Chapter 8

# Greening Municipality Through Carbon Footprint for Selective Municipality

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Additional information is available at the end of the chapter

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**Abstract**

Evaluation of the organizational greenhouse gas (GHG) emissions from operational activities of selective municipality was investigated in this study. The selected municipality is located in Songkhla Province, the southern part of Thailand, and is divided into seven functional units. The total GHG emissions were estimated at 16,920.29 ton $CO_2$ eq. in the fiscal year 2016. The carbon footprints under direct, indirect, and optional indirect emissions (scopes 1, 2, and 3, respectively) were found to be 1129.92, 255.24, and 15,535.13 ton $CO_2$ eq./year, respectively. The highest carbon footprint was from methane emissions related to solid waste decomposition in sanitary landfills (15,524 ton $CO_2$ eq./year). Therefore, the main GHG mitigation strategy proposed was the installation of waste to energy recovery in order to reduce waste throughput to the landfill. For specific municipal operations, diesel combustion in municipality-owned vehicles had the highest carbon emission followed by fugitive emissions from refrigerants and electricity consumption (746.92, 289.60, and 255.24 ton $CO_2$ eq./year, respectively). The important constraints in reducing GHG emissions from upstream and downstream of the organizational activities were identified in terms of time, cost, and data accessibility. Further, convergent cooperation and public participation are also significant for effective implementation of global warming mitigation strategies.

**Keywords:** carbon footprint for organization, GHGs emission, global warming, waste to energy

# 1. Introduction

## 1.1. Significance of carbon footprint for organization evaluation

Global warming and climate change have become a serious problem the world is faced with today. Global warming results from the emission of greenhouse gases (GHGs) as a result of anthropogenic activities related to agriculture, transportation, energy production, and use. The production and combustion of carbon-rich fossil fuels, especially coal, oil, natural gas, as well as agricultural activities including deforestation are undoubtedly the chief generators of GHGs. Global warming and climate change are adversely impacting on human and animal life.

The Kyoto Protocol identified the main GHGs accelerating climate change. The Intergovernmental Panel on Climate Change (IPCC) reports has shown that there is a strong correlation between the increasing $CO_2$ emissions and climate change. Consequently, increasing awareness of the impact of this crisis as well as GHG mitigation is indeed an important achievement, globally. As a result, many countries are making tremendous effort in preparing, coordinating, protecting, and developing strategies aimed at carbon mitigation and effecting changes at both local and national levels.

Carbon footprint (CF) is defined as the measurement of GHG emissions from an individual, product, or organization. According to Wiedmann et al. [1], CF is the measure of $CO_2$ emissions related either directly or indirectly to an activity during the complete life cycle of a product or a service. However, CF is not only concerned about $CO_2$ but other GHGs as well. Therefore, in order to simplify CF assessments, GHGs are all expressed in terms of carbon dioxide equivalent ($CO_2$ eq). This means that an activity is described for a given mixture and quantity of GHGs, in terms of the $CO_2$ that would have the same global warming potential (GWP), when measured over a specified time scale (normally, 100 years) [2].

Carbon Footprint for Organization (CFO) refers to an approach where the GHGs associated with an organization's activities are evaluated and calculated in terms of $CO_2$ eq. This is important in order to formulate mitigation strategies for activities where outstanding gains in $CO_2$ reduction can be achieved. This enables the development of a set of guidelines for the effective reduction of GHG emissions from urban, transportation, industrial, and service sections at both local and national levels. For this reason, CFO evaluations have been conducted worldwide for various organizations including nongovernmental organizations (NGOs), business enterprises, public authorities, and educational institutions at different scales (personal, institutional, city level, regional, national, and international) [3].

