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TECHNIQUES FOR PLANNING OF THE IOT RADIO NETWORKS
IN INDUSTRIAL ENVIRONMENT

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ABSTRACT

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The Internet of Things (IoT) is very promising concept with a potential to bring an enormous value nearly to all aspects of human's life: from a personal life to a production process. The IoT implies the connection and data exchange of everything to everything through the Internet by using wireless or wired communication links. Successful data transmission and the reliability of communication links will be of great importance for the IoT networks. Particularly, steady and constant connection is vital for industrial sector, where, for example, environmentally dangerous leakages of oil might be prevented by real-time or nearly real-time infrastructure condition monitoring. Within a framework of this thesis, the usage of wireless links for providing the IoT devices with a radio access to the Internet in industrial environment has been studied. Thesis work proposes methodology of the IoT radio networks planning, it describes the main milestones and matters to pay attention to during this process. Besides, thesis work proposes a novel algorithm for automatic radio network planning, that can be applied for ensuring robust and reliable wireless connection between the IoT devices and the global network.

PREFACE

A Master's degree is not an easy path to take, but I'm glad I did it. I have got a lot of experience and valuable knowledge during the studies. Finally, it is time for Master's thesis - a milestone both in the studies and in my life. This thesis work is a drop in the ocean of the research in Information Technology field. However, this drop is there and I'm proud of that. I believe, the results of this work can be used for further studies and research thus making a difference and making our world a better place to leave in.

This work would not have been possible without support and guidance that I have got during the studies and thesis writing. I'd like to express the deepest gratitude to Prof. Evgeny Kucheryavy for supporting and advising me, for the opportunity to work with his team and being an examiner of my thesis work. I'm very grateful to Dr. Alexander Pyatt-aeV for his expert guidance, for his ability to find right words to make me work and thus excel myself, and for all the knowledge that I have got from him. Besides, I'm very thankful to him for the believing in me and giving me the opportunity to contribute in the research field. I also wish to express my gratitude to Aleksandr Ometov for his attentiveness and help.

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The process of Master's thesis writing was a strength test for my loved ones and for myself. I'm extremely grateful to my fiancé for his immense support and infinite patience. I'm glad that he has not change his mind and is still going to marry me. I'm very grateful to Nadezhda Sharatunova and her husband for the time they spent supporting me. I'd like to thank Galina Karnaukhova and Olesya Komashinskaya for urging me take breaks and for making me think about something pleasant during the time I was struggling with my thesis.

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This thesis work is dedicated to my family: Maria, Vladimir, Elena and Yulia.

Tampere, 22.05.2018
Anastasiia Voropaeva

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LIST OF SYMBOLS AND ABBREVIATIONS

IoT	The Internet of Things
IEEE	Institute of Electrical and Electronics Engineers
ICC	International Conference on Communications
D2D	Device-to-Device communication
ITU	International Telecommunication Union
RFID	Radio-frequency identification
IP	Internet Protocol
IPv6	Internet Protocol version 6
IPv4	Internet Protocol version 4
EPC	Electronic product code
uCode	Ubiquitous codes
URI	Uniform Resource Identifier
LTE	Long-Term Evolution
LoWPAN	Low-Power Wireless Personal Area Networks
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Networks.
OS	Operational System
RTOS	Real-time Operating System
RDF	Resource Description Framework
OWL	Web Ontology Language
MIMO	Multiple-Input Multiple-Output
LTE-A	LTE Advanced
BLE	Bluetooth Low Energy
NFC	Near-Field Communication
VSAT	Very Small Aperture Terminal
LPWAN	Low-power Wide Access Networks
GDP	Gross Domestic Product
V2V	Vehicle-to-Vehicle communication
V2I	Vehicle-to-Infrastructure communication
WiMAX	Worldwide Interoperability for Microwave Access
WAVE	Wireless Access in Vehicular Environments
DSRC	Dedicated Short Range Communication
EMR	Electronic Medical Record system
R&D	Research and Development
WSN	Wireless Sensor Network
M2M	Machine-to-Machine
SINR	Signal-to-Interference-plus-Noise Ratio
GSCM	Geometry-based Stochastic Channel Model
LOS	Line-of-Sight
NLOS	Non-line-of-Sight
IMT	International Mobile Telecommunications
AOA	Angle of Arrival
AOD	Angle of Departure
LS	Large-Scale parameter
SS	Small-Scale parameter
UMa	Urban macro-cell scenario
SMa	Suburban macro-cell scenario
UMi	Microcellular scenario

InH	Indoor scenario
RMa	High speed scenario
BS	Base Station
UT	User Terminal
DS	Delay Spread
AS	Angular Spread
SF	Shadow Fading
PL	Path Loss
RNP	Radio Network Planning
SON	Self-Organized Networks
TX	Transmitter
CDF	Cumulative Distribution Function
PDF	Probability Density Function
DSSS	Direct Sequence Spread Spectrum

1. INTRODUCTION

Our society becomes more and more technological. Innovative technologies continuously penetrate our life and affect all aspects of it. Sensors, actuators and smart devices could be met everywhere: in daily life, entertainment, transportation, retail, production, and industry. Nowadays, the trend is to connect anything to anything from a pet at home to a production line or even a city, to monitor things continually, to collect and deeply analyze obtained data. That brings up *the concept of the Internet of Things (IoT), which will be briefly discussed in this thesis*. The IoT allows continuous monitoring and interconnecting of many devices which, in turn, allow making proactive decisions, preventing unwanted situations and bringing new services and experiences to customers. For industries and production, the concept of constant monitoring, controlling and analyzing facilities becomes vitally important, because it provides the possibility to immediately react to an accident, to mitigate an effect of an accident or even to prevent it. Few different use cases will be described in the thesis, but *the significant part of the thesis is devoted to the industrial environment only*.

Most of the IoT applications require wireless connectivity to the Internet. This *thesis work studies main communication technologies that provide the IoT devices with a radio access to the Internet*. For some scenarios, like industrial automation, reliable and robust radio access to the Internet is hugely critical. Therefore, the process of the IoT radio part planning plays a vital role in the IoT networks implementation. Within a framework of this thesis, *a novel IoT radio network planning algorithm was designed* addressing a pure industrial and practical problem, example of which is the IoT radio planning on a refinery. Studied case can be formulated as follows: an oil refinery plans to install thousands of sensors along all pipes installed within a certain area; the task is to provide radio access to the sensors using conventional cellular network; number of base stations should be minimized, and the best possible base station locations should be determined within a reasonable time. Conventional way of radio planning implies a manual selection of base station locations, that might not provide an optimal solution. Besides, manual radio planning requires significant amount of time and human resources. Whereas, an automated tool or algorithm allow finding an optimal or near optimal solution with less resources. Thesis work proposes an automated algorithm and describes methodology which allows to solve the problem, described above or similar, and perform the IoT radio network plan in industrial environment.

Created automatized tool allows finding the locations of base stations in the predefined environment and based on predefined criteria. The proposed methodology is based on a greedy heuristic algorithm with Monte Carlo method elements and with quadratic computational complexity. Within a framework of this thesis, the algorithm is meant to be applied for the deployments of sizes 2000m x 2000m and less (the limitation comes from the applied propagation model) with convex obstacles modeled in 2d space. A maximum number of base stations is limited only by the computational time requirements, not by the algorithm. In the coming years the need in automatized tools capable of providing results will grow dramatically. They can be applied for solving engineering tasks, as one mentioned above, without requiring manual work. Moreover, the technique described in the thesis highlights the main steps and information that should be considered when planning IoT networks in an industrial environment.

The thesis is organized as follows.

1. *Introduction* provides the motivation behind the research and main objectives of conducted work. Chapter 1 describes the thesis content and its structure.
2. *The IoT concept and applications* describes the concept of the IoT, possible use cases and the IoT enabling technologies. Chapter 2 describes radio communication technologies that might be utilized by the IoT devices for accessing the Internet. Historical overview is discussed in this Chapter as well.
3. Methodology of the *Implementation of the IoT in industrial environment* process is reviewed in this Chapter 3. The process of radio network planning and the corresponding challenges for the environment of interest are described in this Chapter. Besides, detailed description of applied propagation model and the proposed automated radio network planning algorithm is given.
4. *Performance evaluation* is conducted in Chapter 4. Performance of the algorithm is discussed. Basic metrics used for evaluation and their prioritization are explained in this Chapter as well.
5. *Conclusion* gives a short overview of the results with the corresponding benefits brought by the developed algorithm. Besides, it provides potential enhancement of the algorithm and scope for future work.

2. THE IOT CONCEPT AND APPLICATIONS

In this Chapter, a brief historical overview of technologies that lead to the emergence of the Internet of Things (IoT) concept is made. The evolution of these networks is explained. In addition to that, possible use cases of IoT concept and applications are defined. The main challenges of IoT implementation in different environments are discussed as well.

2.1 The IoT Concept

Wireless communication is an integral and essential part of human's life. Nowadays, it is difficult to imagine daily routine without wireless networks. They are used for communication, for entertainment, in emergency situations, and so on. The need for such devices as smartphones, sensors, etc. will grow significantly in the upcoming 5th generation of mobile networks [1]. New concepts of communication and pioneering technologies, such as the Internet of Things, Device-to-Device Communication (D2D) and heterogeneous networks require well-built network infrastructure, either wireless or wired, with specific performance characteristics, such as capacity, latency, minimum received power level and other. Network infrastructure should be planned according to continuously growing number of devices and technologies that will use this infrastructure. Because of that, new network planning techniques and methodologies should be applied to cover future communication principles and technologies.

The IoT is a network for the information society, enabling connectivity and data exchange between different physical devices, such as home appliances and sensors or vehicles by means of different communication technologies [2]. The International Telecommunication Union (ITU) does not specify the exact devices in the documentation. There, term "thing" is used to define the IoT. Assuming, that any thing can be connected and thus be used in the data exchange either between human to human, or thing to thing, or human to the thing. In order to achieve the communications, these devices should be equipped with electronics, software, and the last but not the least they should be connected to the Internet either directly or via a gateway. Depending on the scenario, data exchange can be provided through various communication systems. For instance, home appliances can be connected to a wired network. However, the usage of wireless networks is more efficient concerning the installation costs.

2.1.1 Definition of the IoT

In the era of the IoT and Big Data everything is expected to be interconnected and the information exchange should take place starting from a person to a smart kettle in a kitchen. The collected data can be utilized in all aspects of our life: in medicine, production, entertainment and so on and so forth.

The Internet of Things implies the communication and sharing the information between objects of all types and sizes such as vehicles, home appliances, computers, buildings, different sensors, animals, people, plants, different virtual objects, etc. (see Figure 1) [3]. Basically, any physical objects that come to mind can be included in the IoT network and further utilized for the data sharing and collection. Evidently, these objects should be embedded with capabilities of communication and identification, with electronics, sensors, actuators, and software [2]. The IoT suggests that all items can be sensed and controlled via telecommunication infrastructure, so that they are able to interact and cooperate with each other.

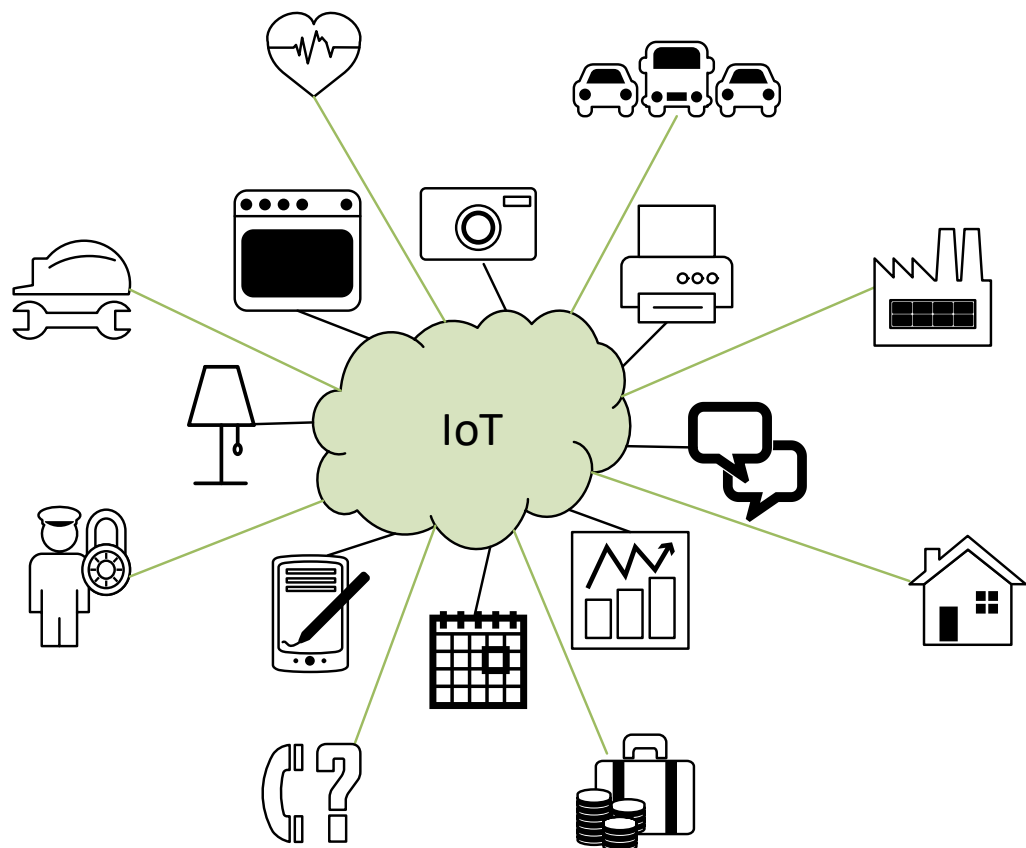


Figure 1. The IoT concept.

Work [2] defines different endpoints whereas the exchange of the information may occur in the IoT network. The most intuitive one is *computer to computer* communication. The

next one, but not least evident is an interaction between a *thing to human*. For example, positioning and physical activity tracking are already widely used nowadays. In that case, sensors track the person's activity overtime and then provide a statistical report showing, for instance, how many steps were done during a particular day.

The next case is the communication *between a thing to a thing* without a person as an intermediary. As an example of this communication type: smart lighting systems in open spaces, such as factories, offices, etc. Based on the time of the day, settings and requirements these systems adjust the light level when and where it is required. For instance, in a big open space with just one person working, the light is needed only near the corresponding table, but not in the entire office. These systems allow to decrease the energy consumption [4]. Interestingly, the ITU defines *human to human* communication not using a computer as the IoT network as well [2]. Strictly speaking, if we consider human as an object capable of being sensed and actuated and able to communicate, the connection between these two objects indeed can be considered as the IoT network.

The IoT is a revolutionary concept of the Internet evolution. It refers to the idea that everything can be reached, connected, identified and addressable anytime and anyplace [5]. Schematic representation of the IoT concept is shown on the Figure 2. This is an example of a thing to human communication, where human can get extra knowledge based on the data collected from the objects and thus make a difference. Regularly gathered, monitored and analyzed data can bring enormous value to various planning processes and administration [6].

