague, is the change in frequency of a wave for an observer moving relative to the source of the wave. It is commonly heard when a vehicle sounding a siren or horn approaches, passes, and recedes from an observer. The received frequency is higher (compared to the emitted frequency) during the approach, it is identical at the instant of passing by, and it is lower during the recession. The relative changes in frequency can be explained as follows. When the source of the waves is moving toward the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave. Therefore, the time between the arrival of successive wave crests at the observer is reduced, causing an increase in the frequency.

$$\boxed{f' = \frac{(v + v_0)}{(v - v_s)} f}$$

f = actual frequency of the sound waves
f' = observed frequency
v = speed of the sound waves
v_0 = velocity of the observer
v_s = velocity of the source

While they are travelling, the distance between successive wave fronts is reduced. Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wave fronts is increased, so the waves "spread out". For waves that propagate in a medium, such as sound waves, the velocity of the observer and of the source is relative to the medium in which the waves are transmitted. The total Doppler Effect may therefore result from motion of the source, motion of the observer, or motion of the medium. Each of these effects is analyzed separately. For waves which do not require a medium, such as light or gravity in general relativity, only the relative difference in velocity between the observer and the source needs to be considered.

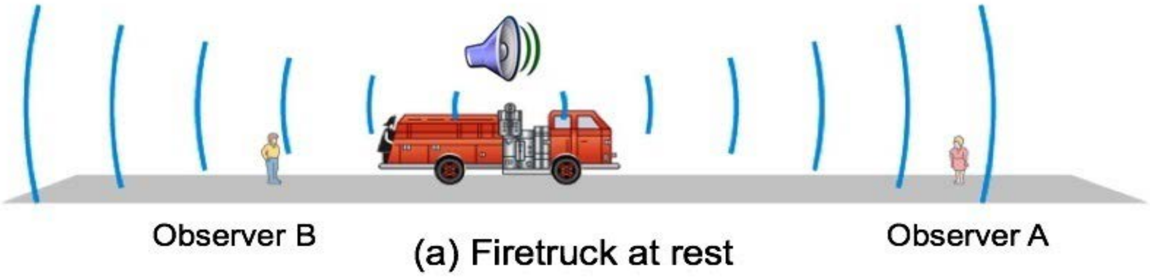


Figure 4: Demonstration of Doppler frequency

Figure 5:Demonstration of Doppler frequency.

In figure (4), both observer A & B experience same frequency of sound.

In figure (5), observer A experience a ***higher frequency*** of sound compared to observer B.

3.2.Frequency dispersion in RF

Frequency dispersion is a phenomenon caused in a multipath environment, which is resulted from user velocity, as the Doppler shift causes all the frequency of the all the multipath components to change. The effects on frequency responses on different multipath components vary from one another, consequently signifying a signal distortion in the resultant frequency response. Doppler spread is referred to as the increase in the overall frequency response.

Ratio of the user velocity to wavelength is the maximum value of the Doppler frequency. Doppler spread which is basically a measure of the spectral broadening caused by the time rate of change of the mobile radio channel, is also estimated to be the deviation of the frequency response equal to twice as much of the maximum Doppler shift. In order to fully understand the time-varying nature of the channel in a small-scale region the parameters Doppler spread along with the coherence time needs to be comprehended, given that these two parameters are inversely proportional to each other. The range of time with unvarying impulse response of the multipath channel is the coherence time. The main criteria for distinguishing and comparison between the Doppler spread and the signal bandwidth is related to the comparison between the coherence time of the multipath channel and the symbol period of the transmitted signal.

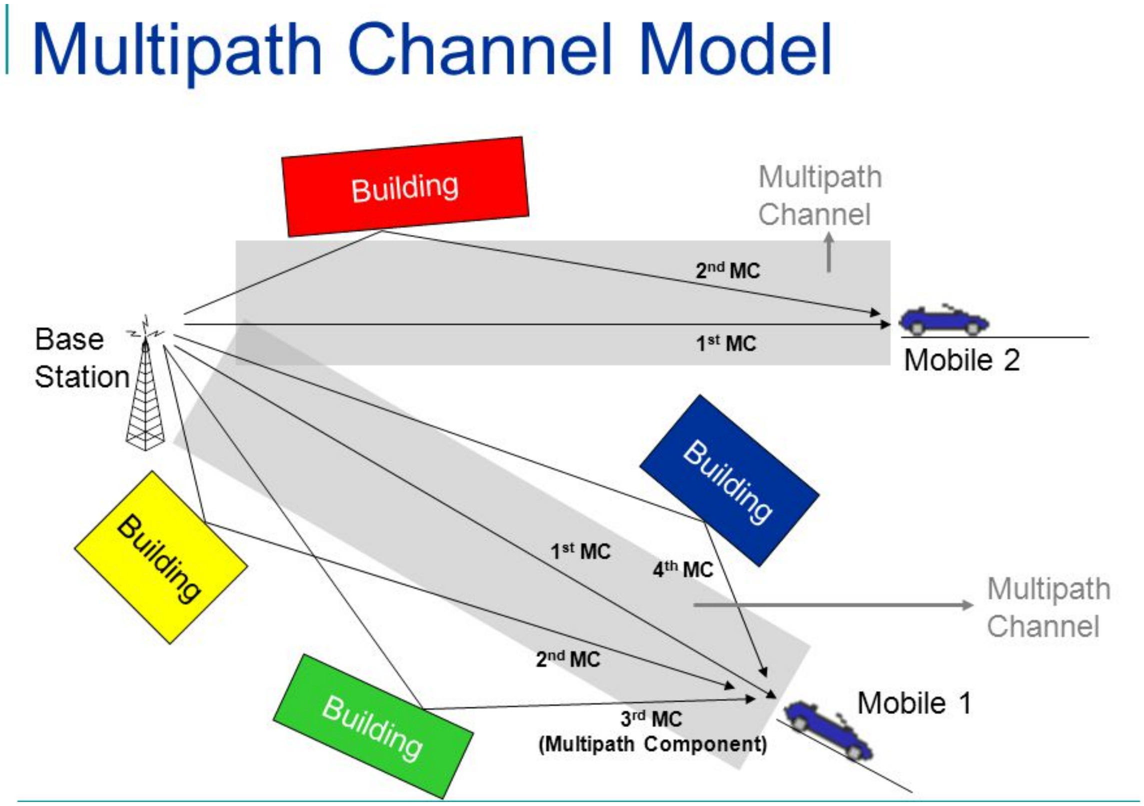


Figure 6:Multipath channel model

Slower channel impulse variation compared to variation in the transmitted signal results in transmitted signals to be faced with slow fading. Faster channel impulse variation within the symbol period causes significant distortion resulting in the transmitted signal to be faced with fast fading effects. In the frequency domain, similar phenomena of fast fading is observed when Doppler spread is large compared to the signal bandwidth, signifying that the frequency response of the transmitted signal has deteriorated too a great extent and has caused signal distortion.

3.1. Fading

Variation in the signal strength with respect to time as it is received at the antenna from the transmitter at a distant end is addressed as fading. Multiple versions of the transmitted signal arrive at the receiver at slightly different time instants. The multipath channel is time-varying and it varies constantly with time. The variation is unpredictable to a great extent. The variation occurs both due to change in the environment and due to movement of the UE. For devices that are in mobility, the degrading performance is due to slow fading where signal paths change due to shadowing and obstructions. The coherence time is very much greater than the symbol period causing the impulse response changes to be much slower than the transmitted signal. Equivalently in the frequency domain, the signal bandwidth is much greater compared to the Doppler spread.

For objects placed in extremely remote locations, the devices are subject to fast fading resulting from the effects of constructive and destructive interference patterns caused due to multipath. Channel impulse response changes rapidly within the symbol duration. Considering the frequency domain, the signal bandwidth is much smaller than the Doppler spread which equivalently means that the symbol period is much smaller than the coherence time in the time domain.

NB-IoT devices are presumed to be an integral part of the future when the full deployment of 5G is done, with about a million devices constantly communicating with each other in an area as small as a square kilometer. There will be devices located in the basements and quite obviously they will not be able to communicate with the transmitter with as much ease as the devices in more convenient locations, and will be subject to fast fading problems. NB-IoT devices are also seen to be found in high speed vehicles. While LTE can support high performance for UE speeds up to 120 km/h but at speeds over 300 km/h or even 500 km/h, the service is borderline sustained but quite close to unusable. Such NB-IoT devices can be found in high speed bullet trains or similar vehicles. The dilemma faced in this case is the slow fading phenomena.

3.2. Effect of Doppler frequency on NB IoT

For the purpose of analyzing the extent of the effects that these scenarios have on NB-IoT devices, thorough simulations have been carried out that tested the performance variation of these devices under different changing parameters. Uplink data transfer as well as the downlink data transfer were tested under a perfect channel estimator which is a perfect MIMO channel estimate after OFDM modulation. This is done by setting the channel with desired configuration and sending a set of known symbols through it for each transmit antenna in turn. A range of data sets have been collected showing results for uplink and downlink channels. There are simulation results for throughput against Doppler frequency and block error rate (BLER) against Doppler frequency. Throughput is how much data actually does travel through the 'channel' successfully while BLER is a ratio of the number of erroneous blocks to the total number of blocks transmitted. Simulation results were also obtained for throughput and BLER against the signal-to-noise ratio (SNR).