However, in Thailand, the evaluation of CFO has progressed at a very slow pace. Only a few large organizations have started to cooperate with the Thailand Greenhouse Gas Management Organization (TGO) in evaluating and verifying GHGs emissions. Most organizations still lack the knowledge, technical expertise, and skills for carbon foot printing. Due to the urgency of this issue, the focus of research in Thailand in relation to climate change is shifting, and already, carbon footprint analysis for local authorities has begun. "Promoting the Carbon Footprint of Local Government Organizations and Reporting Greenhouse Gas Emissions" project was established in order to activate the development of low carbon cities by supporting the implementation and budget of the TGO to report on GHG emissions from various activities and corporate service within the local municipalities. Several municipalities were selected to be part of this project. A GHGs reduction guideline is also in place to support the organization's carbon footprint assessment for Thailand. In order to achieve sustainable low carbon cities, improving the capacity of Thai local government organizations is imperative.

### 1.2. Carbon footprint for organizations for sustainable municipality

Local governments have a crucial role to play in the management of natural resources and the environment. However, rapid urbanization leading to an increase in both the number and size of cities directly works against their efforts. Consequently, urban areas have the highest GHG emissions due to the high-energy consumption, waste generation, and reduced forest cover. The latter also means reduced natural carbon sinks as forests are able to absorb most of the $CO_2$ naturally. Local governments should therefore play an instrumental role in global warming mitigation through the effective management of GHGs from their internal activities. Through CFO, they can account for all the GHGs emitted in terms of $CO_2$ eq, thereby enabling the formulation of management guidelines aimed at reducing GHG emissions.

A number of local authorities also calculated their carbon footprint to achieve various objectives, for example, to integrate sustainability into work performance, to perform a sustainability assessment of their operations, for use as a management tool with staff and customers, as well as for use in policy development. CF analysis can be a strategy through which a municipality can reduce their GHG emissions, promote sustainability, and raise public awareness for the organization as a low carbon city. The current project emphasizes CF performance calculation and mitigation of GHG emission for selected municipalities. Based on the results of the assessment, scenarios for sustainable environmental management were suggested. Mitigation approaches were discussed with operational teams and proposed to the municipality management committee.

In light of this, the Kho-hong Municipality, Hat Yai District, Songkhla Province, Thailand, joined the local GHG emission and reduction program in order to become a carbon neutral city and support the voluntary carbon market in Thailand with TGO. For the purpose of the project, data were collected from municipal activities in one fiscal year. The benefits for municipalities from participating in this program could be divided in terms of output, outcome, and impact. The GHG emission inventory showing the activities of the municipality together with the respective quantities of GHG emissions represents the "Output." In the scope of municipal responsibility and cooperation, there are several strategies for reducing GHG emissions from various activities and operations. Further, the municipal staff and administrators receive knowledge and gain valuable skills and experience in carbon evaluation and mitigation. Previously, lack of these skills and experience hindered efforts to conduct proper carbon foot printing for the municipality. "Outcome" represents the result of the implementation of the GHG emission reduction program in the organization. Consequently, budgetary management for personnel and organizations with improved consciousness of the need to conserve natural resources and the environment is made easier. The "impact" would be the realization of sustainable municipalities. Further, this can be developed as part of the Thailand Voluntary Emission Reduction Program (T-VER) in which case the carbon credits in the voluntary carbon market of Thailand can generate additional revenue for the municipalities [4].

## 2. Literature review

### 2.1. Sources of GHG and UNITS OF measurement

#### *2.1.1. GHGs types*

The seven GHGs identified in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) on Climate Change 2014 [5] are considered in the carbon footprint calculation. These are carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$).

#### *2.1.2. Equivalency factors of global warming potential*

The global warming potential (GWP) was established for the comparison of environmental impacts of different gases. Generally, the period set for GWPs is 100 years. GHG evaluation is determined in terms of carbon dioxide equivalents ($CO_2$ eq) in which case the other GHGs are converted to the universal unit based on their respective equivalency factors for GWP over the 100-year period in line with the latest version of the IPCC report. For example, the GWP of $CH_4$ as compared to $CO_2$ is 25. This means that 1 kg of $CH_4$ has an impact on global warming equivalent to 25 kg of $CO_2$ for 100 years. In other words, the emission of 1 kg $CH_4$ is 25 kg $CO_2$ equivalent. **Table 1** shows the GWPs of the various GHGs in terms of IPCC's Fifth Assessment Report (AR5) [6].