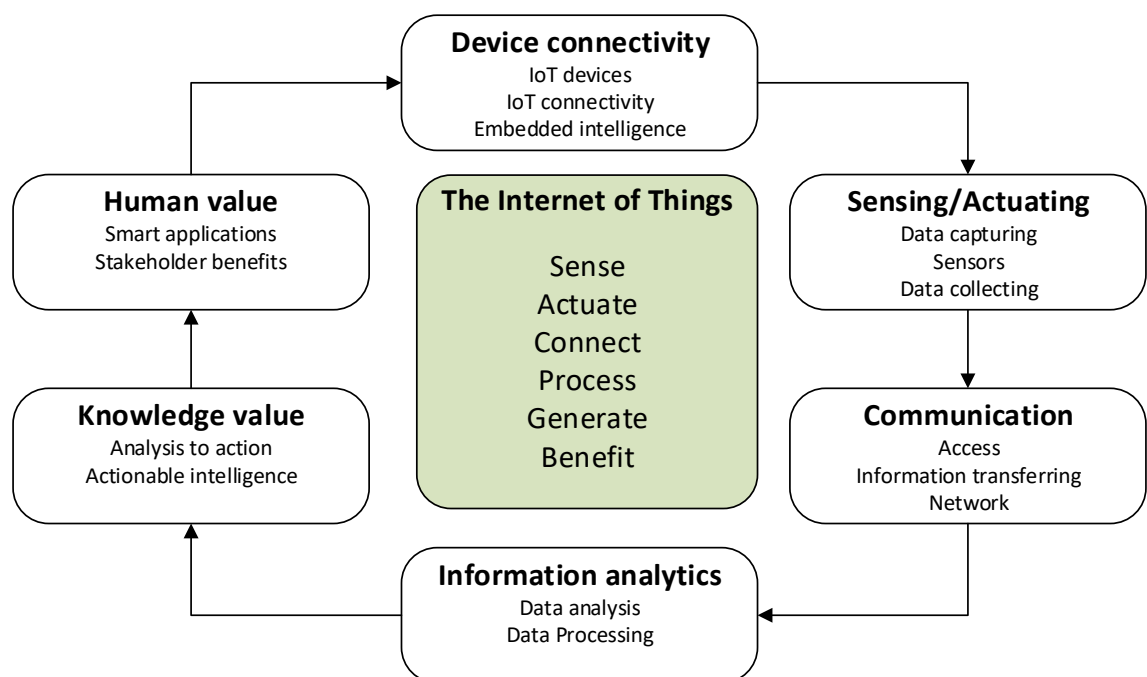


Figure 2. The IoT cycle [7].

2.1.2 Fundamental characteristics and requirements of the IoT

As it was stated earlier, the IoT is a concept, not a technology. All things are supposed to be connected via various technologies, thus bringing up unique characteristics and requirements to the IoT network itself and the IoT devices [2].

The primary characteristic is *connectivity* [5]. In order to reach anything anywhere any-time, the IoT devices should have access to telecommunication networks continuously. Consequently, the next trait is *interconnectivity*. The IoT implies that every thing and every object can be reached and sensed via global communication infrastructure. Notably, many different networks, technologies, software and hardware platforms are utilized to transfer the information in the global communication infrastructure. It leads us to the following characteristic of the IoT network – to *heterogeneity*. Even though all devices might be based on different platforms, they still should be capable of interacting with each other. Besides, the heterogeneity of the IoT network make ubiquitous IoT services a reality.

With rapid and continuous growth of the number of objects connected to IoT network, there are still more objects to be connected [8]. Thus, one of the features of IoT network should be a capability of handling *enormous scale* of connected things. Moreover, these things or devices might be mobile, their state might change dynamically from sleep to connected mode, etc. This promotes that the IoT network should be very flexible and *dynamic*.

According to [2] the following requirements should be met in the IoT:

- a unique identifier for every “thing”;
- interoperability between heterogeneous and distributed systems;
- automatic networking in control functions of the IoT;
- capability of positioning of the devices;
- security;
- privacy protection;
- seamless integration and cooperation of connected things;
- manageability.

2.2 History of the IoT

The concept of connected things raised right after the birth of the Internet in 1991. The first application of that kind was Trojan Room coffee pot, camera installed in front of the coffee pot was translating the image of the pot to the monitors of the employees and was showing if it is full of coffee or not [9]. Though, it was not the first smart device, as a modified Coke machine at Carnegie Mellon University was. This machine was able to

report its status and the information about the coldness of the drinks. In 1990 the first pure the Internet connected device was created by John Romkey. That was a toaster, that could be switched on and off via the Internet. In 1994 the first “near-real-time” wearable camera was created by Steve Mann [10]. Starting from 1999 the Auto-ID Center at Massachusetts Institute of Technology and some market-analysis publications the concept of the IoT became popular. With the invention of radio-frequency identification (RFID) in 1999, RFID-based systems have been widely used in civil and military areas. In 2008 the IPSO Alliance was established to promote the use of Internet protocol (IP) together with smart objects to enable the IoT. Later, IPv6 triggered rapid growth of interest in this area. Nowadays, the IoT is a very hot topic, such giants as Cisco, IBM, Nokia, etc. make a lot of research and implementations of the IoT networks.

Sensor networks might be considered as a predecessor and a base for the IoT networks. With the evolution of the technologies, the requirement to and the understanding of how sensor networks should work changed. Nowadays, in addition to the measuring and sharing the data, these networks are expected to be self-aware, self-organized and to have context-awareness. In the nearest future, the IoT networks are expected to be cognition, self-learning and self-organized [11]. From the hardware perspective, RFID tags and sensors built into mobile devices are evolving towards more secure and low-cost tags, and to smarter and smaller sensors or actuators. Knowledge from such areas as biochemistry, nanotechnology and new materials will be used in the 2020s to create hardware for the IoT networks.

With a great potential of the IoT technology and its heterogeneity, the growth and the development of the concept look endless. These networks will be integrated in our everyday life faster and faster, because the benefits that they bring are remarkable and, in some areas, immediately measurable.

2.3 Architecture and Enabling technologies of the IoT

To list enabling technologies for the IoT, first we need to understand the logical architecture of the network and classify the main components required to deliver functionality of the IoT [12].

The primary architecture is presented by three different layers: application layer, network layer and perception layer. Sensing devices connected to the IoT network and sharing the data are related to the perception layer [13]. The data is shared via the network layer represented by various wireless and wired communication technologies. Network layer connects perception layer with the application layer. Application layer receives all the collected data, analyzes and post-processes it and then, after making decisions, sends the result and feedbacks back to the perception layer via network layer.

The above described architecture of the IoT network is rather basic does not provide detailed enough understanding of the system operation. Figure 3 describes more detailed architecture of the network, consisting of few building elements. Here, perception layer is represented by identification and sensing elements, network layer is linked with communication element, application layer includes computation element, services and semantics.



Figure 3. Buildings elements of the IoT.

Based on fundamental characteristics and considering the requirements imposed for the IoT networks, the first element is *identification* and *addressing*. There are different identification methods available for the IoT such as RFID tags, electronic product code (EPC) and ubiquitous codes (uCode) [14]. Besides, the newest suggestion is to identify things in the network by IP address or Uniform Resource Identifier (URI). Addressing is done through IP technology, IPv4 can be used, but due to the limited address space of IPv4, IPv6 solution is preferable. Additionally, for low power wireless devices IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) compression mechanism can be used, which reduces the configuration overhead.

The next element is *sensing* or data gathering by sensors, actuators and other sensor-like devices. The collected data is transferred to the server/cloud for further processing and analysis. For example, some mobile applications that allow people to monitor and control the IoT devices have been available on the market for more than a decade already [15].

As it was stated above, the IoT devices should be connected to a network all the time to be reachable and capable of the data sharing. Therefore, telecommunication technologies providing the Internet access have vital importance for the IoT networks. That brings up the next element of the IoT logical architecture – *communications*. The Internet access can be granted by wired or wireless technologies. Wired technologies such as Ethernet-based systems have been in use for a long time providing reliable and guaranteed connection. However, wireless technologies are considered as more promising due to the flexibility of the deployment and ease of the maintenance [16]. The type of wireless technologies utilized for the IoT networks depends on the range of the communication link being either short-, medium-, or long-range. Communication technologies from Table 1 will be described in detail in Chapter 2.4.

The next step after receiving the data on the network side is processing of the collected raw data, which is of vital importance for the IoT applications. *Computation* unit allows

to manage and control the network thus providing the IoT functionality. There are big number of hardware platforms to be utilized such as Arduino, Intel Galileo, Raspberry Pi, WiSense, etc. Naturally, only certain software can be utilized in IoT due to the limitations of complexity, energy consumption, real time support, etc. Development of the software suitable for the IoT networks is rather trending topic. Different operational systems (OS) are being designed for the IoT needs, such as LiteOS [17], TinyOS [18], Riot OS [19]; various Real-time Operating System (RTOS) such as Contiki RTOS [20]. Because of the vast number of the IoT devices, capacity of the commonly used hardware and capabilities of the software are still limited. Colossal number of physical objects that might be connected to the IoT network and sharing the data generates so called “Big Data” paradigm, which requires efficient storage and smart post processing. Cloud-assistant IoT is an auspicious solution to data growing problem [21].

The whole concept of IoT emerged to provide various revolutionary *services* to people, business, and society in whole. There are plenty of possible scenarios such as smart houses, buildings and cities, smart healthcare, intelligent transportation systems, industrial automation, etc. The utilization of IoT is a hot topic nowadays, new ideas of how to use this concept appear all the time. The IoT services will be discussed in detail in Chapter 2.5.

Heterogeneity and the number of connected devices are the main features of the IoT concept and, at the same time, the key issues for the data post processing. Data types collected for the need of a particular service might vary a lot, since it might have been collected from different sources and by different technologies. This raw data should be somehow extracting, interpreted and analyzed. *Semantic* part of the network is responsible for this process and its main goal is to provide the developers with a set of interoperable and semantically described data. This is the starting point of the efficient decision-making process creation which would lead to valuable service experience. Such technologies as the Resource Description Framework (RDF) and Web Ontology Language (OWL) are used on this level [22]. The IoT logical elements and technologies used for each layer are shown in the Table 1.

Table 1. *Enabling technologies for the IoT.*

The IoT element		Technologies
Identification	Naming	RFID, uCode, EPC
	Addressing	IPv6, URI
Sensing		Sensors, actuators
Wireless communication	Short-range	Bluetooth Low energy (BLE), Li-Fi, NFC, Wi-Fi, Wi-Fi Direct, Z-wave, ZigBee
	Medium-range	Wi-Fi HaLow, LTE-Advanced (LTE-A)
	Long-range	LPWAN, VSAT
Wired communication		Ethernet, MoCA, PLC
Computation	Hardware	Arduino, BeagleBone, Cubieboard, Gadgeteer, Intel Galileo, Phidgets, Raspberry Pi, Smart Phones, SmartThings
	Software	Various OS, Cloud
Service		Various IoT applications
Semantic		RDF, OWL, etc.

2.4 The IoT communication technologies

This thesis work is devoted to the radio part of the IoT networks. Therefore, only wireless communication technologies from the above Table 1 will be examined in this Chapter. The IoT applications can be built based on various long-range or short-range wireless technologies. The capabilities and behavior of the wireless networks may vary depending on the data rate, bandwidth, network size, power consumption and coverage areas. For example, some of the applications are extremely demanding from power-consumption perspective of the radio module. Therefore, in case of short-range communication, BLE might be more beneficial than, for example Wi-Fi. Consequently, for each IoT application appropriate wireless communication technology should be carefully chosen.

One of the dominant candidates for indoor broadband wireless access is IEEE 802.11 standard based *Wi-Fi*, which is widely used nowadays. Wi-Fi devices connected to an access point can form a star topology with an access point acting as a gateway to the Internet. Wi-Fi operates in 2.4 GHz and 5 GHz unlicensed bands, providing more channels and higher data rates on the upper band. However, operating on lower frequency provides better coverage. IEEE 802.11n has introduced the utilization of Multiple-Input Multiple-Output (MIMO) technology, that supports throughput from 54 Mbit/s up to 600 Mbit/s [23]. IEEE 802.11ac supports higher modulation up to QAM-256 and wider radio channel bandwidth (up to 160 MHz) in 5GHz band.

Controversially, IEEE 802.11ah introduced so called *Wi-Fi HaLow* protocol in 2017 standard. It uses lower frequency band 900 MHz in order to provide extended operational

range of up to 1km outdoor, while conventional 802.11 are expected to operate on distances no longer than tens of meters indoor. Wi-Fi HaLow also benefits from low power consumption but in tradeoff with lower throughput from 100 Kbit/s to 40 Mbit/s [24]. IEEE 802.11ah supports 8191 devices per one access point [25]. Wi-Fi HaLow is also compatible with previous Wi-Fi standards [26]. One more Wi-Fi family standard IEEE 802.11af also called “White-Wi-Fi” or “Super-Wi-Fi” uses licensed (unlike other standards from the family) bands between 54 and 790 MHz providing extended coverage with data rates up to 24 Mbit/s [27].

Bluetooth Low Energy (BLE) is an enhanced version of classic Bluetooth technology. BLE is optimized for short burst data transmission which is ideal for some IoT applications. It operates at the same band as Bluetooth at 2.4 GHz, but consumes much less energy. Data rates supported by BLE are from 125 Kbit/s to 2 Mbit/s [28] and the range is up to 100 m in open space. In the nearest future, more than 90% of smartphones will be equipped with BLE modules, making majority of wearable and smart devices easily integrable with smartphones. Mobile phones also can act as gateways to the Internet.

ZigBee Smart is a new IEEE 802.15.4-based protocol for short-range low-power devices, that relies on ZigBee IP and 6LoWPAN. ZigBee IP routes IPv6 traffic over IEEE 802.15.4 using 6LoWPAN header compression method, that was developed for low-power devices with limited processing capabilities [29]. ZigBee works at 2.4 GHz band and offers data rates from 20 Kbit/s to 250 Kbit/s and supports up to 65000 nodes in a star topology.

Technologies described above (Wi-Fi HaLow, BLE, ZigBee Smart) are candidates for short-range IoT applications such as smart home or smart health. However, these types of the communication networks might be unfeasible in some other IoT use cases such as Smart City, where devices require to transmit information over the long distances from indoor or outdoor, that requires quite robust connection link. For that kind of application *Low Power Wide Area Networks (LPWAN)* were introduced. They are designed for long-range, low bit rate and low power devices. It worth mentioning, that while ZigBee and Wi-Fi networks can be extended by using mesh technologies and thus producing additional signaling overhead, LPWAN provides sufficient coverage by itself. The LPWAN bit rates are from 0.3 Kbit/s to 50 Kbit/s per channel [30]. One of the most promising technologies is *LoRaWAN*, the physical layer of which is also known as *LoRa*. It is expected that a single LoRaWAN gateway can collect data from thousands of devices deployed kilometers away similarly to that of cellular networks. However, unlike cellular networks, LoRaWAN is designed for low data rates and offers maximum data rate of 27 Kbit/s (50 Kbit/s when using FSK instead of LoRa). LoRa supports adaptive data rate scheme as well, allowing to optimize power consumption of the devices according to the application requirements.

The conventional cellular networks, such as GSM, LTE or LTE-A, can also be utilized for IoT applications providing high data rates at long-range distances. Cellular networks can support large number of devices as well. However, they are not optimized for power consumption sensitive IoT devices. Besides, cellular networks are overwhelmed with the number of mobile users, introduction of enormous number of new devices, even low-rate, will have a big impact on the current customer's experience.

The comparison between described above technologies is given in the Figure 4 [31]. LTE and conventional Wi-Fi are the most power consuming technologies compared to NFC, BLE, Wi-Fi HaLow and LoRA. From the coverage perspective, LoRa and LTE do not have any competitors at this point, which makes them the most suitable candidates for Smart City application. Conventional Wi-Fi features the highest bit rate with short-range coverage and high energy requirements. This technology might be suitable for smart home application, where all the sensors might be connected to electrical network.