Doppler frequency depends on carrier frequency and maintains a proportional relation with it and maintains an inverse relation with the wavelength. Simulations help us to have a deeper understanding of the change in performance. The performance analysis data is used to control the carrier frequency via the cognitive radio. Cognitive radio is basically a software defined radio that automatically detects the available channel and bandwidth vacancy. Cognitive radio will be implemented in the base station where it senses the traffic and allocates it and then routes it from one node to another. Moreover, the exponential increase in the number of devices in the near future means that the cognitive radio will play a major role in the selection of carriers.

The result obtained from the performance analysis is then analyzed under the algorithm and the suitable carrier frequency is selected that is going to ensure a greater performance by the NB-IoT devices.

Chapter 4: Cognitive Radio

4.1. Introduction:

A Cognitive Radio (CR) is a radio that can be programmed and configured dynamically to use the best wireless channels in its vicinity to avoid user interference and congestion. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location. This process is a form of dynamic spectrum management. In this process communication systems are aware of their internal state and environment, such as location and utilization on RF frequency spectrum at that location. They can make decisions about their radio operating behavior by mapping that information against predefined objectives. It also has the capability of learning waveforms and protocols, to adapt to the local spectrum availability and to learn the current needs of its user.

4.2. HISTORY

The concept of cognitive radio was first proposed by Joseph Mitola III in a seminar at KTH (the Royal Institute of Technology in Stockholm) in 1998 and published in an article by Mitola and Gerald Q. Maguire, Jr. in 1999. It was a novel approach in wireless communications, which Mitola later described as: The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs. Cognitive radio is considered as a goal towards which a software-defined radio platform should evolve: a fully reconfigurable wireless transceiver which automatically adapts its communication parameters to network and user demands. Traditional regulatory structures have been built for an analog model and are not optimized for cognitive radio. Regulatory bodies in the world (including the Federal Communications Commission in the United States and Ofcom in the United Kingdom) as well as different independent measurement campaigns found that most radio frequency spectrum was inefficiently utilized. Cellular network bands are overloaded in most parts of the world, but other frequency bands (such as military, amateur radio and paging frequencies) are insufficiently utilized. Independent studies performed in some countries confirmed that observation, and concluded that spectrum utilization depends on time and place. Moreover, fixed spectrum allocation prevents rarely used frequencies (those assigned to specific services) from being used, even when any unlicensed users would not cause noticeable interference to the assigned service. Regulatory bodies in the world have been considering whether to allow unlicensed users in licensed bands if they would not cause any interference to licensed users. These initiatives have focused cognitive-radio research on dynamic spectrum access.

The first cognitive radio wireless regional area network standard, IEEE 802.22, was developed by IEEE 802 LAN/MAN Standard Committee (LMSC)[3] and published in 2011. This standard uses geolocation and spectrum sensing for spectral awareness. Geolocation combines with a database of licensed transmitters in the area to identify available channels for use by the cognitive radio network. Spectrum sensing observes the spectrum and identifies occupied channels. IEEE 802.22 was designed to utilize the unused frequencies or fragments of time in a location. This white space is unused television channels in the geolocated areas. However, cognitive radio cannot occupy the same unused space all the time. As spectrum availability changes, the network adapts to prevent interference with licensed transmissions.

4.3. Functions:

The main functions of cognitive radio system include power control, spectrum sensing and spectrum management. Power control is used so that the capacity of the secondary users is maximized along with applying certain constraints to protect the primary users. A cognitive radio can sense empty spectrum without causing any form of interference to other users. There are three spectrum-sensing techniques:

- Power Control: Power control is usually used for spectrum sharing CR systems to maximize the capacity of secondary users with interference power constraints to protect the primary users.
- Spectrum sensing: Detecting unused spectrum and sharing it, without harmful interference to other users; an important requirement of the cognitive-radio network is to sense empty

spectrum. Detecting primary users is the most efficient way to detect empty spectrum. Spectrum-sensing techniques may be grouped into three categories:

- <u>Transmitter detection:</u> Cognitive radios must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum. There are several proposed approaches to transmitter detection:
- <u>Matched filter detection</u>
- <u>Energy detection:</u> Energy detection is a spectrum sensing method that detects the presence/absence of a signal just by measuring the received signal power.[19] This signal detection approach is quite easy and convenient for practical implementation. To implement energy detector, however, noise variance information is required. It has been shown that an imperfect knowledge of the noise power (noise uncertainty) may lead to the phenomenon of the SNR wall, which is a SNR level below which the energy detector cannot reliably detect any transmitted signal even increasing the observation time.[20] It[21] has also been shown that the SNR wall is not caused by the presence of a noise uncertainty itself, but by an insufficient refinement of the noise power estimation while the observation time increases.

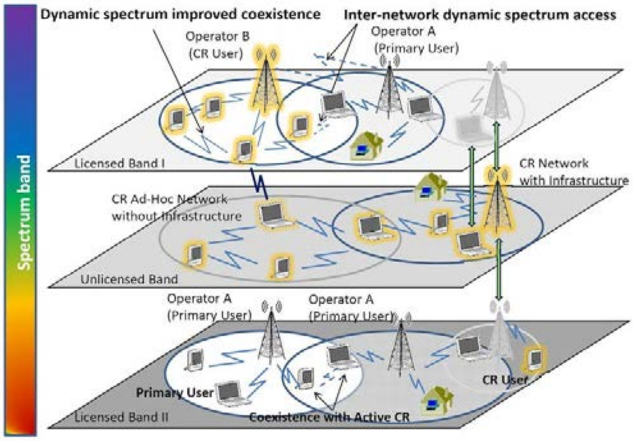


Figure 7: Spectrum Management of CR

- <u>Cyclo-stationary-feature detection:</u> This type of spectrum sensing algorithms is motivated because most man-made communication signals, such as BPSK, QPSK, AM, OFDM, etc. exhibit cyclo-stationary behavior.[22] However, noise signals (typically white noise) do not exhibit cyclo-stationary behavior. These detectors are robust against noise variance uncertainty. The aim of such detectors is to exploit the cyclo-stationary nature of man-made communication signals buried in noise. Their main decision parameter is comparing the non-zero values obtained by CSD of the primary signal. Cyclo-stationary detectors can be either single cycle or multicycle cyclo-stationary.

- <u>Wideband spectrum sensing:</u> refers to spectrum sensing over large spectral bandwidth, typically hundreds of MHz or even several GHz. Since current ADC technology cannot afford the high sampling rate with high resolution, it requires revolution techniques, e.g., compressive sensing and sub-Nyquist sampling.[24]
- <u>Cooperative detection:</u> Refers to spectrum-sensing methods where information from multiple cognitive-radio users is incorporated for primary-user detection
- <u>Interference-based detection</u>
- <u>Null-space based CR:</u> With the aid of multiple antennas, CR detects the null-space of the primary-user and then transmits within the null-space, such that its subsequent transmission causes less interference to the primary-user
- <u>Spectrum management:</u> Capturing the best available spectrum to meet user communication requirements, while not creating undue interference to other (primary) users. Cognitive radios should decide on the best spectrum band (of all bands available) to meet quality of service requirements; therefore, spectrum-management functions are required for cognitive radios. Spectrum-management functions are classified as:
- <u>Spectrum analysis</u>
- <u>Spectrum decision</u>

The practical implementation of spectrum-management functions is a complex and multifaceted issue, since it must address a variety of technical and legal requirements. An example of the former is choosing an appropriate sensing threshold to detect other users, while the latter is exemplified by the need to meet the rules and regulations set out for radio spectrum access in international (ITU radio regulations) and national (telecommunications law) legislation.

4.4. Application

- The application of CR networks to emergency and public safety communications by utilizing white space
- The potential of CR networks for executing dynamic spectrum access (DSA)
- Application of CR networks to military action such as chemical biological radiological and nuclear attack detection and investigation, command control, obtaining information of battle damage evaluations, battlefield surveillance, intelligence assistance, and targeting.[34]
- They are also proven to be helpful in establishing Medical Body Area Networks which can be utilized in omnipresent patient monitoring that aids in immediately notifying the doctors regarding vital information of patients such as sugar level, blood pressure, blood oxygen and electrocardiogram (ECG), etc. This gives the additional advantage of reducing the risk of infections and also increases the patient's mobility.

4.5. Advantages:

Cognitive radio system uses the spectrum efficiently. For utilizing the radio bands in a country, a license is required from the government. This is a costly procedure. There are certain licensed spectrum bands that are underutilized and unutilized. Cognitive radio can utilize this spectrum and license holders are also not disturbed. This unutilized spectrum is known as white space.