#### *2.1.3. Sources of GHG emissions*

These following sources of GHG emissions are taken into account for carbon footprint:

- raw material acquisition
- electricity production and consumption
- combustion processes
- chemical reactions in industry
- processing, manufacturing and operations
- transportation of entire process
- leakage of refrigerants and other fugitive gases
- livestock, agricultural production and waste generation
- waste and waste management
- fossil fuel are included in carbon footprint calculation but $CO_2$ emissions from biogenic sources are excluded.

#### *2.1.4. Unit of analysis*

Unit for GWPs calculation could be obtained from the common unit of measurement which provides a simple guide enabling the policymakers to compare GHGs emission and effectiveness of mitigation measures for various sectors and gases. The unit of analysis can therefore be set as per unit of product such as per kg, per liter, per piece, and so on.

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| Common Name | Formula | (AR5) |
|---|---|---|
| Carbon dioxide | $CO_2$ | 1 |
| Methane | $CH_4$ | 25 |
| Nitrous oxide | $N_2O$ | 298 |
| Hydrofluorocarbon | HFCs | 124-14,800 |
| Perfluorocarbon | PFCs | 7,390 – 12,200 |
| Nitrogen trifluoride | $NF_3$ | 17,200 |
| Sulfur hexafluoride | $SF_6$ | 22,800 |

**Table 1.** GHG and the global warming potential (GWP) [6].

### 2.2. GHGs protocol emission scopes

**Figure 1**, adapted from the World Resources Institute (WRI) GHG Protocol, illustrated the three different groups, or "scopes," including direct, indirect, and optional sources of GHG emissions under the GHG Protocol. As the rule of thumb, data for direct emissions, including wastewater treatment, direct energy generation, travel in the company-owned vehicles, landfill gas, and fugitive GHG emissions, should be reported. Further, indirect emissions from subscribed electricity and steam, for example, must be included. Most of the programs do not report GHG emissions from optional source, such as from vehicles that are not owned by the company, outsourced activities, waste disposal, purchased materials, and product use [7].

#### *2.2.1. Principle of GHG protocol*

The five principles of the GHG protocol are relevance, completeness, consistency, transparency, and accuracy (**Figure 2**) [8].

##### *2.2.1.1. Relevance*

The GHG sources to be selected, the GHG sinks, reservoirs, data, and methodologies for assessment must be appropriate to the specific needs of the intended user.

##### *2.2.1.2. Completeness*

It includes all relevant GHG emissions and removals.

All the relevant GHG emissions and removals must be included.