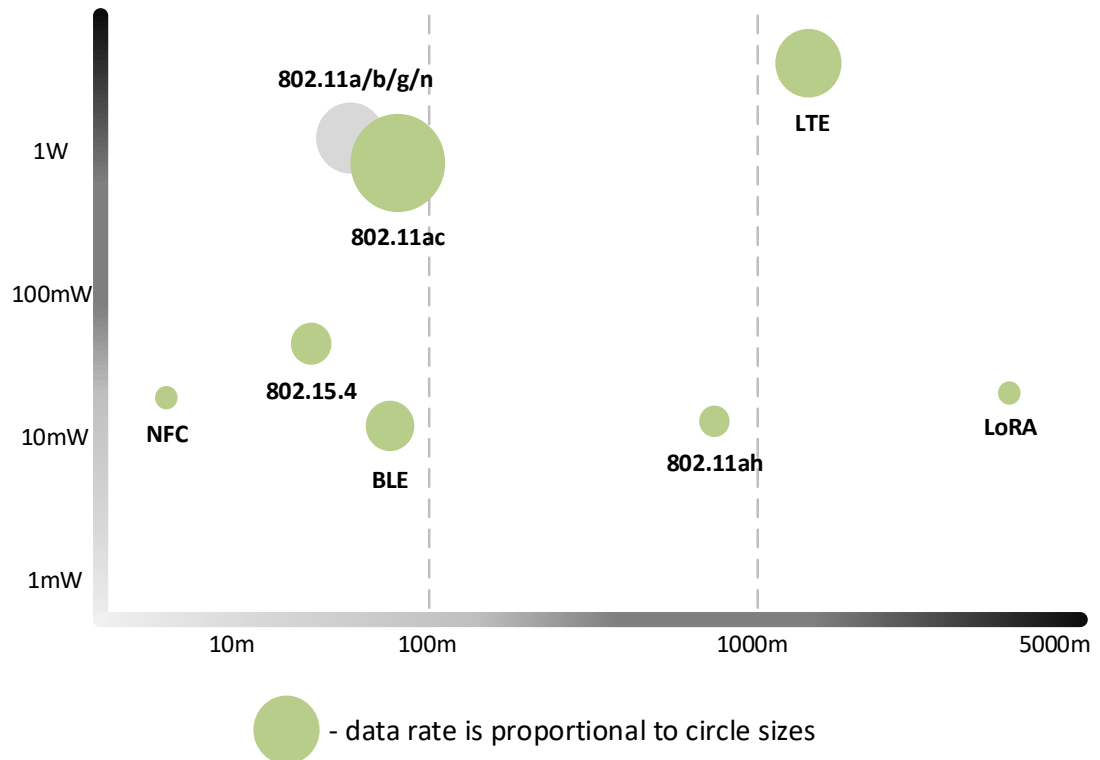


Figure 4. Technologies vs IoT requirements.

Each of the described above technologies brings a value to certain applications. For example, Wi-Fi is mostly suitable up to 150m range use cases, such as video and monitoring based smart home applications. Bluetooth is applicable for short range scenarios (10-100m) such as smartphone-based applications, indoor positioning, etc. ZigBee can be used on longer distance (up to 300m) thus enabling applications as smart energy, home

and building automation, retail services, etc. NFC devices are for very short ranges and for personal use cases, such as smart wearable.

2.5 The IoT applications

The IoT applications are numerous and diverse, existing in almost all business and areas of every day's life. The IoT applications refer to "smart" solutions in such domains as agriculture, urban communications, culture and tourism, emergency, environment, energetics, healthcare, logistics, transportation, user communication, etc. In this Chapter, the main applications of interest are described.

2.5.1 Smart cities

Migration to urban areas in majority of countries all over the world. According to the report by the United Nations Population Fund more than half of the world's population (around 3.5 billion people) lives in cities. The forecast is that within 35 years, two out of three people will live in urban areas [32]. That's why smart planning of the city services and facilities is a question of great importance for future inhabitants.

The main purpose of the Smart City scenario is to improve the quality of the services offered to city dwellers and to use public resources more efficiently while reducing the operational costs and losses. This is achieved by deploying the IoT networks: an infrastructure that provides an access to the public services data, thus making the entire cycle transparent for citizens. Smart city incorporates the following elements [33]:

- smart governance (e.g. public and social services, transparent governance);
- smart economy (e.g. flexibility of labor market, entrepreneurship);
- smart mobility (e.g. sustainability of the transport system, accessibility);
- smart environment (e.g. resource management, ecological awareness);
- smart living (e.g. cultural facilities, touristic attractiveness).

Table 2 describes the main services of a smart city and their characteristics.

Table 2. City services and their technical characteristics in IoT environment re

Service	Communication networks	Traffic rate	Tolerance delay	Energy Source
Structural health	802.15.4, Wi-Fi, Ethernet	1 every 10 min per device	30 min for data, 10s for alarms	Batteries
Waste management	Wi-Fi, 3G and 4G	1 every 10 min per device	30 min for data	Batteries, energy harvesters
Air quality monitoring	802.15.4, Bluetooth, Wi-Fi	1 every 30 min per device	5 min for data	Photovoltaic elements
Traffic congestion	802.15.4, Wi-Fi, Ethernet	1 every 10 min per device	5 min for data	Batteries, energy harvesters
City energy consumption	PLC, Ethernet	1 every 10 min per device	5 min for data	Mains powered
Smart parking	802.15.4, Ethernet	On demand	1 min	Energy harvesters
Smart lighting	802.15.4, Wi-Fi, Ethernet	On demand	1 min	Mains powered
Automation of public buildings	802.15.4, Wi-Fi, Ethernet	1 every 10 min per device	5 min for data	Battery, mains powered
Noise monitoring	802.15.4, Ethernet	1 every 10 min per device	5 min for data, 10s for alarms	Batteries, energy harvesters

2.5.2 Intelligent transportation systems

The performance of the transportation infrastructure is of vital importance for our mobility, wellbeing, economic growth and our society in general. Nowadays, people face more traffic jams, parking difficulties, car accidents, safety and efficiency issues of transportation systems. According to [34], USA economy loses more than 101 billion dollars every year in this field, the UE losses about two percent of its Gross Domestic Product (GDP) due to the traffic congestions. Over 1.3 million people are killed and more than 50 million are injured in road crashes, causing over 65 billion dollars are lost because of the traffic accidents in some countries. In the future, these numbers are expected to increase with the growth of the population.

As it has been proven by the experience, building new roads and extending existing ones do not resolve the traffic congestion issues. Instead, sustainable and intelligent transportation system should be developed and implemented. The IoT networks with advanced

communication technologies and computing capabilities can assist in providing smart management and administration of transportation infrastructure. There is a number of intelligent systems that have been operating in transportation systems on their own. The concepts of the IoT implies that all already existing systems need to be interconnected and emerged seamlessly in one big heterogeneous network.

Figure 5 depicts how the smart transportation system might look like in a few years. All cars are expected to be equipped with a transmitter thus transferring an information about their location, speed, etc. to other cars and the infrastructure, thus, allowing others to avoid traffic jams; the best route or rerouting during the trip could be improved based on the data collected from other vehicles or from roadside infrastructure units; such features as intelligent speed adaptation are to be used by autonomous cars based on the data from sensors installed within the car, etc. Nowadays, some of these scenarios are separated from each other but in the IoT concept all of them are expected to be interconnected in the cooperative manner. For example, data collected from the vehicle sensors, radars, road infrastructure would allow making intelligent decisions such as dynamic traffic light change, changing the number of lines available in each direction, adding extra trains, etc. [35]. In addition, stored data can be analyzed from drivers' behavior point of view to detect stress levels, mood changes and predict possible road crashes and, subsequently, enable notification to nearby vehicles and drivers about aggressive or dangerous driving allowing them to prevent an accident.

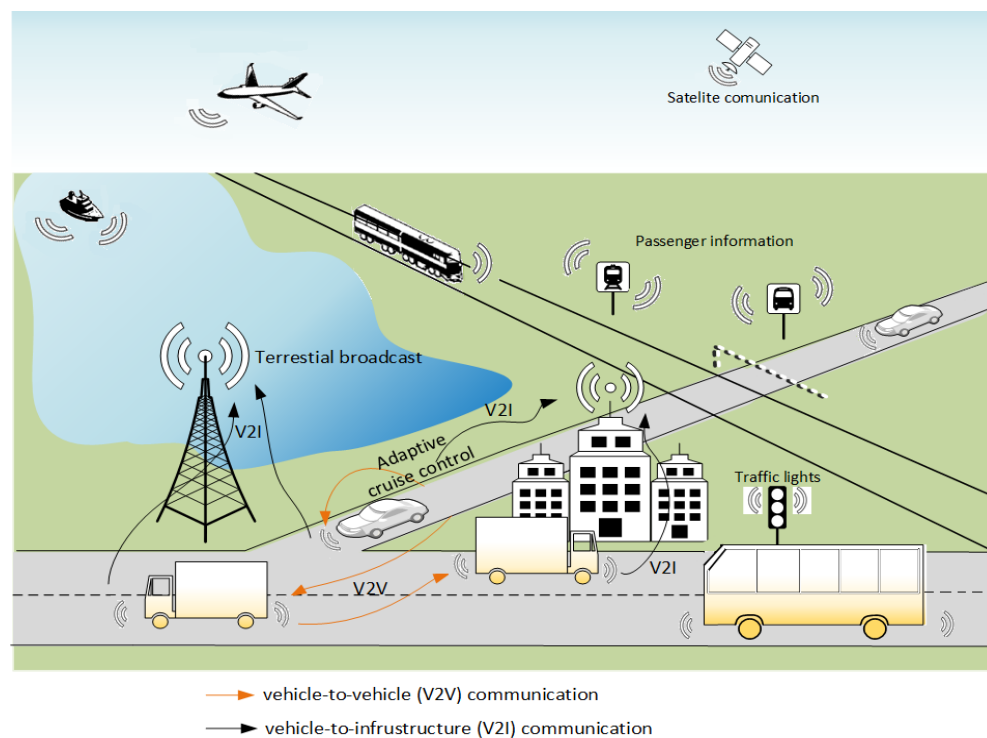


Figure 5. Smart wireless transportation system.

The performance of all described above scenarios depends on the access technologies, collecting and processing capabilities of the network. Communication technologies used for accessing the network include cellular networks, Wi-Fi, Worldwide Interoperability for Microwave Access (WiMAX) and Wireless Access in Vehicular Environments (WAVE). Vehicles with broadband access can communicate with each other via the Internet, vehicles equipped with Dedicated Short-Range Communication (DSRC) module can transfer data in vehicle-to-vehicle (V2V) mode and in vehicle-to-infrastructure (V2I) mode.

2.5.3 Smart healthcare

The IoT network offers a promising solution for delivering outstanding progress in the healthcare area. Proactive health data analysis, anomaly detection, fast and remote diagnostics would allow to improve quality of life and even save human lives. Smart devices will make diagnosis and treatment more effective and personalized since the amount and the quality of the data that can be collected by sensors and wearable devices can show a more detailed picture of what is happening with an individual and adjust treatment plan accordingly. According to IBM report [36], 20% of medical errors are caused by delayed diagnostics and by inaccurate explanation of symptoms by patients, what would have been more difficult with continuous self-monitoring and timely scheduled visit to a doctor. The IoT devices can transfer information in real-time to the patients' and medical staff's smartphones, computers, or any other electronic devices about the state of patient's health and can influence on their behavior.

In addition to the high value that smart healthcare can bring to patients, it also has the potential to transform the industry completely. The emergence of digital healthcare technologies, real-time and remote patient monitoring can make healthcare systems more efficient, accessible and cost-effective [37]. Real-time monitoring and advance home care facilities can significantly cut down on unnecessary visits by doctors, on hospital stays and re-admissions.

Coupling the existing healthcare systems and products with developing ones, making them interconnected, accessible and smart, will make a difference. Figure 6 shows how some of the existing technologies can be merged in one heterogeneous IoT network. Mobile apps and wearable devices can collect the data about abnormalities in the health conditions or in the surrounding environment. Then these data can be stored in, for example, a cloud, making it accessible to medical staff or an individual himself. Electronic medical record (EMR) system can combine and store in one place the data about individuals' health state from the places of every-day activities, such as schools, fitness clubs, home, workplaces, etc. Thus, making it easier for a doctor or a nurse to access the data and make right decisions.

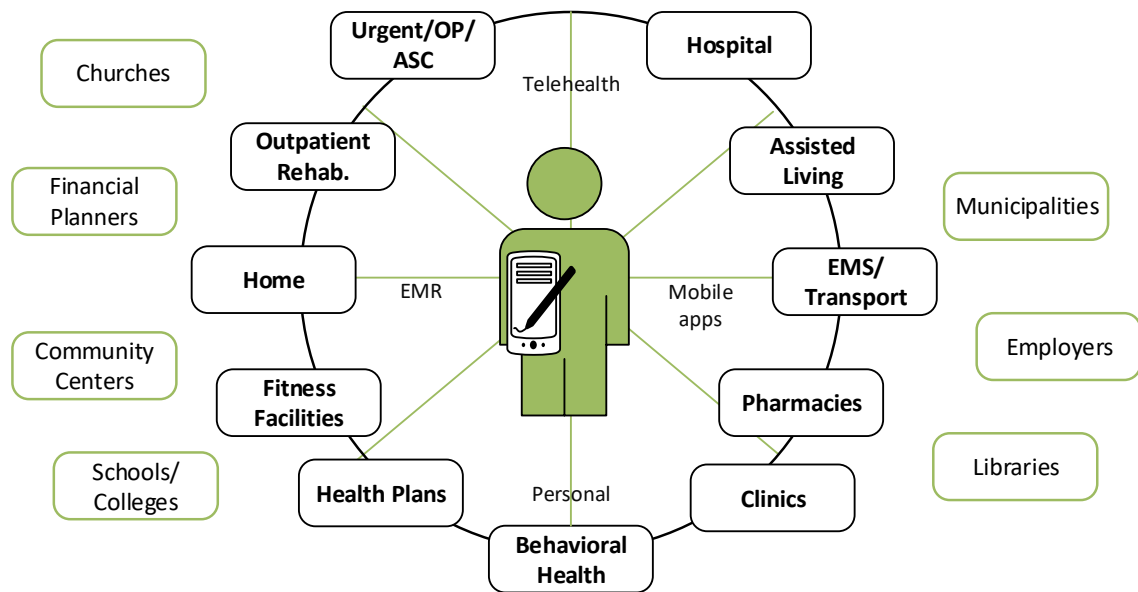


Figure 6. Smart healthcare system.

In addition to above, there are many ways of how the interconnectivity, data exchange and monitoring can be applied to peoples' life to excel health care services:

- fall detection, physical activity monitoring, patients' surveillance for elderly or disabled people living independent;
- sportsmen care;
- chronic disease management;
- hygienic, sleep control;
- dental health.

2.5.4 Smart industry

We are entering the new era of manufacturing, so-called Industry 4.0, with strong digital transformation to unprecedented level of controlling, administration and automatization of manufactures [38]. This is ensured by integrating systems where humans and machines are interconnected and communicating freely with each other via the IoT networks; by decentralization, when machines in a factory are operating independently; by real-time monitoring of the collected data allowing to make decisions instantly and to retrieve immediate insights. Based on the Aberdeen Group research, introducing the IoT to industry will reduce costs of production up to 55%, increase operations speed by 45% and improve product quality by 36%.

The number of industrial IoT applications is vast: monitoring of water, oil and gas levels in storage containers; detection of the gas, oil or chemicals leakages; machine diagnosis, assets control and prediction of equipment malfunctions; temperature, air quality, ozone

level monitoring; remote operating, monitoring and managing of the manufacturing process. The example of the IoT in manufacturing is shown in Figure 7. Evidently, every step of the manufacturing is supposed to be transparent and monitored in real-time with the constant access to the smart meters, sensors and actuators data. Another example use case can be an oil factory, where constant monitoring of the leakages is the question of great importance because of the environmental pollution threats. Because of the remote extraction facilities and number of tanks, the usage of smart devices is necessary. Besides, by collecting, storing and making a predictive analysis of the data from collected from the devices, it will be easier to foresee upcoming problems, to take appropriate and proactive actions.