In a traditional wireless sensor network, a single channel is used for communication. When an event is detected, the sensor nodes generate packets. In a dense network, sensor nodes try to occupy the single communication channel at the same time. This increases the possibility of collisions and the communication quality is decreased. Moreover, there is more power consumption and packet delay. Cognitive radio gives the opportunity to utilize multiple channels thereby reducing the chances of collision and also increases the communication quality. Cognitive Radio is used in various military and public services like chemical, biological and nuclear radiation detection, war surveillance etc. Traditional wireless sensor networks face the problem of signal jam. But this problem is no longer exist if we use cognitive radio wireless sensor network. Cognitive Radio can handoff a wide range of frequencies. It is also useful when the applications need large bandwidth.

1.Overcome radio spectrum density

By sensing spectrum utilization (irrespective of channel allocation), cognitive radios can broadcast on unused radio spectrum, while still avoiding interference with the operation of the primary licensee.

2. Avoid intentional radio jamming scenarios

By sensing channel availability and even predicting the jammer’s tactics , cognitive radios can evade jamming by dynamically and preemptively switching to higher quality channels.

3. Switch to power saving protocol

By switching to protocols that trade off lower power consumption for lower bandwidth, cognitive radios conserve power when slower data rates suffice.

4. Improve satellite communications

How? By predicting rain fade and reconfiguring transmitters/receivers for optimum bandwidth, cognitive radios improve communication quality when and where the information is needed most.

5. Improves quality of service (QoS)

4.6. Cognitive Radio and NB-IOT:

The increased popularity and urgency to accommodate a huge amount of IOT devices with a highly efficient network has led us to further analyze the performance paradigm of one of these technologies called Narrow band Internet of things and introduce the idea of cognitive radio in NB- IOT. This proposal aims to solve the spectrum shortage and improve resource allocation for the huge data traffic.

So, we are merging NB-IOT with Cognitive Radio. So, the CR will sense the vacancy in the frequency band and shift the carrier for spectrum efficiency

Due to doppler spreading out SNR increases so throughput decreases as it is inversely proportional to SNR. So, we need to find out which carrier frequency will be suitable for different situations give high spectrum efficiency and spectrum management will reduce the amount of waste will be decided by the intelligence system that is cognitive radio.

It will measure the throughput and BLER with a periodic interval. If the value falls below the threshold value for minimum criteria of good SNR it will search for the required carrier frequency available in the white space and band hole and with the routing technique it will adapt with the fading situation.

As these IOT devices doesn’t require that huge bandwidth it can easily find the needed bandwidth from the unused bandwidth portion during a transmission that is called bandwidth hole or unused band that is called white space

As the number of IOT devices are increasing drastically we should focus on building up Cognitive Radio Networks where the CR will be placed in the Base Stations.

4.7. The Proposed Algorithm

At first the CR of base-station will measure the Throughput and BLER. Throughput decreases and BLER increases due to doppler spread. Then CR will compare the value with the sample value that we have gained form the simulation. If it doesn’t satisfy the threshold value then it will calculate the change that is required to improve the condition. By changing carrier frequency, the effect of doppler spread can be reduced. As NB-IoT needs a very small operating bandwidth like 200khz it is very easy to find it from white space or any bandwidth hole. So, CR will search for frequency band to change the carrier for that circumstances. If there is no vacancy it will search for sharing option. Primary users use licensed band but they don’t always need the full band for transmission. So, secondary users can transmit in the same band if it is possible. If none of these two techniques can be achieved CR will keep searching in network until it gets it. As soon as it gets it will select the carrier frequency. Thus, it will improve the situation. Threshold values are different for different situations. This shifting is not permanent. Everything will go back to previous state when the cause of imbalance disappears.

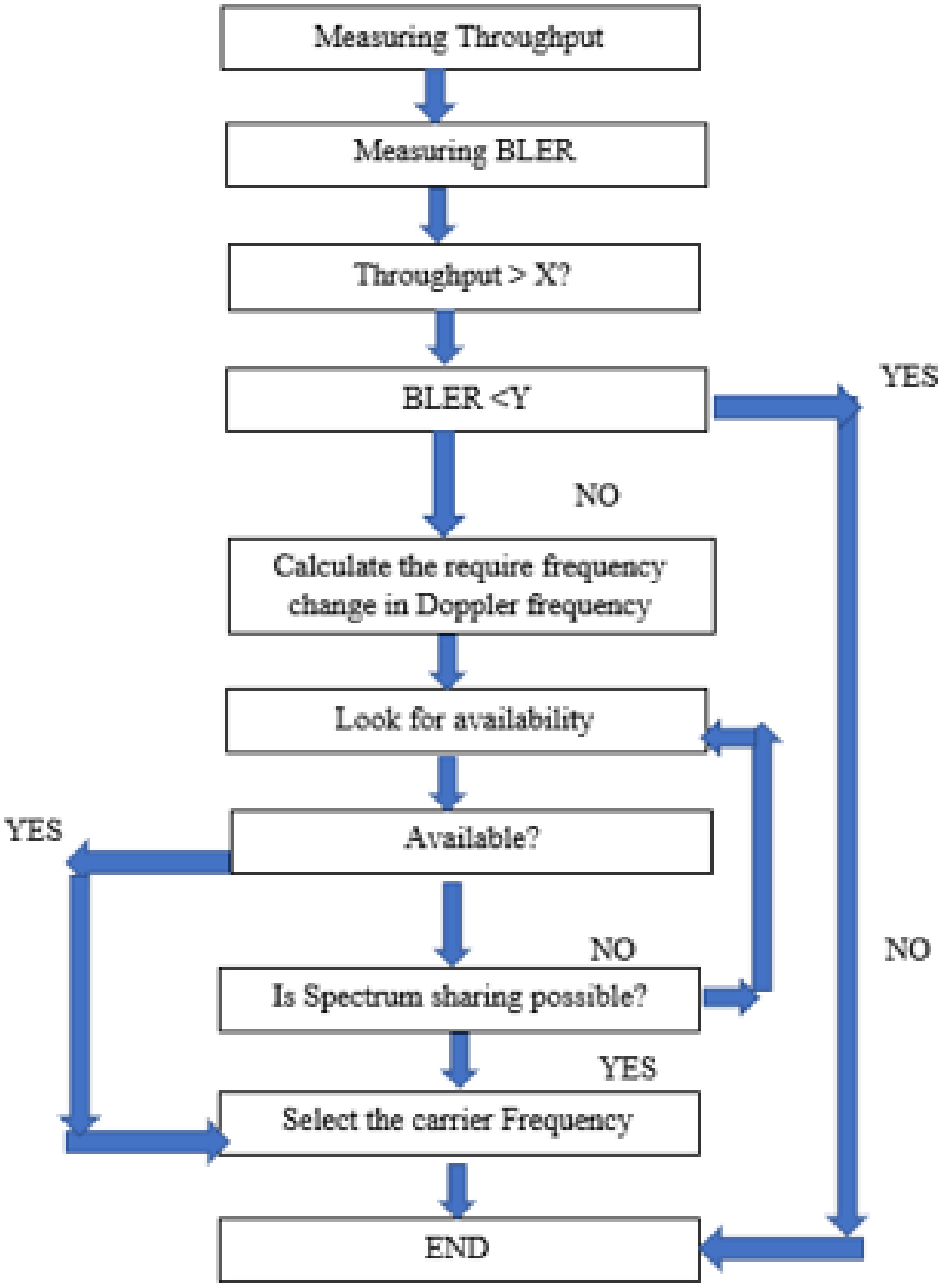


Figure 8: The Algorithm

Chapter 5: Simulation and Result Analysis

5.1: Simulation parameters

In order to establish the problem statement of this proposal we scrutinized the effect of doppler spread on the performance of NB IOT. The simulation was originally carried out to calculate the percentage throughput and block error rate (BLER) of both NB-IoT Narrowband Physical Downlink Shared Channel (NPDSCH) and NB IoT Narrowband Uplink Shared Channel (NPUSCH) under frequency selective fading and Additive White Gaussian Noise (AWGN) channel for a range of signal to noise ratio (SNR) at a particular doppler frequency. All the relevant parameters used to model this simulation are recorded in table 1. Keeping all other channel parameters constant, we changed the doppler frequency from 1000 Hz to 3000 Hz at 500 Hz interval. The frequency range was selected after an approximate calculation of relative speed with carrier frequency from equation (1)

$$fd = \frac{v}{\lambda}\cos(\theta) \qquad (1)$$

Where the f_d is the doppler frequency and v is the relative speed of the UE, θ is the angle between the base station and UE and λ is the wavelength of the carrier frequency.

If we approximate carrier frequency to be about 1800 MHz and θ to be 0 or 180 degree than from the equation (1) we get a doppler frequency of 1000 Hz for corresponding speed of 160 m/s. This is our lower limit speed and for the higher limit we took a speed of 500 m/s, the speed of a bullet train, which gives a corresponding doppler frequency of 3000 Hz.