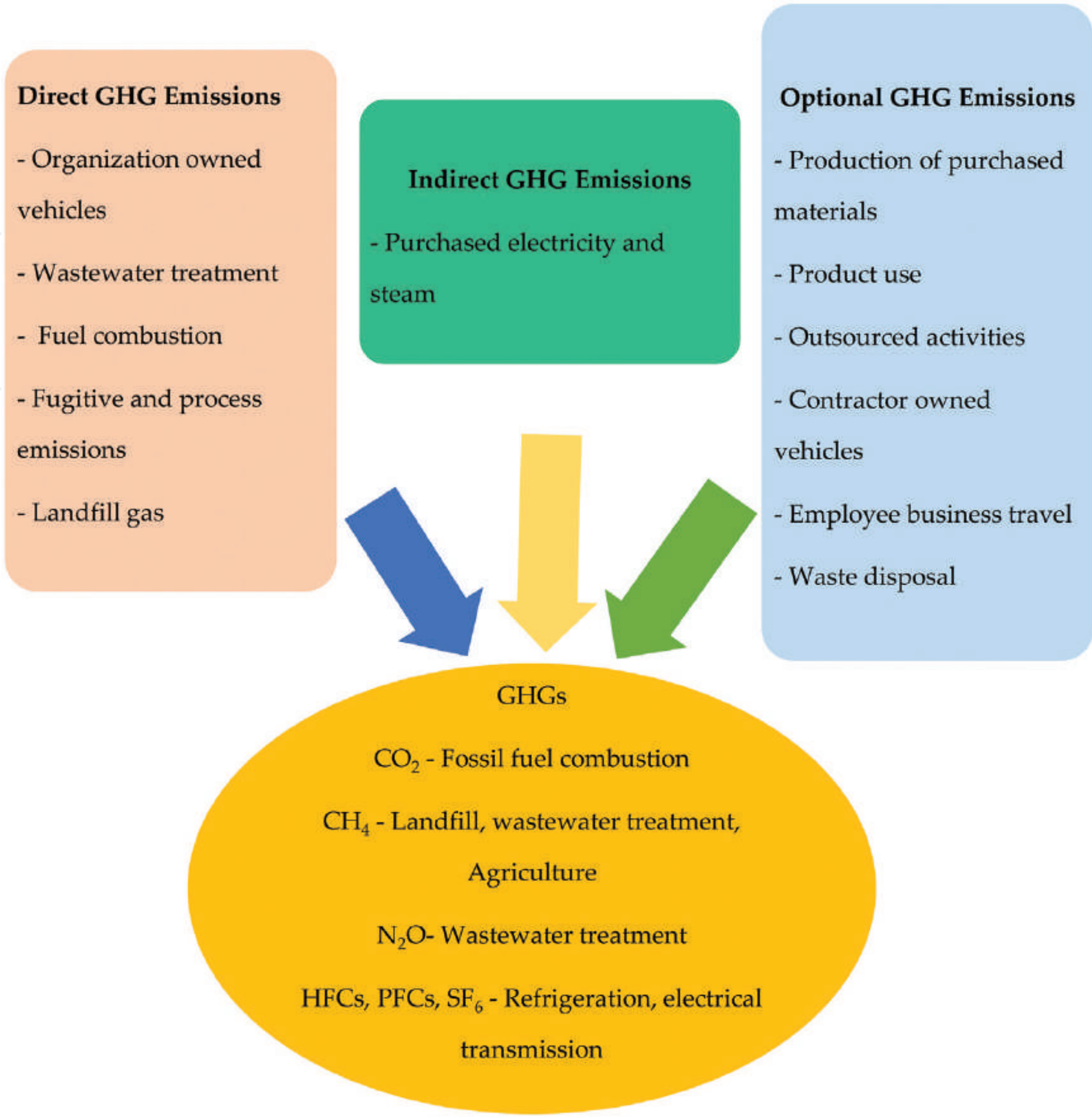


**Figure 1.** GHGs protocol emissions scopes.

#### *2.2.1.3. Consistency*

It enables meaningful comparisons in GHG-related information.

#### *2.2.1.4. Accuracy*

It reduces bias and uncertainties as far as is practical.

Bias and uncertainties must be reduced as far as is practical.

#### *2.2.1.5. Transparency*

It discloses sufficient and appropriate GHG-related information to allow intended users to make decisions with reasonable confidence.