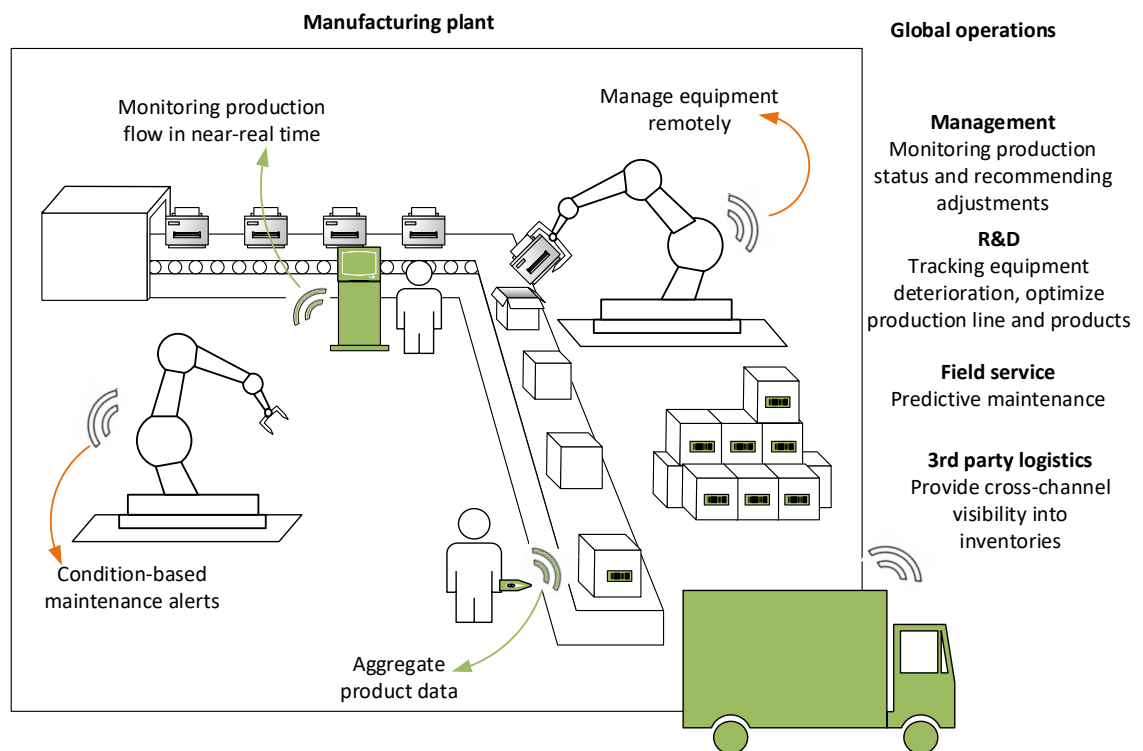


Figure 7. *The IoT in manufacturing [39].*

The IoT networks in factories could also be enabled by such technologies as Wireless sensor network (WSN) and by Machine-to-Machine (M2M) communication with a gateway to the Internet and with identifiable sensors.

As it was stated earlier, this thesis work is devoted to the radio part of the IoT networks and only industrial application is considered. The aspects of the radio network planning specific for this environment will be explained in detail in Chapter 3.

2.5.5 Other applications

Many other IoT concepts could be also considered as a part of big IoT picture, such as smart retail, smart farming, smart grid, environment protection, public security, etc. In case of smart farming and in some use cases of environment protection, because of remoteness and difficulties to reach installed sensors or devices, the IoT network can revolutionize the work and monitoring process. There might be even those applications, that are not possible to imagine at this point.

3. IMPLEMENTATION OF THE IOT RADIO NETWORKS IN INDUSTRIAL ENVIRONMENT

This Chapter is devoted to the planning of the IoT radio networks in an industrial environment and the study case description. Since the industrial environment is a somewhat complicated one for the radio planning, the choice of propagation model for coverage prediction plays a significant role in the reliability of the connection. This Chapter describes propagation models that can be used in such a complex environment. Besides, the Chapter presents the algorithm proposed for radio network planning in the described use case.

3.1 Studied use case

As discussed in Chapter 2.5.4, factory automation will provide great opportunities for the production and manufacturing development. Besides, sensor networks implemented as part of the IoT networks are expected to enable higher level of safety during manufacturing process, proactive reacting on possible alarms, real-time monitoring of the production process or factory facilities, etc.

Based on the number of research [40]- [41], there is a demand on refineries in real-time monitoring and sensing technologies for controlling corrosion which is one of the major challenges in gas and oil industry. The vast expanses of pipelines and metal surfaces are subject to corruptions because of the exposition to harsh temperatures and processing environments continuously. Ultrasonic sensors attached to pipes detecting the smallest changes in pipes' wall thickness is a solution for this challenge. Wirelessly connected, these sensors can be installed even in difficult to access places, thus providing early warning of unexpected corrosion events, before leaks occur, and improving the safety and integrity of the manufacturing facilities.

In described above use case, sensors transmit small amount of data periodically, thus updating the status of the pipes in monitoring system. In case of alarm signal or a threat of a pipe break, a critical message should be send outside the scheduled time and with guarantee of successful message transfer within a short latency period. Meaning, that reliable and stable wireless connection should be provided.

Technologies described in Chapter 2.3 can be used to provide sensors with radio network access. In this use case, such networks as wireless mesh networks, or, for example, widely spread LTE networks are usable. Because of the size of the refinery, sensors can be connected to cellular networks, such as GSM, Wi-Fi, LTE or LPWAN technologies. In this

thesis work, it is assumed, that the refinery is covered by conventional LTE network, thus providing exceptional easiness of deployment.

As it was mentioned above, it is required to provide sensors installed all over the factory with the Internet access through the existing LTE radio. Thus, the very first step is to estimate and predict coverage of the existing network and to understand if it is sufficient for the sensors to have access to the network or not. In case the number of existing LTE base stations is not sufficient, locations of new LTE base stations should be planned taking into account the location of the sensors and existing base stations.

The challenges of coverage prediction and radio channel simulation are described in Chapter 3.2. Propagation model applied for calculations in this thesis is described in Chapter 3.2.2. When coverage of the existing LTE base stations is predicted and received signal levels are checked for every sensor, the next step is to evaluate the coverage based on the predefined requirements. Evaluation can be done, for example, by checking signal-to-interference-plus-noise ratio (SINR) for every sensor and verifying that they are able to transmit when required. Evaluation of the proposed radio plan based on predicted coverage and its impact of the performance of the network is given further in Chapter 4.

3.2 Radio channel model for industrial environment

The robustness, reliability and constant availability are the key characteristics of the communication links in such applications as smart industry. The attention should be paid to the accuracy of radio channel simulation models to predict the performance of communication links. The development of realistic radio channel model is a challenge for radio engineers and researchers. The channel model should precisely and efficiently predict the performance of a radio link. Note, that radio channel model varies depending on the type of the system or technology for which simulations are done. As an example, for different frequencies, simulation model is different. For example, conventional Hata model is applicable only for frequency up to 1500 MHz. In addition to that, prediction of a single-receiver narrowband system can be done taking into account only received power level and fading, but this is not acceptable in case of multi receivers wideband systems [42]. Besides, the environment and the type of base stations plays a big role in the radio channel modeling. Thus, different models should be used for indoor and outdoor, micro and macro deployments.

Industrial environment is very complex in terms of wireless radio links planning [43]. A refinery located in town Schwechat near Vienna, Austria is shown in Figure 8. Indeed, the installation of sensors along all these pipes is not a trivial task. Moreover, providing these devices with a wireless connection is a rather complicated task as well. Radio propagation in industrial environment differs from propagation in office buildings or in outdoor micro

(antennas are installed on the walls of the buildings) deployments, due to various machines and highly reflective materials all over the factory. Large number of obstacles, fading and diffraction effects, penetration losses strongly impact on the radio link performance. The presence of reflective materials creates highly multi-path propagation link between transmitter and receivers, thus making the impact of large-scale and small-scale fading effects dramatically [44].



Figure 8. OMV refinery in Schwechat, Austria [45].

3.2.1 Selection of a propagation model

To model a radio channel, the following phenomena should be taken into account [46]:

- path loss, that implies power reduction of a radio signal because of the propagation through the space;
- shadowing, that implies the fluctuation of a radio signal between receiver and transmitter due to various obstacles, such as trees, buildings, etc.;
- multipath propagation, that implies numerous reflected components of a transmitted signal.

Besides, there are different types of propagation models used for wireless radio channel simulation:

- empirical models, that are based on measurements and observations and are linked to the environment;
- deterministic models, that are based on fixed geometry of buildings, streets, etc.;
- statistical models, that predicts channel parameters as stochastic variables.

Note, empirical models are mostly used for path loss prediction. Such models as Hata model, Cost-231 model are examples of these models. Deterministic ones usually require three-dimensional modelling of the environment geometry. Path loss, shadowing and multi-path are calculated based on predefined geometry. Ray-tracing models are example of deterministic models. Statistical or stochastic models are the considered to be the least accurate, but they require the least information about the environment [47].

Various combinations of the described propagation model types are possible as well: geometry-based stochastic channel models (GSCM), non-geometry-based stochastic models, semi-deterministic and standardized models. METIS model [48] is an example of semi-deterministic model, where the propagation paths are computed deterministically based on simplified 3d geometric model of the environment. Whereas, such objects as people, vehicles are modeled stochastically. GSCM models can be divided into two different types: those models where geometry implies locations of scatters such as COST models [49] and those models where geometry implies determination of propagation conditions (Line-of-Sight (LOS) and non-Line-of-Sight (NLOS)) such as WINNER II [50] model. In GSCM other parameters like scatters are determined stochastically, based on appropriate, typically empirical, probability distribution rules. Non-GSCM models are pure stochastic models, meaning that geometry of physical environment is not considered at all (e.g. Saleh-Valenzuela model [51]). The next group is standardized models, such models as ITU IMT-Advanced model and Third Generation Partnership Project (3GPP) spatial channel models (SCMs) are belongs to this group. The IMT-Advanced model is based on the WINNER II model, meaning that it can be classified as GSCM, with some channel parameters modifications.

To accurately evaluate the radio channel for the particular deployment and make the calculations not too complex, as it would be in case of using a ray-tracing model, GSCM model was decided to be applied in this thesis. There are two main candidates for evaluation in this work: WINNER II and ITU IMT-Advanced models. Both propose similar features as, for example, cross-correlation matrixes, delay spread calculation, etc. They are usable from 2 to 6 GHz frequency band and can be applied in the use case described in Chapter 3.1 **Error! Reference source not found.** However, ITU IMT-Advanced model is supposed to be used for IMT-Advanced technologies' performance evaluation, in other words, for LTE and LTE-Advanced systems. Since, in the current study conventional LTE network will be used to provide the IoT sensors with a radio access to the Internet, it was decided to use ITU IMT-Advanced channel model. Besides, it should be

mentioned, that rural scenario of ITU IMT-Advanced model can be used in frequency band from 450 MHz to 6 GHz. Considering, that LPWAN networks, particularly LORA, is supposed to work at 868 MHz in Europe and can be used to provide access to the IoT sensors as well, implementation of ITU IMT-Advanced channel model will allow to perform the study for LTE network and, in case of a need in future work, can be applied with simple modifications for LORA network performance evaluation. Selected ITU IMT-Advanced model will be used in proposed algorithm, which is described in Chapter 3.3.3.

3.2.2 ITU-R IMT-Advanced channel model

In this thesis, the ITU model described in the report ITU-R M.2135-1 was utilized [52] to perform radio link simulation in industrial environment. Applied ITU-R IMT-Advanced channel model is geometry-based stochastic one that supports multi-antenna technologies, polarization, multi-user and multi-cell systems.

As it was stated above, the multi-path components play significant role in the radio link simulation. Signal components redirected by the highly reflective materials arrive at the receiver with different angle of arrival (AOA). Besides, these components delayed by the propagation paths arrive at the receiver with diverse propagation delays and with phase shift. Various AOA and phase shifts can either degrade or enhance received signal significantly. That's why it is the question of great importance to consider multi-path effect.

In ITU-R IMT-Advanced channel model multi-path effect is taken into consideration by splitting transmitted link onto certain number of clusters, each having a number of rays. After that, such parameters as received delays, powers, angles of departure (AOD) and arrivals are stochastically generated for every ray according to predefined distribution functions and large-scale (LS) parameters. LS parameters such as shadow fading delay, angular spread are generated based on the normal distribution functions and correlated with each other. That way of defining small-scale parameters (SS) and LS brings two levels of randomness to the ITU-R IMT-Advanced channel model.

Figure 9 describes the process of the channel parameters generation using the ITU model [52]. The first step is to set a scenario, network layout and antenna parameters. The calculations and parameters used in channel model are different for each scenario. The following possible scenarios are defined: base coverage urban, microcellular, indoor and high speed. *Base coverage urban scenario* is meant to be applied for macro cells, providing ubiquitous coverage in urban area. *Urban macro-cell (UMa) scenario* assumes that the transmitting base stations are installed on the roof top and higher, while mobile devices are located on approximately 1.5 meters above the ground outside on the streets. Obstructed line of sight (LOS) link is considered to be a common case to that scenario. Buildings are mostly four floors or higher, uniformly spread over the area. *Suburban*

macro-cell (SMa) scenario is also related to base coverage urban scenario and assumes lower height of the buildings and density. *Microcellular (UMi) scenario* implies smaller cells and higher user density. Base station antennae are installed below rooftops. *Indoor (InH) scenario* focuses on the smallest cells and the highest user density in buildings. *High speed (RMa) scenario* is for large cells and high-speed vehicles (up to 350 km/h). Network layout implies the location of the base stations (BS) and the user terminals (UT). The antenna parameters are introduced for both BSs and UTs, BS and UT antennae gains, and the direction of radiation are defined with respect to North.

The next step is to define the propagation conditions. For every BS-UT link line-of-sight (LOS) and non-light-sight (NLOS) conditions should be checked, because it determines the way of channel modelling and correlation between LS parameters. Besides, the value of such parameters as AOD and AOA strongly depends on the LOS and NLOS conditions.

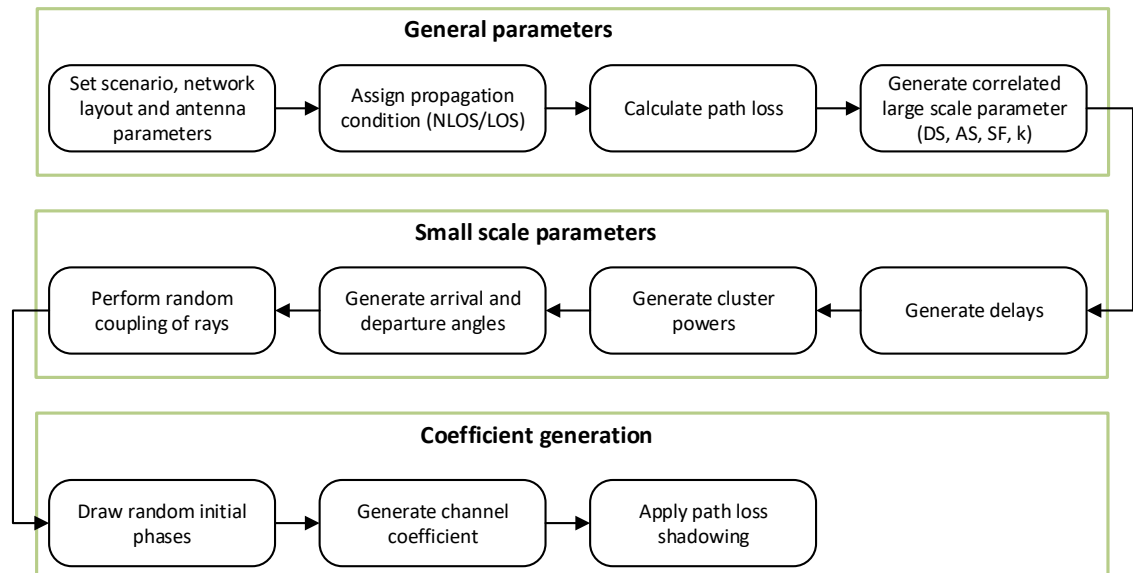


Figure 9. Channel coefficient generation procedure [52].

Calculating path loss is the next step. Path loss should be calculated for every BS-UT link. The calculation depends on the selected scenario and LOS and NLOS propagation conditions. Besides, each scenario imposes restrictions on the path loss calculations by BS and UT heights, maximum speed, etc. Shadow fading deviation depends on scenario and propagation conditions as well [52].