Parameter	**Value**
Number of Transmission blocks	2000
SNR (dB) range	-10 to +15
Repeat simulated (ireps)	[1]
NPDSCH data type	Not BCCH
Modulation scheme	QPSK
Number of NRS antenna port	1
Operation mode	In band
Doppler frequency (Hz)	1000, 1500, 2000, 2500,3000
Subcarrier spacing	15 KHz

Table 7: Simulation parameters

For our experiment we have selected the number of downlink shared channel (DL-SCH) transport blocks to be 2000 blocks. A large number of transport block provides better accuracy for throughput calculations. By iteration we found 2000 transmission block corresponding to 2000 subframe gave an acceptable accurate reading of BLER and throughput. We have used the least channel quality to emphasize more on the effects of doppler frequency. Thus, repetition pattern was set to 1. The NPDSCH data type defines that the NPDSCH carries with it no broadcast channel or system information block. The modulation scheme as per 3GPP is fixed to be QSK.

NB-IoT can operate in three different modes, namely

1) the in-band mode
2) the guard band mode
3) standalone mode.

The modes suggest the deployment of NB-IoT in the LTE spectrum, in the guard band between LTE carriers or outside LTE spectrum respectively. For our simulation we used only in band mode because this is the mode of highest priority for any application that is the interoperability of NB IoT in the LTE spectrum.

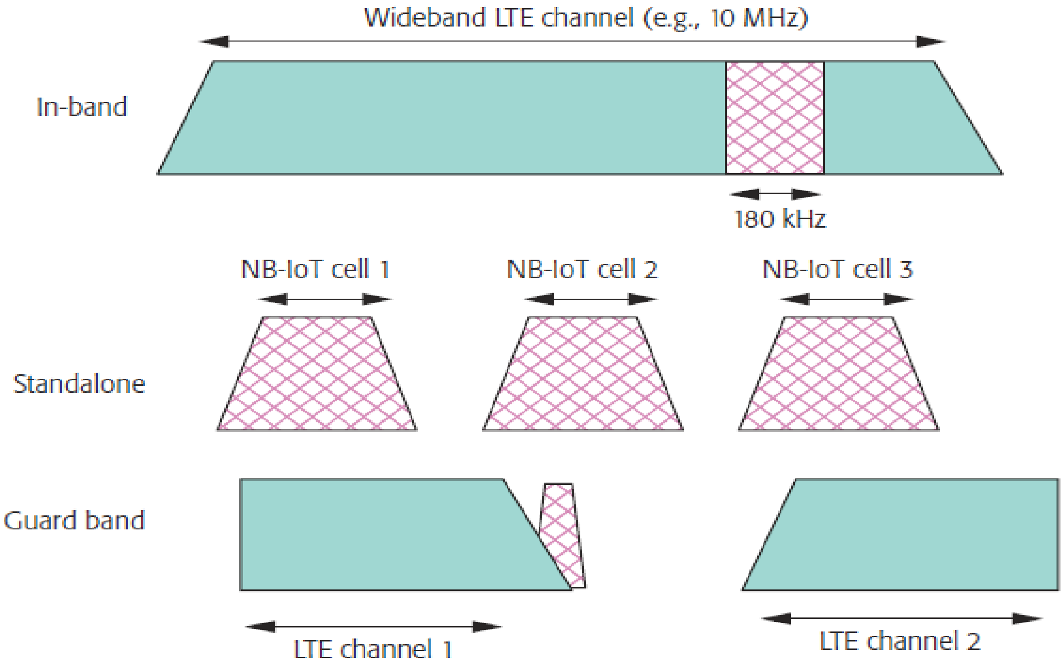


Figure 9: Modes of Operation of NB IoT

For the downlink model we generated a random stream of bits corresponding to the number of transport block upon which we implied CRC encoding, convolutional encoding and rate matching and produced NPDSCH bits. These bits are converted to symbols by Scrambling, modulation, layer mapping and precoding. The symbols are then OFDM modulated to create a time domain waveform. The waveform is transmitted through a preconfigured fading channel with additive white gaussian noise (AWGN) added. At the receiver end the transmitted waveform is synchronized and demodulated using perfect channel estimation which provides a perfect MIMO channel estimate after OFDM modulation. For every point of SNR, the block error rate and percentage throughput are calculated and stored.

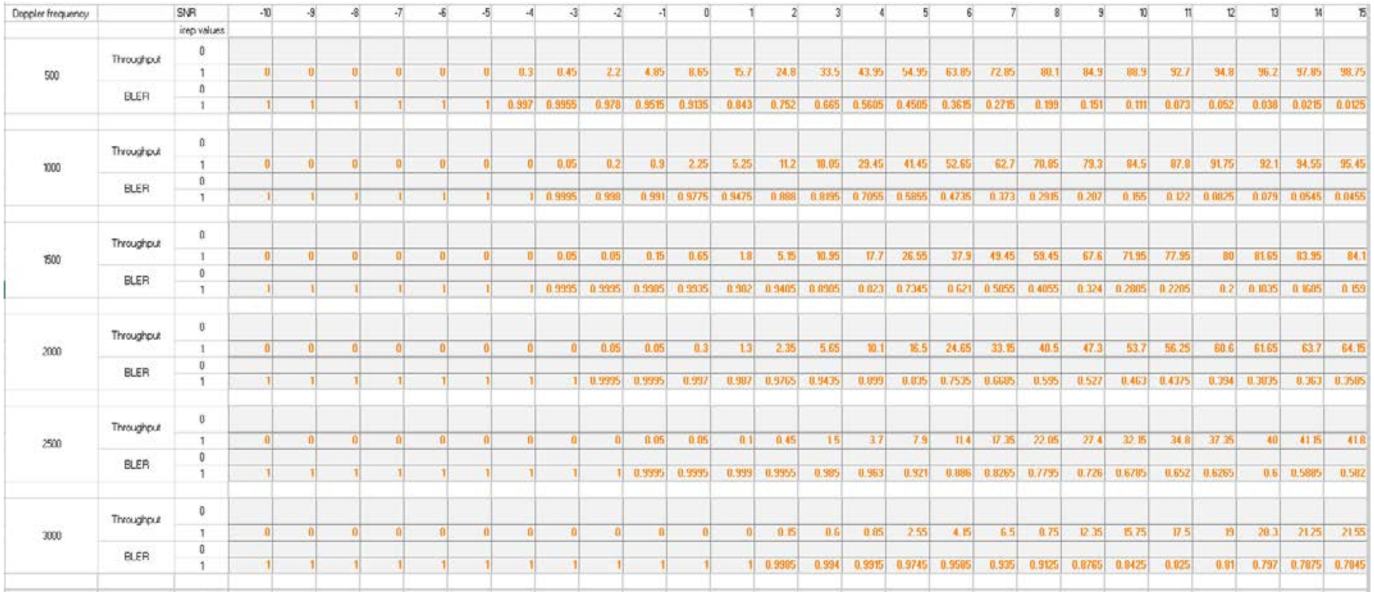
For the uplink model a similar process is used except a SC- FDMA modulation is used. All the other parameters are kept constant to produce a reliable data set. With our simulation we produced two data sets, uplink and downlink. Each data set consists of throughput and BLER for different SNR at different Doppler frequency.

5.2 Simulation results for uplink signal

The data sets collected are used to plot the following graphs

1) Throughput vs SNR
2) BLER vs SNR

The data set:



Doppler frequency		SNR	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		irep values																										
500	Throughput	0																										
		1	0	0	0	0	0	0	0.3	0.45	2.2	4.85	8.65	15.7	24.8	33.5	43.95	54.95	63.85	72.85	80.1	84.9	88.9	92.7	94.8	96.2	97.85	98.75
	BLER	0																										
		1	1	1	1	1	1	1	0.997	0.9955	0.978	0.9515	0.9135	0.843	0.752	0.665	0.5605	0.4505	0.3615	0.2715	0.199	0.151	0.111	0.073	0.052	0.038	0.0215	0.0125
1000	Throughput	0																										
		1	0	0	0	0	0	0	0	0.05	0.2	0.9	2.25	5.25	11.2	18.05	29.45	41.45	52.65	62.7	70.85	79.3	84.5	87.8	91.75	92.1	94.55	95.45
	BLER	0																										
		1	1	1	1	1	1	1	1	0.9995	0.998	0.991	0.9775	0.9475	0.888	0.8195	0.7055	0.5855	0.4735	0.373	0.2915	0.207	0.155	0.122	0.0825	0.079	0.0545	0.0455
1500	Throughput	0																										
		1	0	0	0	0	0	0	0	0.05	0.05	0.15	0.65	1.8	5.15	10.95	17.7	26.55	37.9	49.45	59.45	67.6	71.95	77.95	80	81.65	83.95	84.1
	BLER	0																										
		1	1	1	1	1	1	1	1	0.9995	0.9995	0.9985	0.9935	0.902	0.9405	0.8905	0.823	0.7345	0.621	0.5055	0.4055	0.324	0.2805	0.2205	0.2	0.1835	0.1605	0.159
2000	Throughput	0																										
		1	0	0	0	0	0	0	0	0	0.05	0.05	0.3	1.3	2.35	5.65	10.1	16.5	24.65	33.15	40.5	47.3	53.7	56.25	60.6	61.65	63.7	64.15
	BLER	0																										
		1	1	1	1	1	1	1	1	1	0.9995	0.9995	0.997	0.987	0.9765	0.9435	0.899	0.835	0.7535	0.6685	0.595	0.527	0.463	0.4375	0.394	0.3835	0.363	0.3585
2500	Throughput	0																										
		1	0	0	0	0	0	0	0	0	0	0.05	0.05	0.1	0.45	1.5	3.7	7.9	11.4	17.35	22.05	27.4	32.15	34.8	37.35	40	41.15	41.8
	BLER	0																										
		1	1	1	1	1	1	1	1	1	1	0.9995	0.9995	0.999	0.9955	0.985	0.963	0.921	0.886	0.8265	0.7795	0.726	0.6785	0.652	0.6265	0.6	0.5885	0.582
3000	Throughput	0																										
		1	0	0	0	0	0	0	0	0	0	0	0	0	0.15	0.6	0.85	2.55	4.15	6.5	8.75	12.35	15.75	17.5	19	20.3	21.25	21.55
	BLER	0																										
		1	1	1	1	1	1	1	1	1	1	1	1	1	0.9985	0.994	0.9915	0.9745	0.9585	0.935	0.9125	0.8765	0.8425	0.825	0.81	0.797	0.7875	0.7845