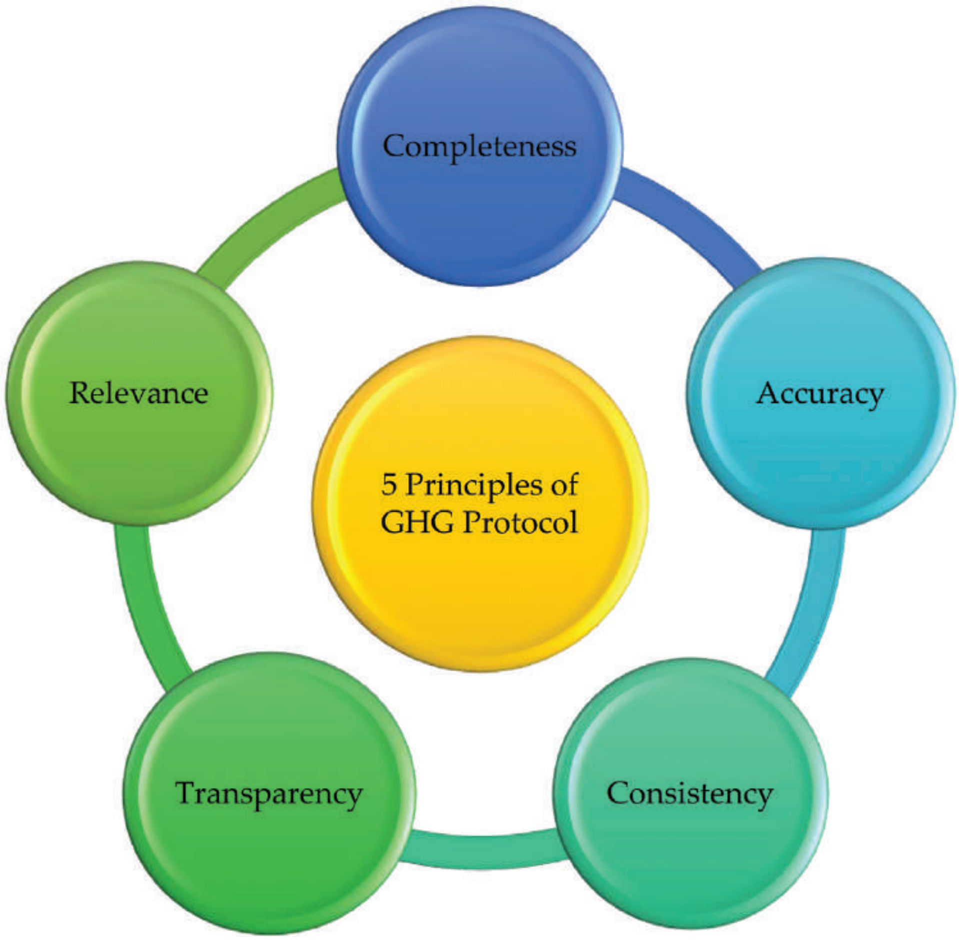


**Figure 2.** Principles of GHG protocol.

The first principle of relevance is important for providing available information to stakeholders both internal and external to the company. The completeness of the GHG report is measured in terms of how comprehensive and meaningful the compiled information is. Consistency in the organization's reporting of GHG emissions will allow them to track emissions over time to identify trends. Transparency within the GHG report allows for a clear audit trail of the information presented. Accuracy, along with the four other accounting and reporting principles, will ensure that the organization produces a true and fair representation of their GHG emissions [9].

### 2.3. Scope of the GHG emission source

The GHG emission sources were categorized into three different "scopes." Scope 1 accounts for direct emissions from sources that are controlled or owned by the organization; scope 2 refers to indirect emissions that occur from the generation of subscribed electricity, steam, or heat used by the organization; and scope 3 accounts for all other indirect emissions resulting from the company activities, but emitted from sources not controlled or owned by the company as presented in **Figure 3** [8].