Then, such LS parameters as delay spread (DS), angular spread (AS), shadow fading (SF) and Rician K factor should be generated. LS parameters are generated with normal distribution and correlated to each other. Correlation matrix for each scenario and propagation conditions is defined in [52] and theoretically explained in [50].

The next step is to generate SS parameters: delays, powers, AOA and AOD. Delays are uniformly and randomly generated for every cluster, the number of which is different for every scenario and propagation conditions (LOS and NLOS). Besides, parameter DS generated earlier, and delay scaling parameter defined for each scenario are used for delays calculations [52]. Powers are generated based on normal distribution for every cluster taking into account calculated earlier SS delays and DS. Then, cluster powers are uniformly spread over all rays within a cluster. AOA and AOD are generated for every ray within a cluster using wrapped normal distribution, using corresponding ASs (angle of arrival and departure spreads) from LS parameters generated before and the power of each ray.

Random coupling of the AOA and AODs of rays should be performed at the next step. For every ray corresponding AOA and AOD are randomly allocated, thus simulating the effect of multi-path.

ITU-R IMT-Advanced channel model takes into account polarization in addition to described above parameters. For each ray of each cluster initial phases should be uniformly generated for four different polarizations vertical-vertical, vertical-horizontal, horizontal-vertical and horizontal-horizontal.

The next step is to generate channel coefficients for each BS-UT pair taking into account all calculated and generated above parameters and to apply them to path loss calculations.

To summarize the above said, first LOS and NLOS conditions are determined for each BS-UT link. Then, every BS-UT link is divided into certain number of clusters, that depends on a scenario and LOS/NLOS conditions. In its turn, each cluster is divided in rays with the corresponding number defined by a scenario and LOS/NLOS conditions. Considering contribution of LS parameters calculated for a certain scenario and propagation conditions and SS parameters calculated for every ray, channel coefficients are determined for each BS-UT link. Thus, received power from each BS can be estimated on each UT and serving BS might be selected based on the best received signal level. Formulas and assumptions applied in this thesis work are described in Chapter 3.2.3.

3.2.3 Path loss calculation and assumptions applied for the case study

As it was discussed in Chapter 3.2.2, there are few possible scenarios, where ITU-R IMT-Advanced channel model can be applied. For current use case, Urban Micro (UMi) scenario was selected. Scenario defines the equations, values of main parameters and the correlation between LS parameters. Besides, number of clusters and rays per clusters depends on the scenario. Thus, for UMi number of used clusters in current calculations is 12 for LOS and 19 for NLOS case, number of rays per each cluster is 20 for both preparation conditions.

The next factor that determines parameters and formulas used for calculations in LOS or NLOS propagation condition. Equations (1) and (1a) should be used for LOS case.

$$PL = 22.0 \log_{10}(d) + 28.0 + 20 \log_{10}(f_c), \text{ for } 10 \text{ m} < d_1 < d'_{Bl}, \quad (1)$$

and

$$PL = 40 \log_{10}(d_1) + 7.8 - 18 \log_{10}(h'_{BS}) - 18 \log_{10}(h'_{UT}) + 2 \log_{10}(f_c), \quad (1a)$$

for $d'_{Bl} < d_1 < 5000 \text{ m}$,

where d – is a distance between BS and UT in m, f_c – is carried frequency in GHz, h'_{UT} and h'_{BS} – are effective antenna heights computed as follows: $h'_{BS} = h_{BS} - 1.0 \text{ m}$, $h'_{UT} = h_{UT} - 1.0 \text{ m}$; d'_{Bl} – is a break point distance, computed as follows: $d'_{BP} = \frac{4h'_{BS}h'_{UT}f_c}{c}$; c – is speed of light and is equal to $3.0 \times 10^8 \text{ m/s}$.

For NLOS case, the path loss formula depends on the layout used in the planned area: Manhattan grid layout or Hexagonal cell layout. In this work and since the distances between BS and UT do not exceed 2000 m, it is assumed that layout is Hexagonal. It is required to mention, that base station locations are not planned with respect to Hexagonal layout. However, since this layout is rather more generalized, than the Manhattan grid, it was used in current work.

Thus, equation (2) can be applied for NLOS path loss (PL) calculation:

$$PL = 367 \log_{10}(d) + 227 + 26 \log_{10}(f_c), \text{ for } 10 \text{ m} < d < 2000 \text{ m}. \quad (2)$$

ITU-R IMT-Advanced propagation model requires the calculation of departure azimuths φ_{LOS} from the base station for every BS-UT link in LOS case. That is done with respect to North direction and limited to 104 degrees.

According to channel coefficient generation procedure presented on Figure 9, the next step is to generate LS parameters, which are correlated to each other. Cross-correlation matrix used in the current work is presented in Table 3.

Table 3. LS parameters cross-correlation matrix.

NLOS	DS	ASD	ASA	SF	K
DS	1	0	0.4	-0.7	NA
ASD	0	1	0	0	NA
ASA	0.4	0	1	-0.4	NA
SF	-0.7	0	-0.4	1	NA
K	NA	NA	NA	NA	NA
LOS	DS	ASD	ASA	SF	K
DS	1	0.5	0.8	-0.4	-0.7
ASD	0.5	1	0.4	-0.5	-0.2
ASA	0.8	0.4	1	-0.4	-0.3
SF	-0.4	-0.5	-0.4	1	0.5
K	-0.7	-0.2	-0.3	0.5	1

LS parameters are generated based on the normal distribution. Mean and standard deviation of the distribution are defined for each LS parameter: for Delay Spread (DS) $\mu=-7.19, =0.4$ for LOS and $\mu=-6.89, =0.54$ for NLOS; for AoD spread (ASD) $\mu=1.2, =0.43$ for LOS and $\mu=1.41, =0.17$ for NLOS; for AoA spread (ASA) $\mu=1.75, =0.19$ for LOS and $\mu=1.84, =0.15$ for NLOS; for Shadow fading (SF) $=3$ for LOS and $=4$ for NLOS; for K-factor (K) $\mu=9, =5$ for LOS and is not defined for NLOS case.

The next step is to generate SS parameters. First, delays τ should be generated for every cluster using equation (3):

$$\tau_n = -r_\tau \sigma_\tau \ln(X_n), \quad (3)$$

where $n=1 \dots N$ – is the cluster number, σ_τ – is DS generated based on normal distributions with μ and σ given above, r_τ – is delay scaling parameter and $r_\tau=3.2$ in LOS case and $r_\tau=3$ in NLOS case, $X_n \sim \text{Uni}(0,1)$ – is randomly generated value. After delays are calculated for each cluster, vector of delays should be normalized by subtracting the minimal calculated τ_n from the rest of the vector values.

In LOS case, delays τ_n should be additionally scaled (each τ_n should be divided) by Rician K-factor dependent constant D , which is defined by:

$$D = 0.7705 - 0.0433K + 0.0002K^2 + 0.000017K^3. \quad (4)$$

After that, power for every cluster should be generated for NLOS case as:

$$P'_n = \exp\left(-\tau_n \frac{r_\tau - 1}{r_\tau \sigma_\tau}\right) \cdot 10^{\frac{-Z_n}{10}}, \quad (5)$$

where Z_n – is normally distributed shadowing term with standard deviation equal to 3 dB for both LOS and NLOS cases. After a vector of powers for each cluster is generated, the values of power should average in a such a way that summed up power of all cluster powers is equal to 1.

In LOS case an additional component is added to the generated vector of powers and is based on K_R value, that's is the Rician K-factor converted to linear scale (see equation (6)). After that LOS power vector is normalized as shown in equation (7).

$$P_{1,LOS} = \frac{K_R}{K_R+1} \quad (6)$$

$$P_n = \frac{1}{K_R+1} \frac{P'_n}{\sum_{n=1}^N P'_n} + \delta(n-1)P_{1,LOS}, \quad (7)$$

where $\delta(n-1)$ – is a delta function.

When powers for each cluster are computed, the power for each ray within a cluster are calculated by dividing the total by the corresponding number of rays. If the difference between the cluster power and cluster with maximum value of power is more than 25 dB, this cluster should be removed.

The next step is to generate arrival and departure angles φ_n as:

$$\varphi_n' = \frac{2\sigma_{AoA} \sqrt{-\ln\left(\frac{P_n}{\max(P_n)}\right)}}{C}, \quad (8)$$

where σ_{AoA} – is ASD generated based on normal distributions with μ and σ given above, C – is a scaling factor that depends on the number of clusters $C = 1.273$ in NLOS case for this work. For LOS case, C is computed using equation (9):

$$C^{LOS} = C \times (1.1035 - 0.028K - 0.002K^2 + 0.0001K^3) \quad (9)$$

where $C = 1.146$ for LOS case.

After φ_n' values are generated, they should be assign with positive or a negative sign by multiplying a random valuable with uniform distribution $X_n \{1, -1\}$. Besides, to introduce random variation of angle values normally distributed component $Y_n \sim N\left(0, \frac{\sigma_\varphi}{7}\right)$, where $\sigma_\varphi = \sigma_{AoA} \times 1.4$. In LOS case, the first cluster should be enforced to φ_{LOS} calculated above. Thus, φ_n values should be computed based on equation (10) in NLOS case and on equation (10a) in LOS case:

$$\varphi_n = X_n \varphi_n' + Y_n + \varphi_{LOS}, \quad (10)$$

$$\varphi_n = (X_n \varphi_n' + Y_n) - (X_1 \varphi_1' + Y_1 - \varphi_{LOS}) . \quad (10a)$$

While arrival angles φ_n values are calculated for each cluster, $\varphi_{n,m}$ values for each ray within a cluster should be generated based on equation (11), applying offset angles α_m different for every ray number [52] and rms azimuth spread of arrival angels c_{AOA} , which is equal to 17 in LOS case and to 22 in NLOS case:

$$\varphi_{n,m} = \varphi_n + c_{AOA} \times \alpha_m . \quad (11)$$

Procedure described above for arrival angles $\varphi_{n,m}$ is similar to the one for departure angles $\phi_{n,m}$. After departure and arrival angles are generated, they should be randomly group within a cluster.

For the calculation simplicity, polarization and antenna elements are not considered in the equation. And since sensors are fixed on their location and are not movable, after simplification formula of channel coefficients becomes:

$$H = \sqrt{\frac{1}{K_R+1}} \sqrt{P_n} \sum_{m=1}^M \exp(j\theta_{n,m}^{vv}) \quad (12)$$

When channel coefficients H are generated, total path loss and received signal level can be computed by adding coefficients from equation (12) to the calculated in equation (1), (1a) and (2) path loss values.

To model the effect of buildings or clusters of pipes, some modifications were introduced to the model. Particularly, extra losses were added to path loss if the BS-UT link intersects with a building or clusters of pipes, showed in Figure 13. The difference between propagation model that apply channel coefficients calculated based on ITU-R IMT-Advanced channel model and propagation model that does not apply channel coefficients is shown on Figure 10 and Figure 11. Besides, the effect of buildings is also shown on these Figures (right). As it mentioned before, the ITU-R IMT-Advanced channel model introduces multi path components in path loss calculations, thus the making the coverage prediction much more realistic.

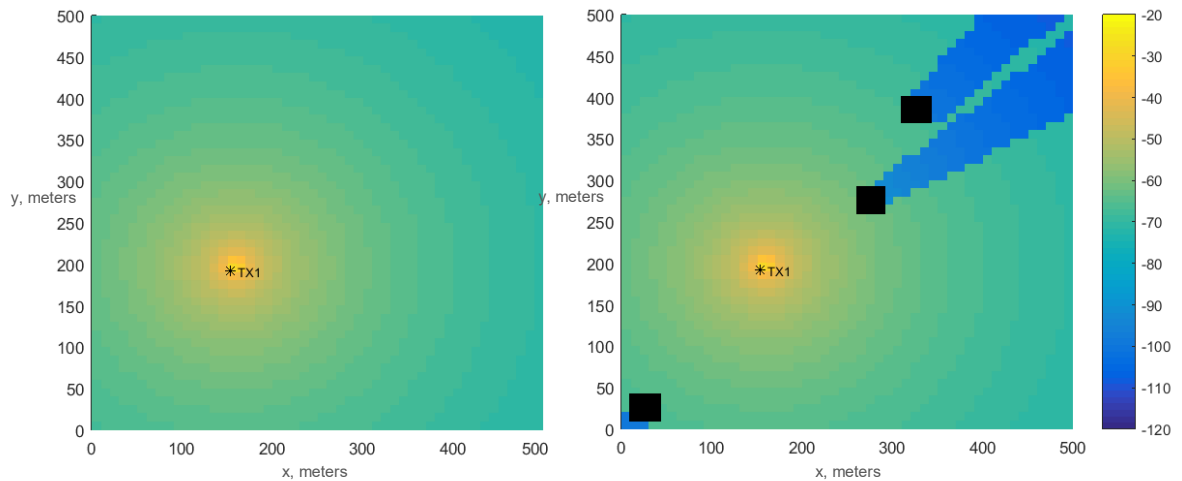


Figure 10. Received signal level (dB) for propagation model without stochastic parameters generation with (right) and without (left) deterministic component (buildings colored in black).

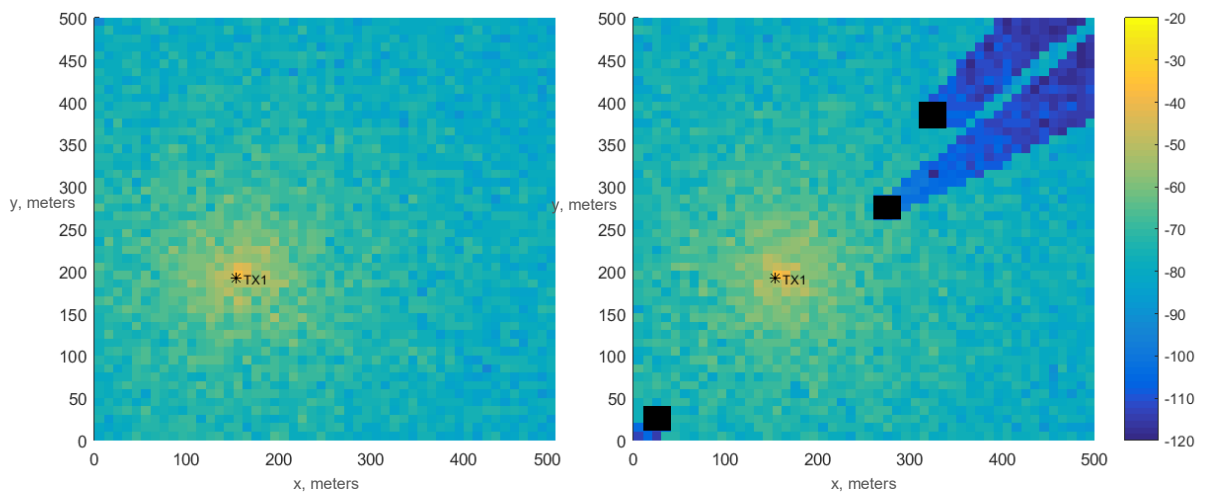


Figure 11. Received signal level (dB) for propagation model with stochastic parameters generation with (right) and without (left) deterministic component (buildings colored in black).

3.3 Radio network planning

Sensors can be granted with a radio access through different radio technologies, for example, through those that were described in Chapter 2.4. However, there is going to be a one common challenge for all of them: radio part of any network should be planned properly. All sensors installed in the area under consideration should be able to reach a base station (and to receive a signal from a BS) or a gateway to transfer information. Meaning, that sensors should be located within an area of a certain coverage level, radiated from a BS. Besides, this BS should be capable of serving all connected sensors, in

other words, capacity of a BS should not be exceeded. Basically, radio network planning (RNP) implies the process of the base station locations planning is a such a way that coverage and capacity maximization goals are achieved [53]. With respect to the case study, BS locations should be determined in a way, that all sensors receive a signal from BSs of a certain strength, that is sufficient for transferring a message with required quality. This task is known as *radio base station location problem*: how many radio base stations are required for a deployment and where they should be located [54]. In the optimization context, this problem objective is to find a set of BSs locations such that the total network cost is minimized while the coverage and capacity requirements are fulfilled. In mathematical programming, this problem can be considered as a *facility location problem* with some modifications imposed by specifics of radio networks.