Table 8: Data set for Uplink Simulations

The Plots

These graphs help to demonstrate how the throughput and BLER varies for the range of SNR values used at different Doppler frequency used. The graphs plotted will also help to understand by how much the BLER and throughput varies for when Doppler frequency increases. This result will be fed to cognitive radio for analysis

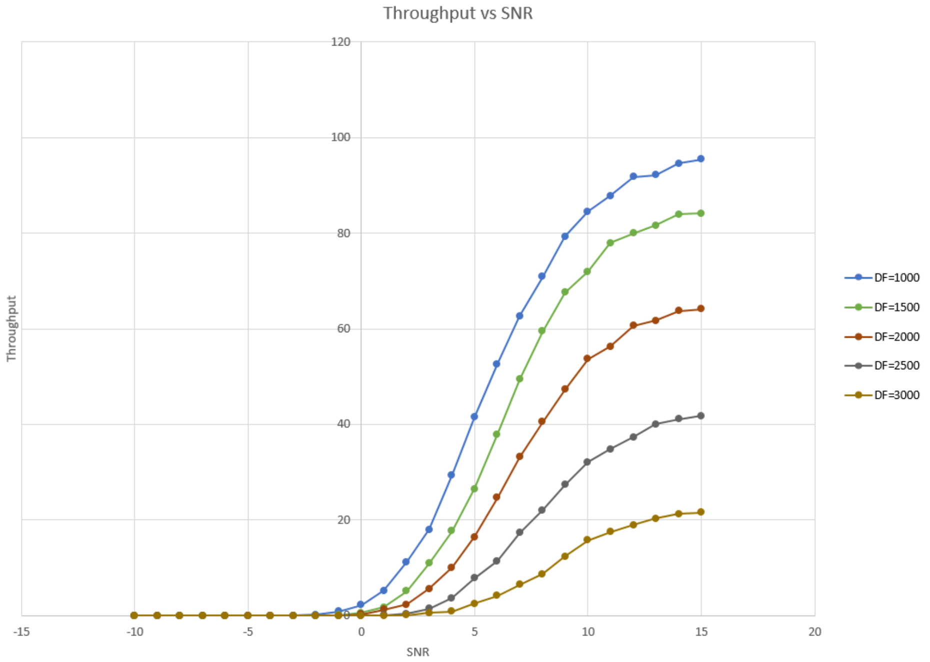


Figure 10: Throughput vs SNR for different Doppler frequency

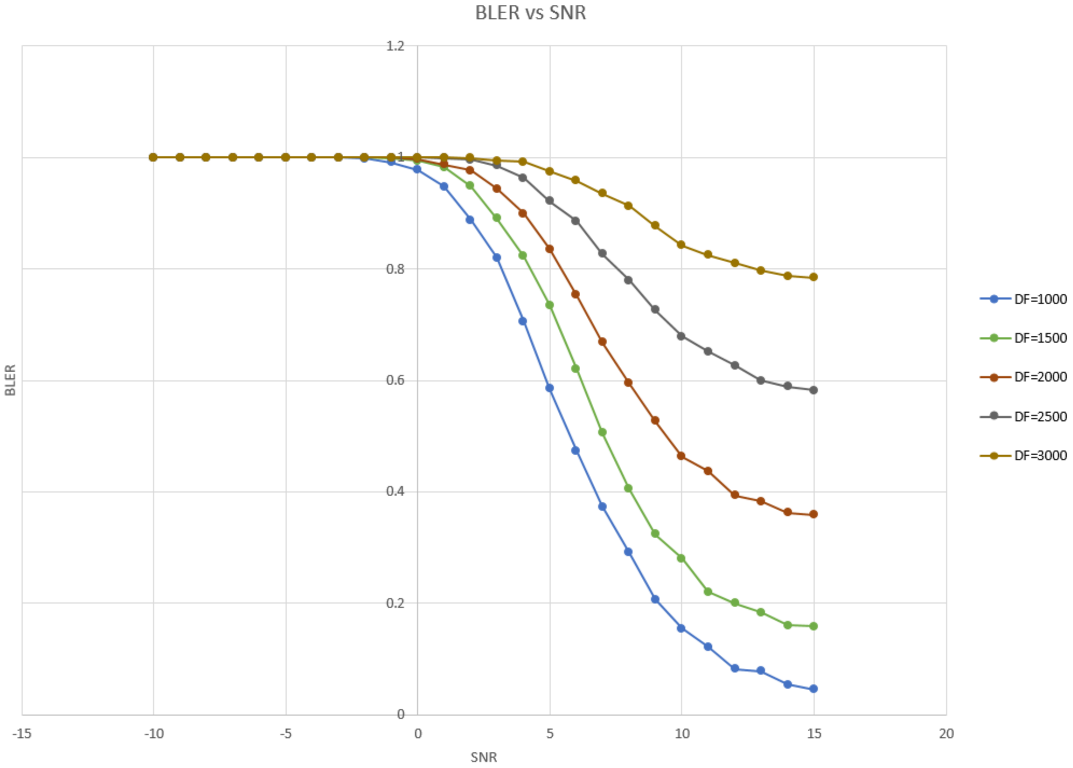


Figure 11 BLER vs SNR for different Doppler Frequency

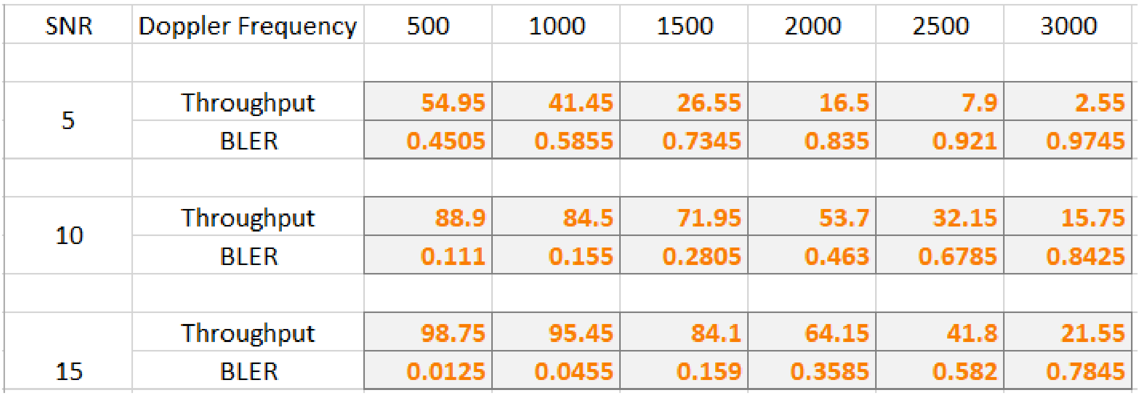
5.3: Performance analysis of Uplink signal

In order to find out by how much the Doppler frequency causes the throughput and BLER to change and better understand their relationship, the data sheets collected is further used to plot graphs of the following:

1) Throughput vs Doppler frequency
2) BLER vs Doppler frequency

SNR values used: 5db, 10db & 15db

The data sets



SNR	Doppler Frequency	500	1000	1500	2000	2500	3000
5	Throughput	54.95	41.45	26.55	16.5	7.9	2.55
	BLER	0.4505	0.5855	0.7345	0.835	0.921	0.9745
10	Throughput	88.9	84.5	71.95	53.7	32.15	15.75
	BLER	0.111	0.155	0.2805	0.463	0.6785	0.8425
15	Throughput	98.75	95.45	84.1	64.15	41.8	21.55
	BLER	0.0125	0.0455	0.159	0.3585	0.582	0.7845