There is a number of tools and algorithms available for RNP that can be applied for solving radio base station location problem, each having its own application area, features and limitations. Contemporary RNP tools require manual work from an engineer, who will be responsible for placing BS to a selected place and then run a coverage prediction or capacity calculation on the tool. The number of available automatized RNP tools is rather small, but nowadays, the automatization is a trend and automatized RNP tools are being under active development [55]. For example, so-called Self-Organizing Networks (SON) are designed to reduce a need in manual work during radio network planning (planning of new roll-outs such as additional sectors, carriers or sites) and optimization process. However, since the IoT network is a rather new concept, there are no (to the best of author's knowledge) available RNP tools specifically for the IoT radio network planning.

Instead, mathematical programming approach could be selected to perform radio network planning in studied use case. Radio network and optimization problem is considered to be a problem of non-deterministic polynomial-time hardness (NP-hardness) [56], that can be solved by, for example, *heuristic* algorithms. This type of algorithms is used to find a suboptimal solution when the time and cost of finding an optimal solution is large [54]. A pure heuristic algorithm is a rather simple 'intuitive' procedure, that does not guarantee to find the best solution. However, it is valuable because it can find a solution in a reasonable time that is sufficient for the problem under consideration. Basically, one can say that manual RNP is a heuristic way of finding a proper location for a BS. In this thesis work, *greedy heuristic* algorithm was used. To find a final solution of the problem, greedy algorithm starts with a random solution and then creates a feasible solution, making locally optimal choice step by step. Every iteration, algorithm assigns new values to variables and stops when predefined feasible solution is achieved. To improve the performance of this procedure, respectively big number of local searches should be performed. With increasing number of local searches, the probability of achieving the most optimal theoretical result grows. More detailed description of proposed algorithm is given in Chapter 3.2.3.

3.3.1 General RNP algorithm

In order to plan a radio network in any environment it is necessary first to assign and define network layout and criteria based on which radio plan can be considered acceptable (or solution to be considered feasible). Network layout implies such parameters as radio technology type, for which radio network plan is supposed to be done, number of planned base stations, characteristics of base stations (outdoor or indoor, micro or macro, etc.) and antennae (frequencies, sizes, patterns, etc.), number of user terminals, characteristics of user terminals (throughput, sensitivity level, etc.), etc. Criteria imply characteristics of the desired radio network, for example, a minimal level of SINR, number of the user terminal with certain received signal strength, total interference level, maximum allowed number of base stations, etc.

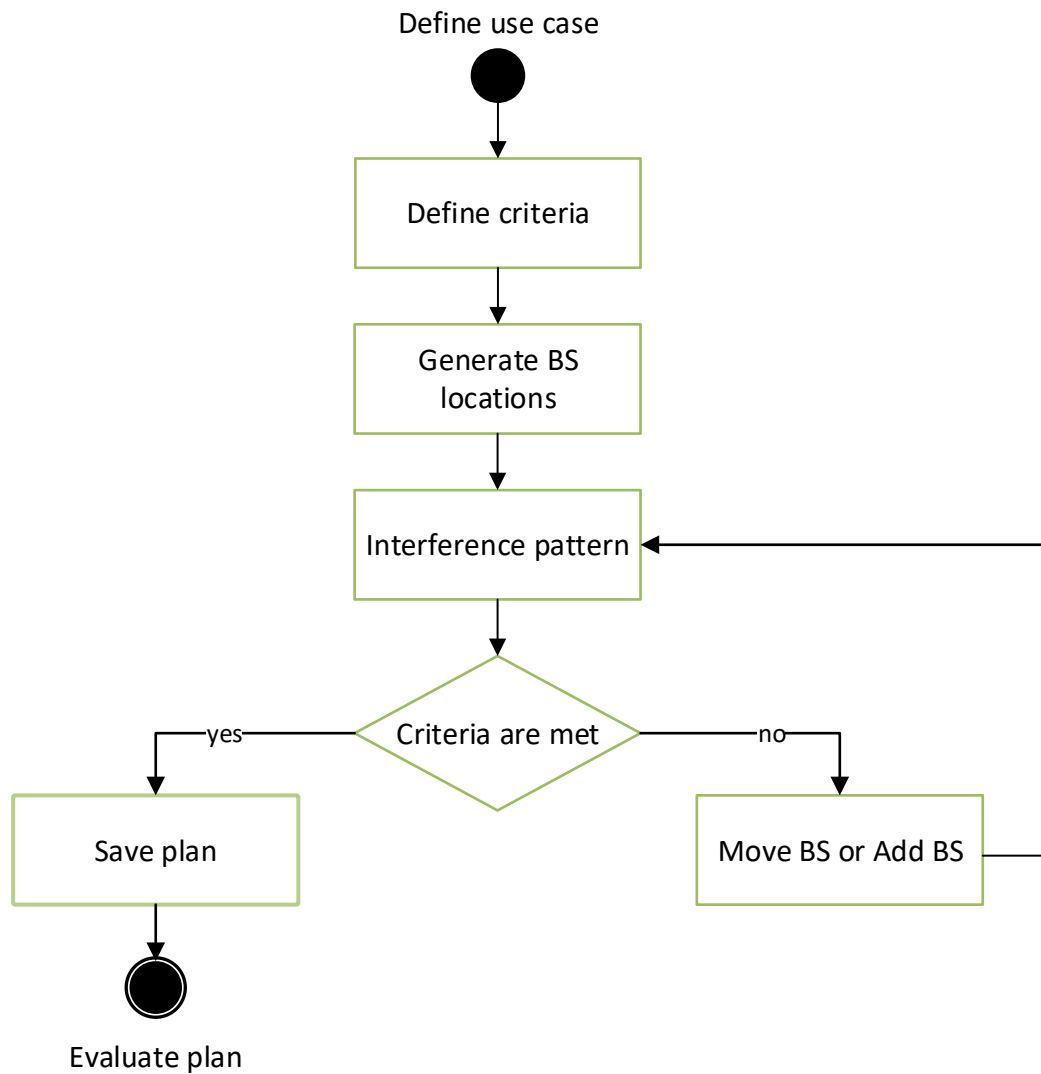


Figure 12. Radio network planning algorithm.

Figure 12 shows simplified algorithm of a radio network planning. Similar algorithm logic is described in [57] and in [58]. After the network layout is defined, the base station locations should be generated. In order to accurately plan the network, precise map layout should be considered with building heights, terrains heights and clutter types (trees, water, open area, etc.). Inside selected area or region, location of base stations can be generated randomly or based on predefined rules such as: minimum distance between planned base stations, clutter type where base stations can be placed or where base stations cannot be placed. After first round base station locations are generated, criteria (whether it is interference level, or received signal level, etc.) should be checked. If criteria are not met, then the program should either move generated base station to some other locations or add extra base station or base stations to the plan and then check criteria again. If the criteria are met, the solution is feasible and generated radio network plan should be saved.

In a given above example, the base station locations were considered as the only metric that changes during the automatic radio planning process. Certainly, such metrics as transmitted powers, azimuths of base stations antennae, tilts, etc. can be added to the algorithm. Thus, adding other degrees of freedom in the algorithm and making it tailored and extremely flexible.

Few different radio plans with unlike base station locations might meet criteria. In that case, in order to achieve an optimal result, it is recommended to evaluate created plans. For that purpose, various methodologies and evaluation techniques might be used. For example, in this thesis work, performance evaluation method from [59] is applied. Plans are prioritized based on the number of blocked sensors, based on polling periods and number of sensors with certain repetition attempts. Evaluation process is described in detail in Chapter 4.

3.3.2 Radio network criteria for the case study

As it was stated in Chapter 3.1, there is a need to place sensors along all the pipes in the refinery and thus it was assumed that there is a sensor in each square meter and they are uniformly distributed all over the planned area. The idea is to use existing LTE coverage to provide sensors with an access to the Internet. Thus, knowing the location or locations of the existing base stations, coverage could be estimated inside the refinery. However, since base station locations are not known, it was assumed that it is possible to plan a few new LTE base stations. Maximum number of new base stations is limited, and the purpose of the program is to minimize required number of LTE transmitter (TX) stations.

Thus, taking into account locations of sensors algorithm proposes possible locations of base stations in the refinery in a such a way, that the following criteria are met:

- maximum allowed number of planned base stations is not exceeded;
- base stations are not placed on the border of the refinery. Otherwise, base stations are inefficient, since they provide coverage outside refinery area;
- predefined percentage of refinery area is covered with minimum allowed SINR level. In current study, it is assumed that 90% of the refinery area should be covered [60] with minimum acceptable SINR value. If there are some places inside considered area with SINR level less than minimum allowed SINR level, then algorithm continues adding or moving base stations;
- all planned base stations have approximately same load and number of UTs;
- maximum number of iterations is not exceeded. This limitation is introduced to decrease processing time and avoid infinite moving of base stations by adding a new one.

It should be noted, that the program is fully customized, and criteria are adjustable based on the needs and a particular case.

3.3.3 Algorithm for the case study

For the refinery shown on the Figure 8, approximated 2d model of the map layout was created (Figure 13). The blocks on the picture represent high clusters of pipes where base stations cannot be placed. The shape of the blocks is convex, while in reality, the shape can be concave, this introduces some simplifications of refinery geometry model. It is assumed that other pipes are located on 1.5 meters height above the ground and base stations can be placed at any location except high clusters of pipes. However, sensors can be located in these blocks. Base stations can be located on masts, or buildings inside the refinery area.

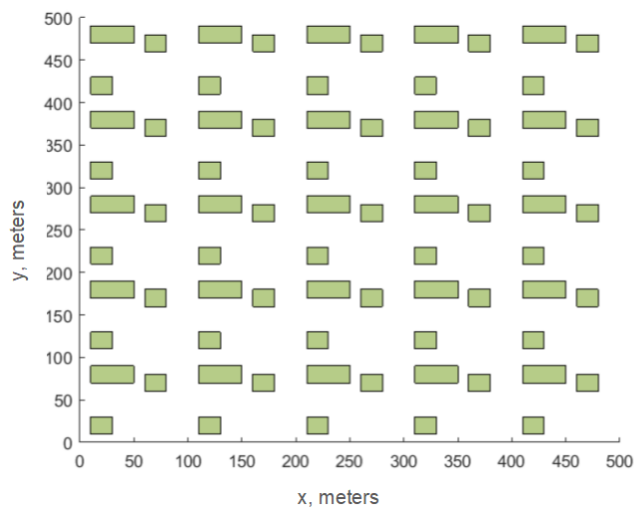


Figure 13. 2D model of the refinery.

The program starts with one base station (or with any other predefined number of base stations) and checks if it is enough to meet criteria listed above, if not then another base station is added and so on and so forth. It should be highlighted, that base stations locations are generated randomly, but in order to optimize this procedure and to avoid situations, when two base stations are placed together, planned area is divided by binary space partitioning method. Thus, Monte Carlo method is applied in the algorithm [61]. This principle is shown on the Figure 14. Every time when the algorithm adds a base station, it splits the whole area to smaller pieces based on the number of planned base stations and then places base stations in these areas. Besides, algorithm checks that proposed locations are not in forbidden areas that could be predefined beforehand. If they are, then algorithm generates locations again.

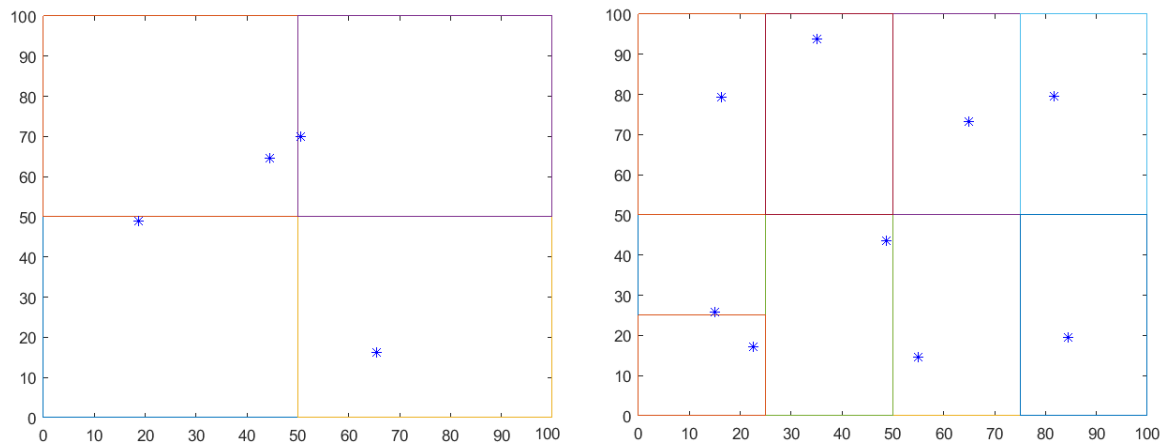


Figure 14. BS location generation for 4 BSs and for 9 BSs.

When base station location is generated, the coverage should be calculated. For that purpose, propagation model described in Chapters 3.2.2 and 3.2.3 is used. As it was discussed, the next step after setting scenario and network layout is determination of propagation conditions, that should be done for every BS-UT link. The example is given on Figure 15 for two BSs and for UTs uniformly distributed over the refinery every 5 meters. Algorithm starts checking LOS and NLOS conditions, which are required to model a signal propagation and is explained in Chapter 3.2.2, and counts number of intersections with obstacles. Intersections with obstacles are marked with black circle. The number of intersections and the location of UTs also plays a significant role in the coverage prediction. Thus, the more intersection points a BS-UT link has, the more signal attenuates through this link.

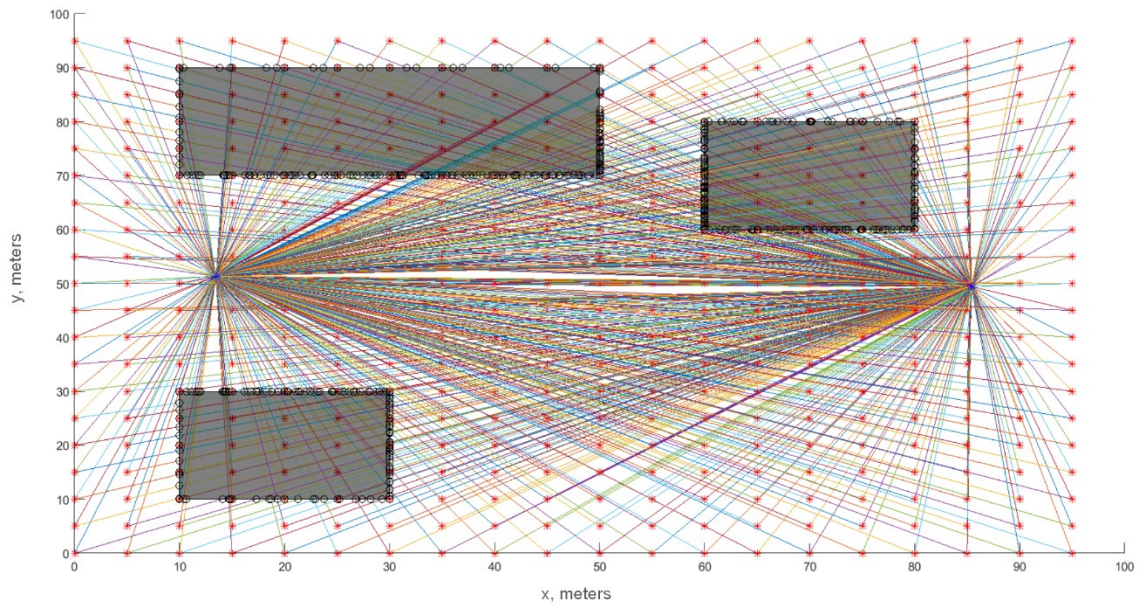


Figure 15. LOS and NLOS propagation condition.

After LOS and NLOS conditions are defined the path loss prediction continues as it was discussed in Chapter 3.2.3. As result of the path loss calculations, matrix of received signal strength from each BS is generated for each UT. As it was mentioned earlier, it is assumed that sensors are distributed uniformly every meter all over the area under consideration. Thus, the number of required sensors and thus the size of the matrix is equal to the area size in meters. The resulted interference matrix is N_{BS} -dimension matrix and is presented on the Figure 16.

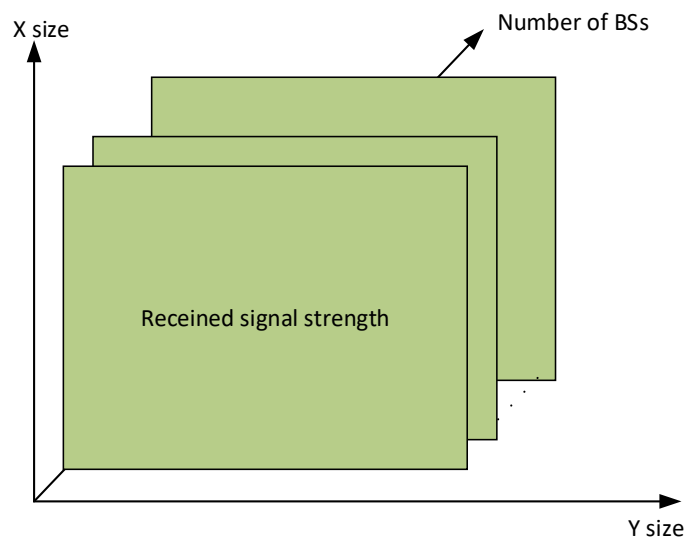


Figure 16. RX signal level matrix.

Based on this N_{BS} -dimension RX signal level matrix and considering receivers' sensitivity value, zones of the interference are determined for each base station. In other words, these zones can be understood as serving areas of each base station. If one base station is placed in the interference zone of another base station, then the level of total interference grows significantly. The total interference level is computed at the receiver end and is a sum of all signals coming from other base stations that are higher than receiver sensitivity level. The task of the algorithm is to minimize the effect of the interference by making sure that:

- base stations are not located in interference (serving) zone of any other base station;
- intersection of interference zones for different base stations is minimal.

After interference zones are defined, algorithm starts to move base stations from high interference places on the map, thus minimizing the total interference. The interference zone can be represented as a “bubble” around each of base stations and the algorithm is trying to push these “bubbles” away from each other, minimizing overlapping between them. Interference zones or serving areas are defined by SNR threshold value, meaning that at some distance from a base station SNR value will be so low, that these areas are not anymore considered as serving area of this site. After that, the algorithm checks the interference level in the serving area and finds regional maximums of the interference matrix using MATLAB function *imregionalmax*. This function returns the binary image of regional maximums, making maximums equal to 1 and all the rest values equal to 0. The exact value of the interference is retrieved from the total interference matrix and values 1 are replaced with it. By normalizing each regional maximum interference value with a global interference maximum level, the strength of each interferer is determined. It is done to understand, which direction a site should be moved to or which direction a site will be pushed to. In other words, if e.g. two interferers are in the serving area of a site and the strength of these interferers is different, then the stronger interferer will, basically, define a direction of moving vector from a TX. The algorithm summarizes the effect of vector directions from all interference regional maximums in the serving area and creates the direction of the final vector. The length of the final vector is equal to the predefined step size. Thus, TX is moved to a new location, that is defined by the vector of direction and by a step size. The step size is a parameter that introduced to the algorithm and can be adjusted based on the need. This process is depicted on the Figure 17. The size of the circles represents the strength of the interferer. As it can be seen from the Figure, since Interferer 2 is much stronger, than Interferer 1, TX will be pushed from Interferer 2 more noticeably.

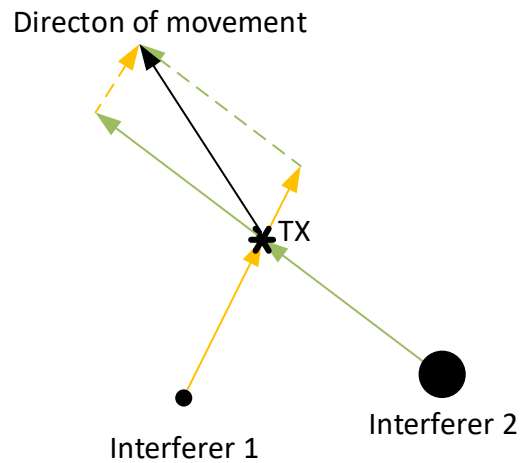


Figure 17. *Direction of movement calculation.*

As it was mentioned above, one thing to consider when generating BS location or moving BS is the proximity of them to the border of refinery. It is rather economically inefficient to place a TX in a corner to provide coverage for few UTs that are suffering from the bad coverage. The algorithm tries to balance the load on each base station and make coverage equal. In order to limit computational time and to make moving of base stations finite, maximum number of iterations was introduced to the program. After maximum number of iterations is reached while percentage of the area with predefined minimum SINR value is not reached, algorithm adds a new location and starts moving base stations again. To make sure that all base stations are moving, the algorithm every time select randomly which TX to move.

The movement of base stations is presented on Figure 18. As it can be seen from this figure, TX1 and TX3 were pushed apart because of their proximity to each other and high total interference level. It should be noted here, that in case there is an obstacle between them, the total interference level might have been lower. Meaning, TX1 and TX3 would have not required new locations. TX2 stayed at the same place and was not moved because other TXs were not in its serving area, thus there were not any interferer to move from.

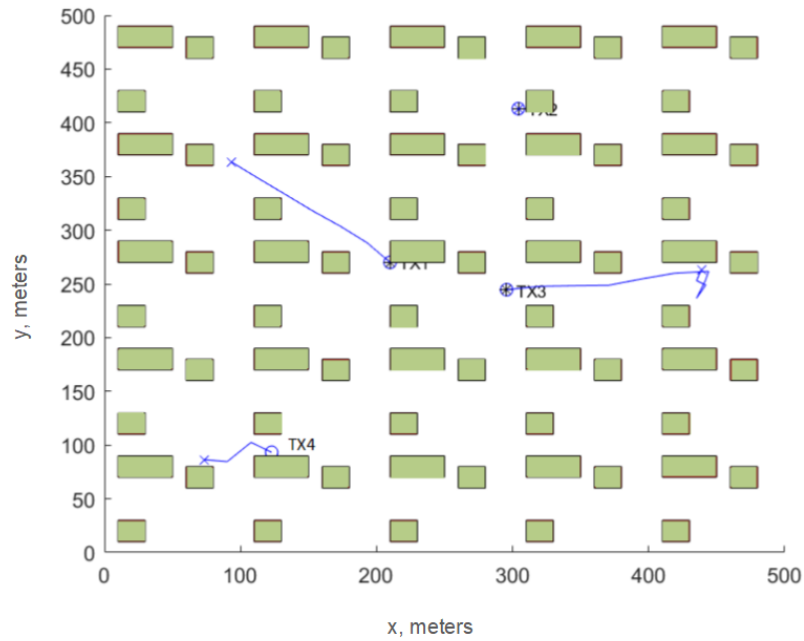


Figure 18. Movement of base stations

As it was mentioned, during the process of moving base stations intermediate SINR matrix is updated. Algorithm continuously checks whether SINR criteria is met or not. If criteria are met, then the plan is considered to be satisfied and SINR matrix and current TX locations are saved and will be used for plan performance evaluation. The impact of moving on SINR level is shown on the Figure 19. The movement presented on Figure 18 increased the number of sensors with $\text{SINR} > 10\text{dB}$ by 4%, thus increasing SINR mean value by 3dB. Meaning, that newly obtained average receiving signal level is twice higher, than it was before.

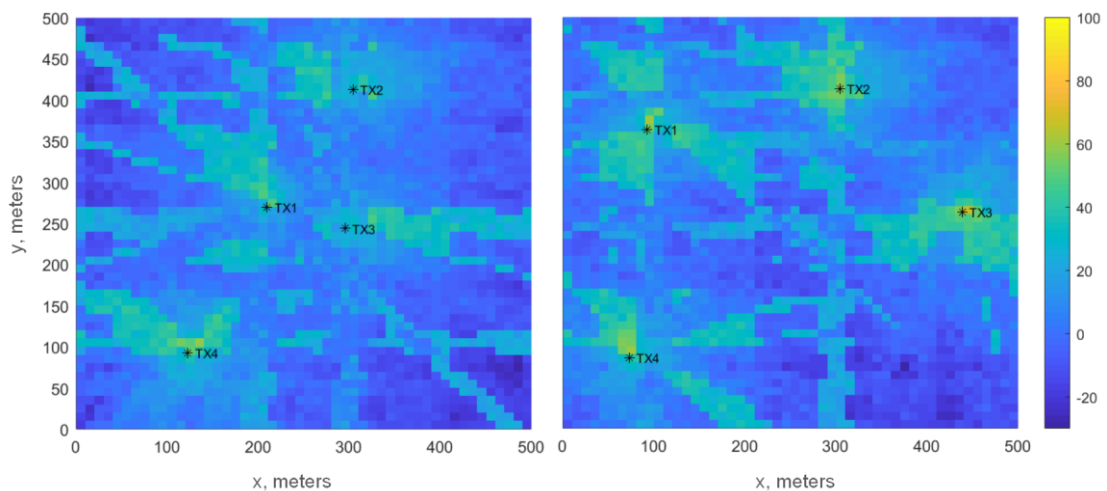


Figure 19. SINR values before (left) and after (right) movement.

To summarize above said, the algorithm for current case study is presented on the Figure 20. It is more detailed than the basic one presented on Figure 12 and tailored for the case study.

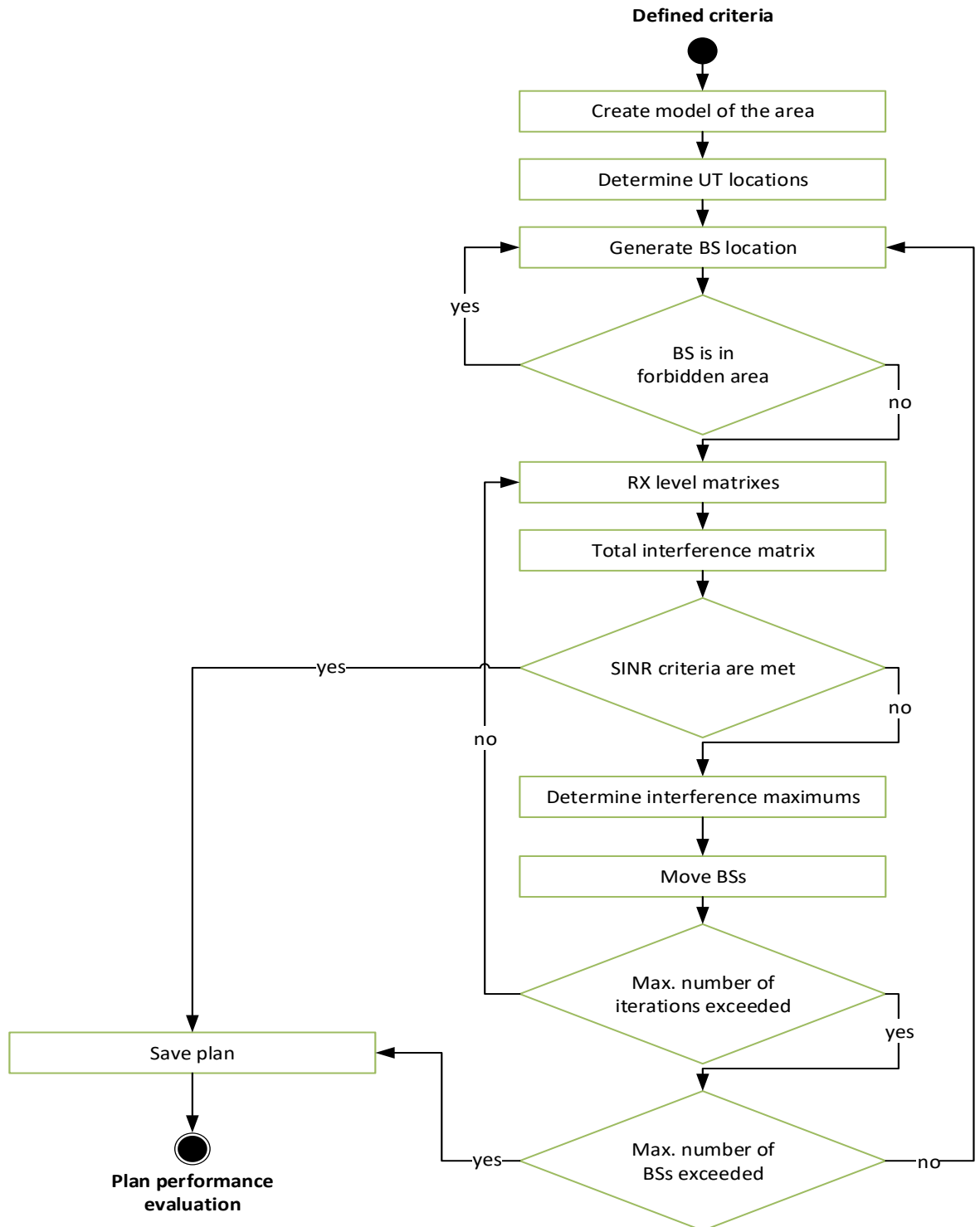


Figure 20. Case study algorithm.

4. PERFORMANCE EVALUATION

This Chapter is devoted to the description of the algorithm performance and evaluation of the radio network plans proposed by the described above algorithm.

4.1 Algorithm performance evaluation

In order to make algorithm performance evaluation clear and transparent, all previously discussed parameters (except channel parameters, defined in Chapter 3.2.3) and their values are listed in Table 4.

Table 4. Values of applied parameters.

Parameter	Value
Deployment size	500m X 500m
Scenario [52]	UMi
BS height [52]	10m
BS TX power	20 dBm
Max. number of BSs	9
Min. number of BSs (starting point)	4
Min. SINR value	-6.5 dB
Required % of area covered with min. SINR value	90%
Number of simulations (seeds)	500
Step of BS movement	20m
Sensors grid	every 5m

Minimum SINR value is selected such that sensors are capable of using modulation coding scheme (MCS) MCS 1 [62], that allows usage of Quadrature Phase Shift Keying (QPSK) modulation. Number of seeds in Table 4 stands for the number of simulations, that has been conducted. Each simulation implies newly generated TX locations and channel coefficients. The step of BS movement defines the distance on which BS will be moved from an interferer. Step of 1m will make the calculations more accurate, but it will have an impact of the time required for calculations. Besides, 1m step will not change an interference picture a lot. Therefore, there was a tradeoff between computational time and the interference picture change visibility when selecting a step of BS movement. As for the sensors grid, they are planned to be installed every 5m, because this distance will make the localization of the detected problem easier [63].

Before selecting a radio plan for the study case based on the criteria described in Chapter 4.2, performance of the algorithm should be evaluated. Within a framework of this thesis

work, the evaluation is done by comparing the output result of the algorithm with quasi-random drop of the base stations. The drop is quasi-random, because base stations locations are generated in planned area divided on approximately same-size zones using binary-tree space portioning method, as it is discussed in Chapter 3.3.3 and is shown on Figure 14. With this kind of comparison, the gain of the proposed algorithm can be easily determined.

For the simplicity of explanation, the result obtained with quasi-random drop is referred as “before” and the output result of the algorithm is referred as “after”. Results will be compared in terms of mean SINR value. Besides, as it was mentioned in Chapter 3.3.2, it is required to provide 90% of the area covered with defined minimum SINR level, which is specified in Table 4. Thus, percentage of the coverage with minimum SINR value is considered as well. Right part of the Figure 21 shows cumulative distribution function (CDF) of SINR mean value and left part shows CDF of the coverage percentage.