Table 9: Data sets for UL SNR vs Doppler frequency

The plots

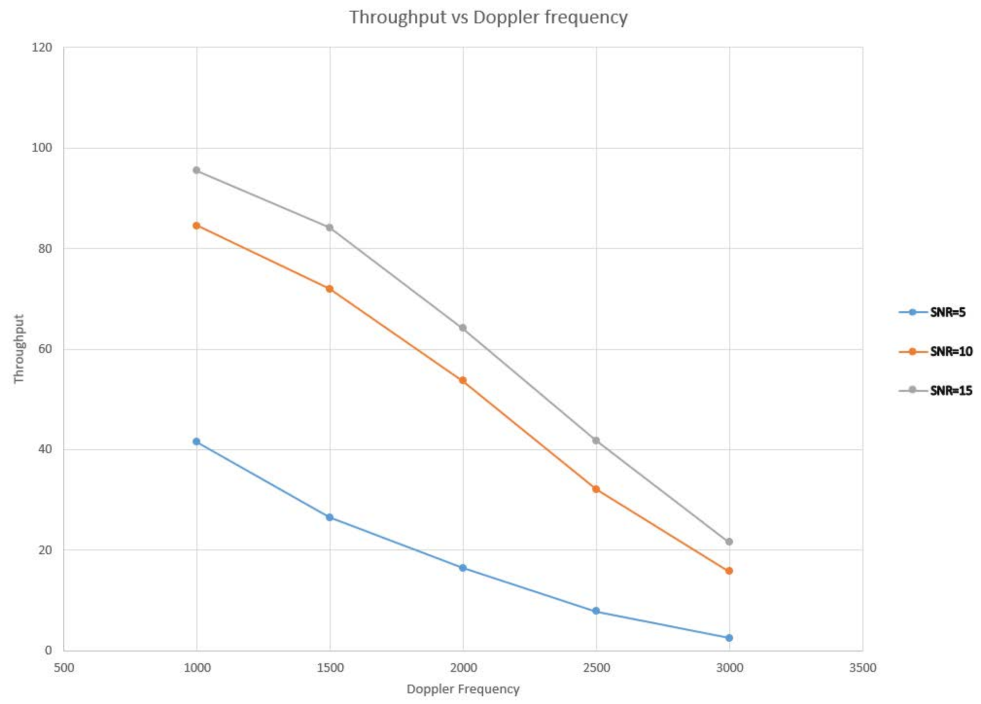


Figure 12 Throughput vs Doppler frequency for different SNR values

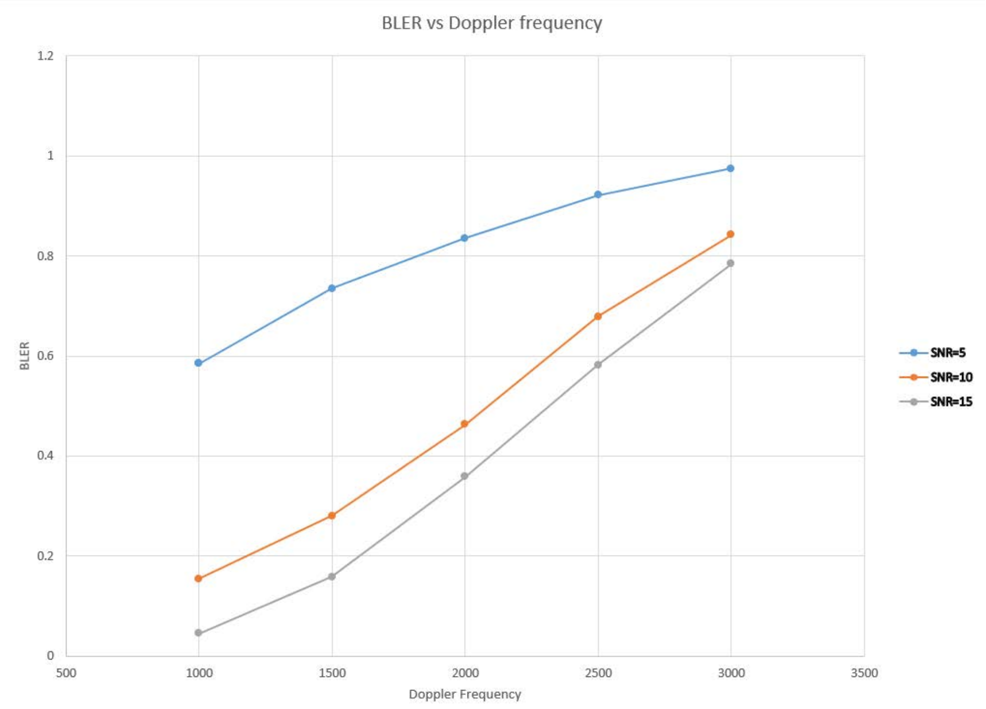


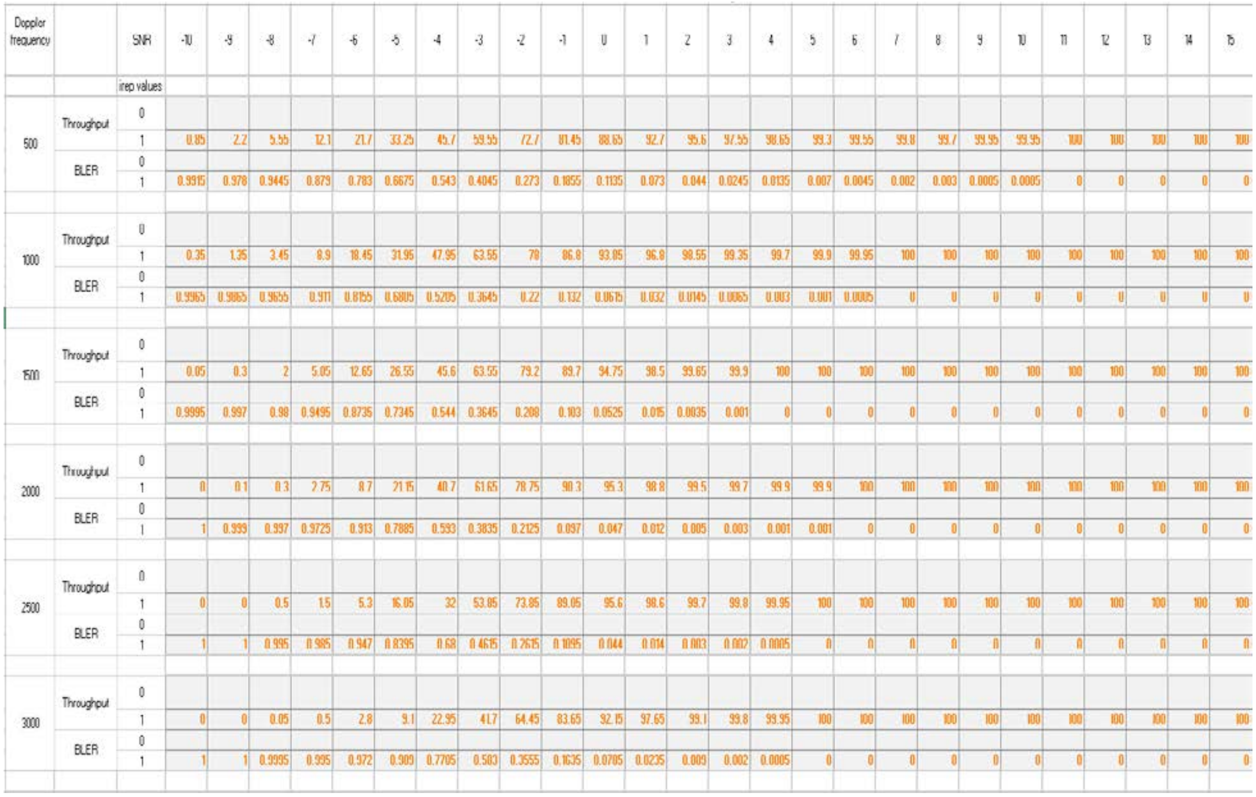
Figure 13 BLER vs Doppler frequency for different SNR values