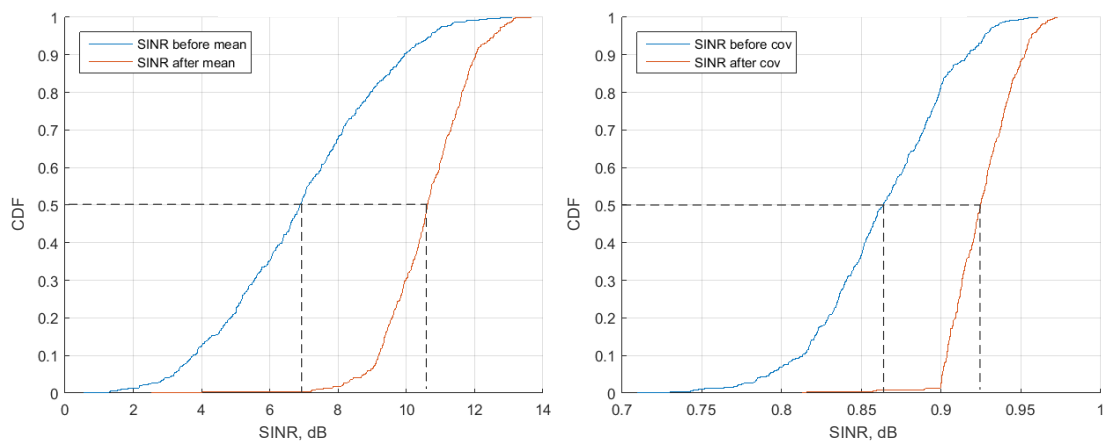


Figure 21. Comparison of mean SINR values (left) and percentages of coverage with required SINR level (right) for quasi-random drop and for output of the algorithm.

As it can be seen from the figure above, in 50% of all simulations the difference between quasi-random drop and the output of the algorithm is approximately 3.8dB. In case of low SINR values, the difference is higher, because the algorithm does not stop moving BSs (thus, decreasing interference and, correspondingly, increasing SINR level) until required part of the planned area is not covered with minimum required SINR value. In case of higher SINR values, the quasi-random drop provides rather good coverage, and algorithm does fewer iterations to achieve the goal, thus making the difference between the results less noticeable. The same principal is confirmed by the second part of Figure 21, where 0.9 represents 90% of required coverage in the planned area. Values below 0.9 for “after” case are obtained because of exceeding maximum iterations number before achieving 90% of the coverage. By any means, majority of the resulted percentages from the algorithm output are above threshold value.

Based on 500 simulations, the number of base stations needed to achieve required coverage in 50% of the case is equal to 6 (see Figure 22 (left)). There is a difference in number of TXs needed to meet the goal, because of the primary pseudo-random BSs' locations generation and maximum number of iterations limitation. Theoretically, the ideal algorithm should give a certain and fixed number of TXs in case of unlimited computational time. Proposed greedy heuristic algorithm can achieve the performance of theoretical algorithm, however, the computational time could increase dramatically. Right part of Figure 22 shows the number of iterations required to achieve desired goal in case of 6 planned base stations. The difference in required number of iterations is caused by the randomness of the primary TXs' location generation. Due to the randomness in the initial TXs' positioning, there might be a case when the required number of iterations exceeds an average value.

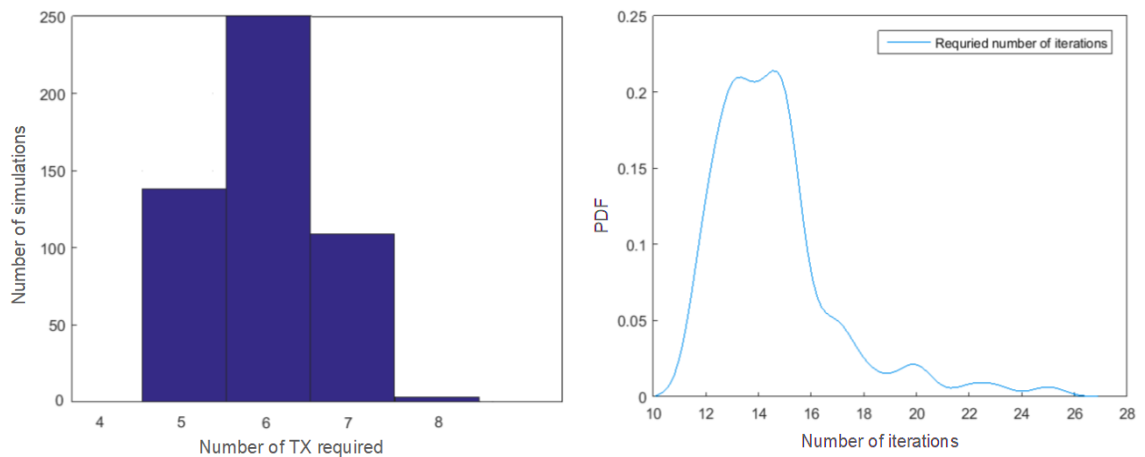


Figure 22. Deviation of required number of BSs (left) and required number of iterations (right).

4.2 Radio network evaluation metrics

The evaluation of the radio plans gathered after running the program described in Chapter 3.3.3 will be done using materials and the calculation method from [59]. In this paper coding-based LTE coverage enhancement schemes were considered. Such coding schemes as repetition coding and direct sequence spread-spectrum (DSSS) were studied. It was concluded in the paper, that coding schemes like DSSS allow to improve radio link conditions significantly by introducing additional coding gain. In order not to overload the whole system with repetitions, maximum number of LTE frames was introduced into calculation. Three different limitations were considered: 1 frame, 3 frames and 5 frames. Meaning, that in case of repetition coding, a sensor can retransmit a message during few time frames, number of which does not exceed maximum number of allowed frames.

Besides, such characteristic as polling period was introduced in the article as well. Polling period implies the time needed to transfer messages sent by all sensors. With the growth of sensors which require usage of coding-based enhancement techniques, polling period time grows and thus decreasing sectors service speed.

In this thesis work and in studied use case, no blocked sensors are supposed to be in the plan, meaning no sensors that are not able to transmit a message because of pure coverage. Otherwise, the monitoring of the pipes will not be fully reliable and accurate. However, the concept of applying coding-based coverage enhancement schemes might be usable in such a complex radio propagation condition as industrial environment. Therefore, the number of sensors normally served and served with coding-extension schemes and polling period will be used to evaluate the performance of the proposed radio network plans.

An optimal radio plan is supposed to maximize the number of sensors with the highest possible SINR provided by a conventional service and minimize a need in any coverage enhancement schemes. Besides, one of criteria defined in Chapter 3.3.2 was percentage of the area coverage with a certain SINR value. Thus, all proposed network plans will be compared in terms of the number of sensors with high SINR value.

In addition to that, it is important to keep all planned base stations equally loaded. A case when one base station is situated in the middle of the refinery and couple of more base stations are located at the border of the refinery, serving couple of dozens of sensors, is not considered to be an acceptable radio network plan. Thus, the load on each base station will be evaluated and the priority will be given to a plan with most equal load.

Certainly, applied evaluation metrics and their priority over other metrics may vary based on the need and use case. In the current thesis work metrics described above are used for the evaluation and are listed in the in order of growing priority:

- number of sensors served with coding-extension schemes;
- number of sensors served without coding-extension schemes;
- polling period;
- SINR values over the planned area;
- load equality on planned base stations.

4.2.1 Final radio plan selection

To perform resulted radio plans assessment, analytic hierarchy decision making process described in [64] was used and the evaluation metrics were weighted according to the priority order given above. Weights are presented in Table 5. As it was mentioned, radio connectivity is critical for sensors in the case study. Therefore, proposed plans of radio

network layout with sensors having SINR level not sufficient to reach a BS even using coverage enhancement techniques were excluded from the consideration.

Table 5. Evaluation criteria weighting.

Criteria	Weight
number of sensors served with coding-extension schemes	0.5
number of required BSs	0.5
number of sensors served without coding-extension schemes	0.6
polling time	0.8
percentage of area covered with min SINR level	0.9
BS load equality	1

Sensors are considered to be served with coding-extension scheme, if received SINR value is less, than minimal SINR level, which is equal to -6.5dB. As it was concluded in the article [59], DSSS coding enhancement scheme can cover sensors with lower SINR, then repetition coding. Within a framework of this thesis, only DSSS coding enhancement scheme is considered. Maximum DSSS coding gain depends on the number of LTE frames allowed for retransmission. To calculate polling time, required to send all messages in the system at a fixed moment, throughput of each BS-UT link should be taken into consideration [59]. BS load equality is calculated in such a manner that number of served sensors is counted for each BS and normalized to a maximum value of served sensors from any of BS in a deployment. After averaging normalized values, the equality of the load can be seen (see equation (13)).

$$EL_i = \text{average}\left(\frac{N_{sensors_per_BS_j}}{\max(N_{sensors_per_BS_j})}\right), \quad (13)$$

where EL_i – equality in i -scenario, $N_{sensors_per_BS_j}$ – number of sensors served by j -BS.

CDF distribution of the equality values is presented on the Figure 23. Out of 500 simulations, in 119 cases (~23%) the average deference between the loads was less than 10%.

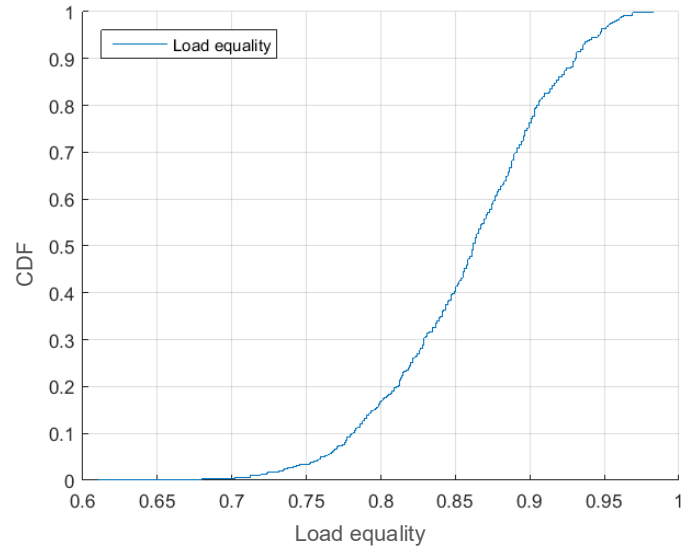


Figure 23. BS load equality distribution.

Out of all performed simulations and taking into account all evaluation criteria and their weights, the radio plan presented on the Figure 24 was selected as the best one out of the proposed ones. This radio plan covers the whole refinery and no blocked sensors appeared here. As it can be seen, SINR values near TXs are quite high, SINR degrades unevenly due to the deployment obstacles presented on Figure 13. Besides, interference coming from the neighboring sites decreases SINR value on the site coverage borders.

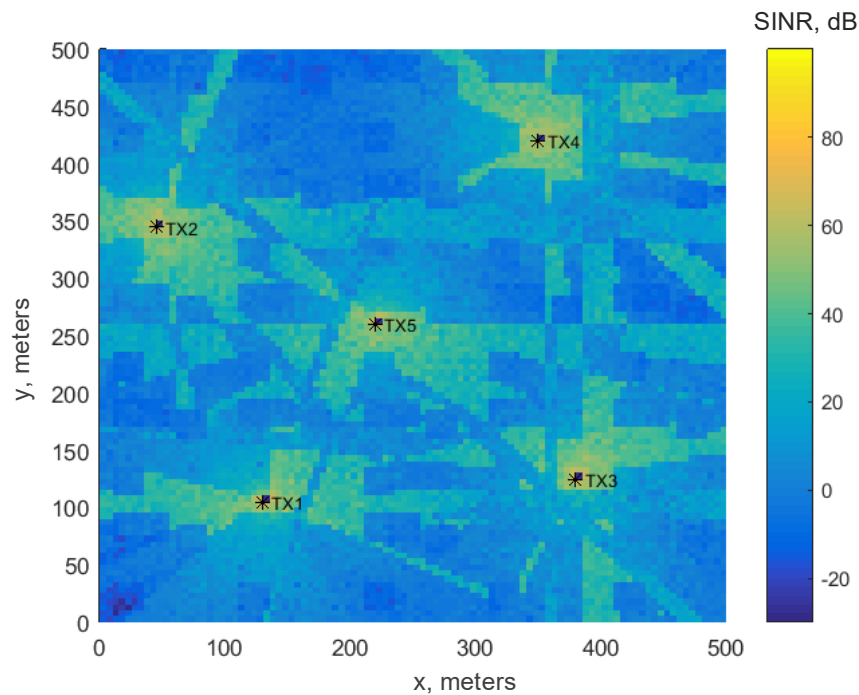


Figure 24. Final radio network plan.

5. CONCLUSION

This thesis work proposed a methodology and algorithm for the radio part of the IoT network planning in industrial use case. Industrial environment imposes certain limitations on the radio planning process. For example, the channel modelling is a question of great importance in such a complex environment. As it was discussed, because of the highly reflective materials used in factories, multi-path components play a vital role in the coverage prediction. Therefore, radio planning in such conditions requires specific propagation models, for instance, spatial consistency models. In contrast to the non-consistent propagation model, where radio channel is simulated with one link only, spatial consistency models consider effect of other links, which appeared due to multi-path propagation. In this thesis work, radio channel was simulated using geometry-based stochastic spatial consistent propagation model.

Greedy heuristic algorithm proposed in this thesis allows to determine the locations of base stations with specified requirements, such as minimum percentage of the area covered with certain received signal level and maximum number of stations that can be planned in the area. Interference analysis plays significant role in this algorithm. It is very important to consider how base stations effect on each other: the closer they are, the higher interference level becomes. Base station locations are planned in such a manner that their mutual negative impact is minimized and the number of the sensors with sufficient received signal level is maximized.

Certainly, with the usage of very complex tools for coverage prediction, radio plan becomes more reliable. However, there is always a trade-of between the price of an expensive and complex tool and required accuracy. An automated algorithm and propagation model proposed in this thesis work balance the accuracy of prediction and the complexity of the tool. Besides, because of the fully customized settings, this program might be used in various use cases and with different technologies. Certainly, the algorithm is relevant not only for cellular networks, but for other types of wireless networks as well, for instance, for so called LoRA wireless network. Worth to mention, that it is one of the very possible use cases, when the LPWAN networks will be used on order to provide coverage to the remote sensors on big distances.

It should be highlighted here, that the value of proposed algorithm could be increased by introducing additional modules and functionality. The very first and possible enchantment that could be done is 3d model creation of the planned area. That will slightly increase complexity of the tool, but at the same time will allow to estimate coverage for sensors located not in the plane. That enhancement is relevant, for example, for industrial

use case, when high vertical pipes are installed over the area under consideration. Besides, as it was mentioned in Chapter 3.3.3, there is a possibility to add more degrees of freedom to the algorithm. Currently, the locations of base stations are taken into account, and in order to obtain better coverage, the locations of base station change. However, that is not the only option to consider, when doing radio network planning. For example, mechanical and electrical tilts of antennae could be considered in the algorithm. That will require an introducing of the antenna pattern to the tool. It is not a complicated task and will not make the tool much heavier, since the propagation model is considered in a such a way, that it is possible to apply antenna pattern there. However, this module is not included in the scope of this thesis work. Besides, such parameter as an azimuth of antenna will be important for accurate radio network plan. Thus, by implementing mentioned above modules, the algorithm could first check if the tilt or azimuth change will improve SINR picture. And, as a next step, if co-called soft changes do not help, then move a base station.

Despite on the lack of certain modules, the algorithm and the process of the IoT radio network planning in industrial environment described in the thesis give an overview of the difficulties and things to pay attention to during implementation of radio part of the IoT. In this thesis, possible technologies to provide coverage in industrial areas were studied. Main challenges in propagation models were discussed and selected propagation model is explained and presented. Proposed algorithm highlighted mains steps of the radio networks planning. Besides, criteria of performance evaluation of the radio network plans were proposed and discussed. Basically, all set goals were achieved and important topics were discussed.

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