5.4 Simulation results for Downlink signal

The data sets collected are used to plot the following graphs

1) Throughput vs SNR
2) BLER vs SNR

The Data set



Doppler frequency		SNR	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		irep values																										
500	Throughput	0																										
		1	0.85	2.2	5.55	12.1	21.7	33.25	45.7	59.55	72.7	81.45	88.65	92.7	95.6	97.55	98.65	99.3	99.55	99.8	99.7	99.95	99.95	100	100	100	100	100
	BLER	0																										
		1	0.9915	0.978	0.9445	0.879	0.783	0.6675	0.543	0.4045	0.273	0.1855	0.1135	0.073	0.044	0.0245	0.0135	0.007	0.0045	0.002	0.003	0.0005	0.0005	0	0	0	0	0
1000	Throughput	0																										
		1	0.35	1.35	3.45	8.9	18.45	31.95	47.95	63.55	78	86.8	93.85	96.8	98.55	99.35	99.7	99.9	99.95	100	100	100	100	100	100	100	100	100
	BLER	0																										
		1	0.9965	0.9865	0.9655	0.911	0.8155	0.6805	0.5205	0.3645	0.22	0.132	0.0615	0.032	0.0145	0.0065	0.003	0.001	0.0005	0	0	0	0	0	0	0	0	0
1500	Throughput	0																										
		1	0.05	0.3	2	5.05	12.65	26.55	45.6	63.55	79.2	89.7	94.75	98.5	99.65	99.9	100	100	100	100	100	100	100	100	100	100	100	100
	BLER	0																										
		1	0.9995	0.997	0.98	0.9495	0.8735	0.7345	0.544	0.3645	0.208	0.103	0.0525	0.015	0.0035	0.001	0	0	0	0	0	0	0	0	0	0	0	0
2000	Throughput	0																										
		1	0	0.1	0.3	2.75	8.7	21.15	40.7	61.65	78.75	90.3	95.3	98.8	99.5	99.7	99.9	99.9	100	100	100	100	100	100	100	100	100	100
	BLER	0																										
		1	1	0.999	0.997	0.9725	0.913	0.7885	0.593	0.3835	0.2125	0.097	0.047	0.012	0.005	0.003	0.001	0.001	0	0	0	0	0	0	0	0	0	0
2500	Throughput	0																										
		1	0	0	0.5	1.5	5.3	16.05	32	53.85	73.85	89.05	95.6	98.6	99.7	99.8	99.95	100	100	100	100	100	100	100	100	100	100	100
	BLER	0																										
		1	1	1	0.995	0.985	0.947	0.8395	0.68	0.4615	0.2615	0.1095	0.044	0.014	0.003	0.002	0.0005	0	0	0	0	0	0	0	0	0	0	0
3000	Throughput	0																										
		1	0	0	0.05	0.5	2.8	9.1	22.95	41.7	64.45	83.65	92.15	97.65	99.1	99.8	99.95	100	100	100	100	100	100	100	100	100	100	100
	BLER	0																										
		1	1	1	0.9995	0.995	0.972	0.909	0.7705	0.503	0.3555	0.1635	0.0705	0.0235	0.009	0.002	0.0005	0	0	0	0	0	0	0	0	0	0	0

Table 10: Data set DL

These graphs help to demonstrate how the throughput and BLER varies for the range of SNR values used at different Doppler frequency used. The graphs plotted will also help to understand by how much the BLER and throughput varies for when Doppler frequency increases. This result will be fed to cognitive radio for analysis

The Plots

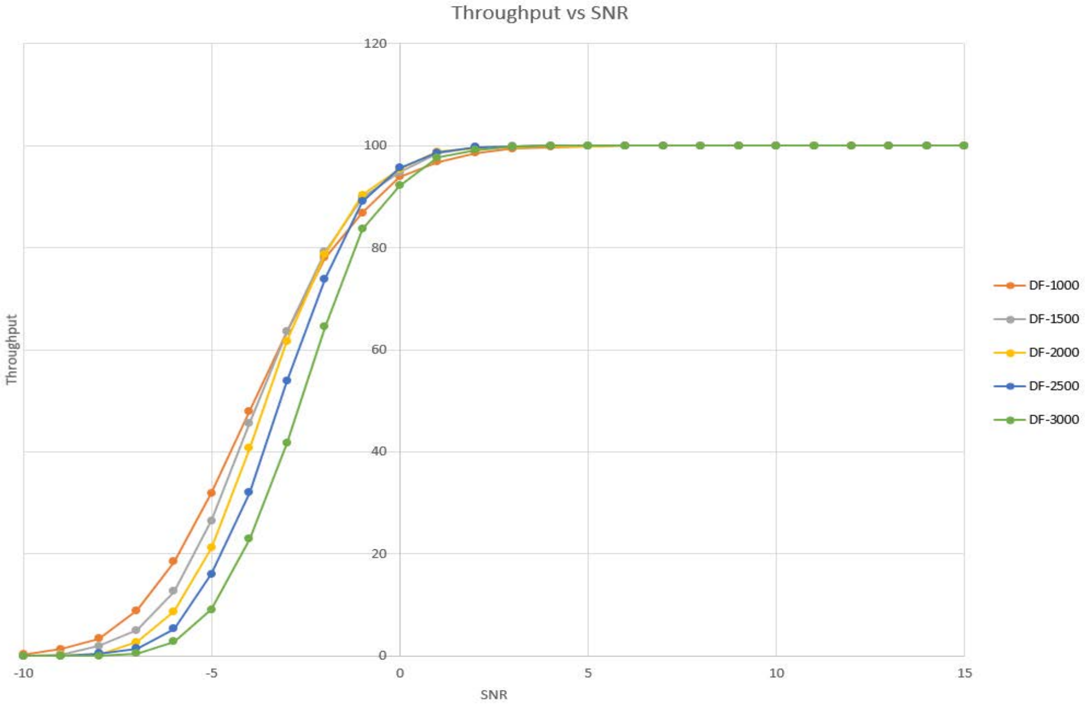


Figure 14 Throughput vs SNR for different Doppler Frequency

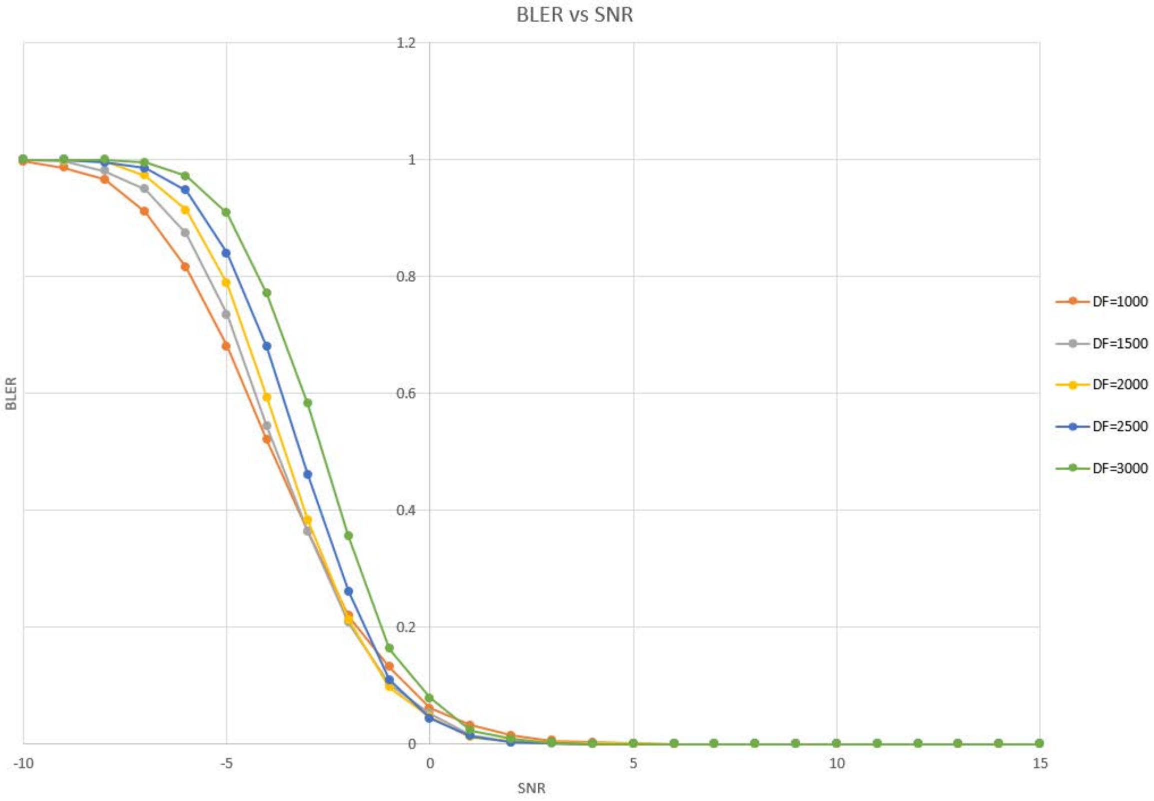


Figure 15 BLER vs SNR for different Doppler Frequency

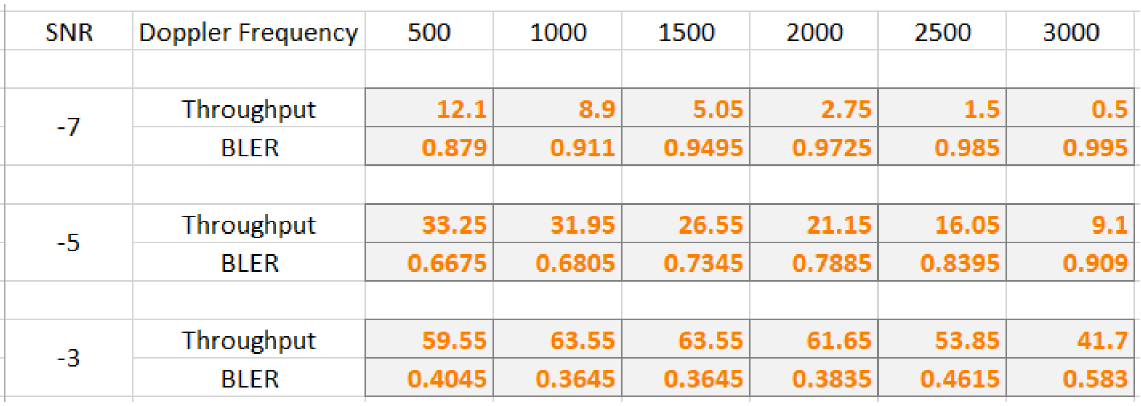
5.3: Performance analysis of Downlink signal

In order to find out by how much the Doppler frequency causes the throughput and BLER to change and better understand their relationship, the data sheets collected is further used to plot graphs of the following:

1) Throughput vs Doppler frequency
2) BLER vs Doppler frequency

SNR values used: -3db, -5db & -7db

The data sets



SNR	Doppler Frequency	500	1000	1500	2000	2500	3000
-7	Throughput	12.1	8.9	5.05	2.75	1.5	0.5
	BLER	0.879	0.911	0.9495	0.9725	0.985	0.995
-5	Throughput	33.25	31.95	26.55	21.15	16.05	9.1
	BLER	0.6675	0.6805	0.7345	0.7885	0.8395	0.909
-3	Throughput	59.55	63.55	63.55	61.65	53.85	41.7
	BLER	0.4045	0.3645	0.3645	0.3835	0.4615	0.583

Table 11: Data sets of SNR vs Doppler Frequency DL

The Plots

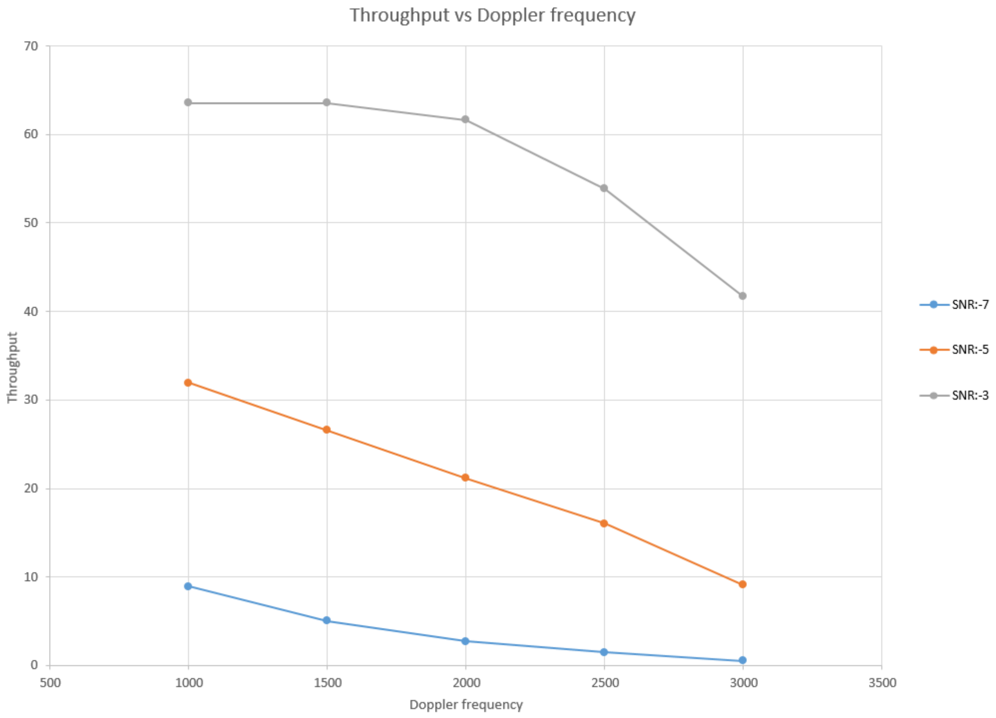


Figure 16 Throughput vs Doppler frequency for different SNR values

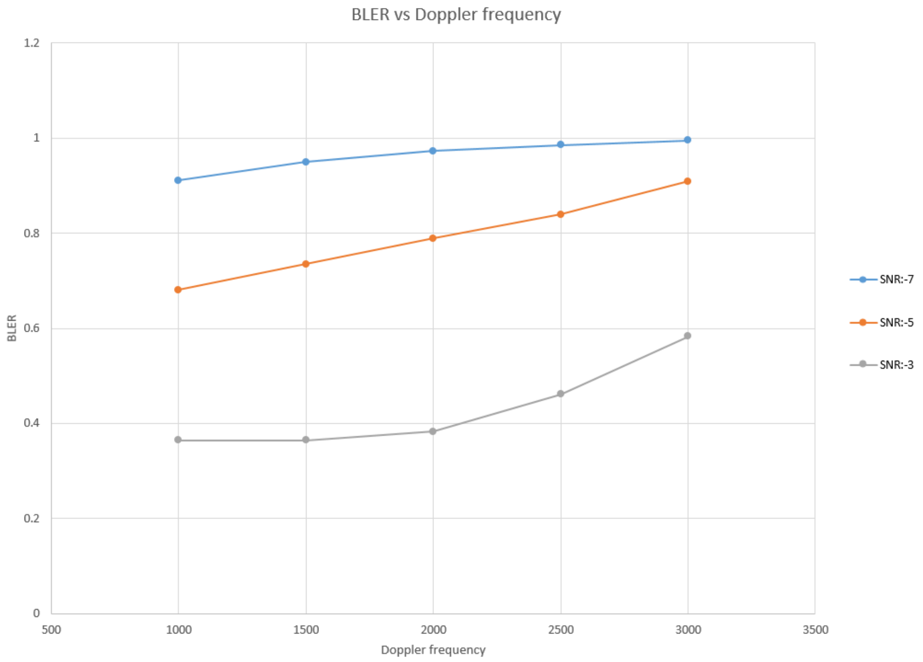


Figure 17 BLER vs Doppler frequency for different SNR values

Chapter 6: Conclusion and Future reference

6.1. Book Summary

Due to increased popularity of IoT devices and applications it is safe to say that in the near future telecommunication engineers will have to accommodate the massive amount of data traffic within the bounds of the limited available radio resources. All the popular Low Power Wide Area Network (LPWAN) discussed earlier, viz SigFox, LoRa, NB-IoT, are developed in an effort to cope with this new era of IoT devices. While SigFox and LoRa operate in the unlicensed band, NB – IoT operates in the licensed spectrum. Thus, it provides a wider network coverage along with other benefits. Furthermore, it can be extrapolated that NB-IoT will engulf the lion share of the IoT market.

Also, one of the primary reasons of the preference of NB IoT is its international standard set by 3GPP. The performance analysis conducted implicates of an underlying problem. For devices that are in mobility, the performance of the signal degrades due to slow fading where signal paths change due to shadowing and obstructions. The results of the performance analysis clearly show the degradation of network due to doppler effect which in turn is linked with the mobility of the device.

In conclusion the adaptive carrier based on channel estimation promises a significant performance enhancement for NB IoT. Cognitive radio theoretically supports this theory. The simulation results not only show the relation between doppler spread and performance of NB IoT but also forges this idea and predicting the extent to which cognitive radio can be used to enhance the performance.

Cognitive radio provides a cutting-edge solution to the problem of spectrum crunch and represents a new paradigm for designing intelligent wireless networks to mitigate the spectrum scarcity problem and provide significant gain in spectrum efficiency. We anticipate that cognitive radio technology will soon emerge from early stage laboratory trials and vertical applications with regard to a theoretical approach and emerge as a multi-purpose spectrum stretching programmable radio that will serve as a universal platform for wireless system development, much like microprocessors have served a similar role for computation. There is however a big gap between having a flexible cognitive radio, effectively a building block, and the large-scale deployment of cognitive radio networks that dynamically optimize spectrum use. Building and deploying a network of cognitive radios is a complex task. Major research themes being pursued include spectrum policy alternatives, system models, and spectrum sensing algorithms, cognitive radio architecture as software abstractions, cooperative wireless communications, DSA technology, Protocol architectures for CRNs (Cognitive Radio Networks), and algorithms for network security for CRNs etc. CRN research must be relatable to the physical world and it is more than important to test the same for real-world situations. Radios work. A CRN research program must develop the tools and techniques to easily move information from field experiments (test beds) to abstract models that confirm to real life issues and move questions from the models to experiments in the field. A range of capabilities such as a flexible physical platform that supports diverse front-ends and a range of programming tools is required. First, experimental platforms are required to gather physical world experience specific to a certain situation and gather measurements in the real-world platform that deploys the cognitive radio technology. Secondly, the arrangement should allow the experiments to be repeated. Third, we need techniques to abstract field experiment measurements into simpler models. This enables us to consider larger CRN systems before extensive deployment.

6.2. Future Plans:

In the future we plan to extend our research and create a prototype of the cognitive radio. In order to completely establish the proposed theories, we have laid a plan.

First, we will need to simulate and carry the performance analysis of the change in doppler frequency with carrier frequencies.

Secondly, we need to start the hardware phase which involves design phase, simulation and finally implementation.

Finally, the prototype should be used to carry the real time performance analysis of the cognitive radio-based carrier adaptation of NB IoT.

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