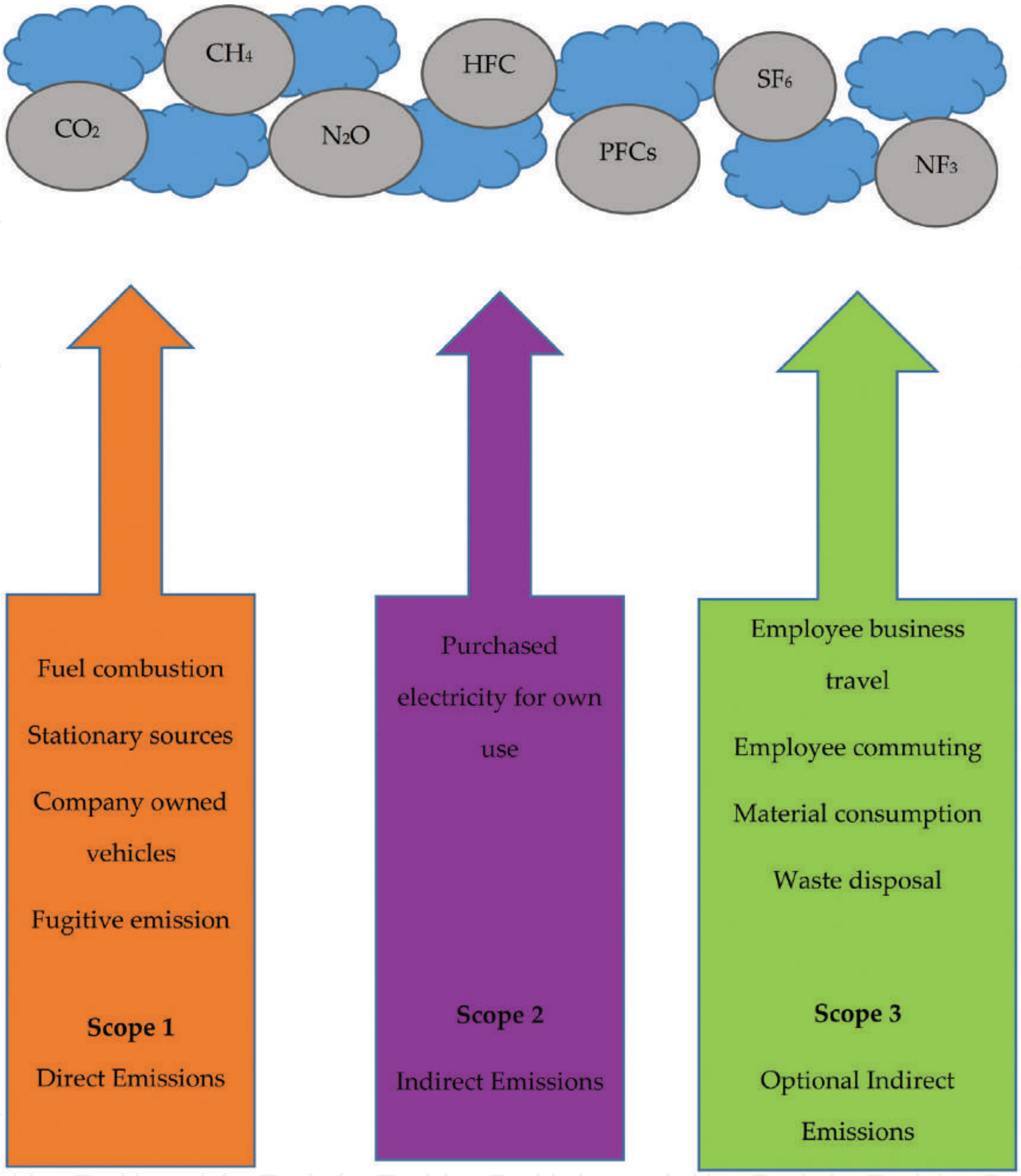


**Figure 3.** The carbon emission sources in three scopes.

GHG inventories reporting now include all direct and indirect emissions for all activities in the upstream supply chain as well as those emissions resulting from the consumption and disposal of an entity's products. This broadened view highlights the necessity for a consumption-based approach [10]. Consequently, the quantification of scope 3 emissions is a demanding task since a number of sectors have to be analyzed in order to capture changes in the consumption patterns. Downstream purchasing entities often lack access to the detailed information pertaining to the manufacturing of each product they purchase. Further, they lack the resources, and in some cases, the technical capacity to investigate the supply chain for each product. Consequently, the estimation of scope 3 emissions makes use of streamlined methods [11].

The GHG emissions emitted from direct and indirect sources by an entity can be categorized into different scopes:

***Scope 1*** accounts for direct emissions of GHG emitted from sources, such as fossil fuels burned on site, emissions from entity-leased or entity-owned vehicles, and other direct sources, which are controlled or owned by the entity.

***Scope 2*** accounts for indirect emissions of GHG emitted from source, such as the electricity generation, the transmission and distribution (T&D) losses associated with some purchased utilities (e.g., chilled water, steam, and high temperature hot water), and heating and cooling, or steam, which are generated off site but purchased by the entity.

***Scope 3*** accounts for emissions of GHG emitted indirectly from sources, such as T&D losses associated with purchased electricity, employee travel and commuting, contracted solid waste disposal, and contracted wastewater treatment, which are not controlled or

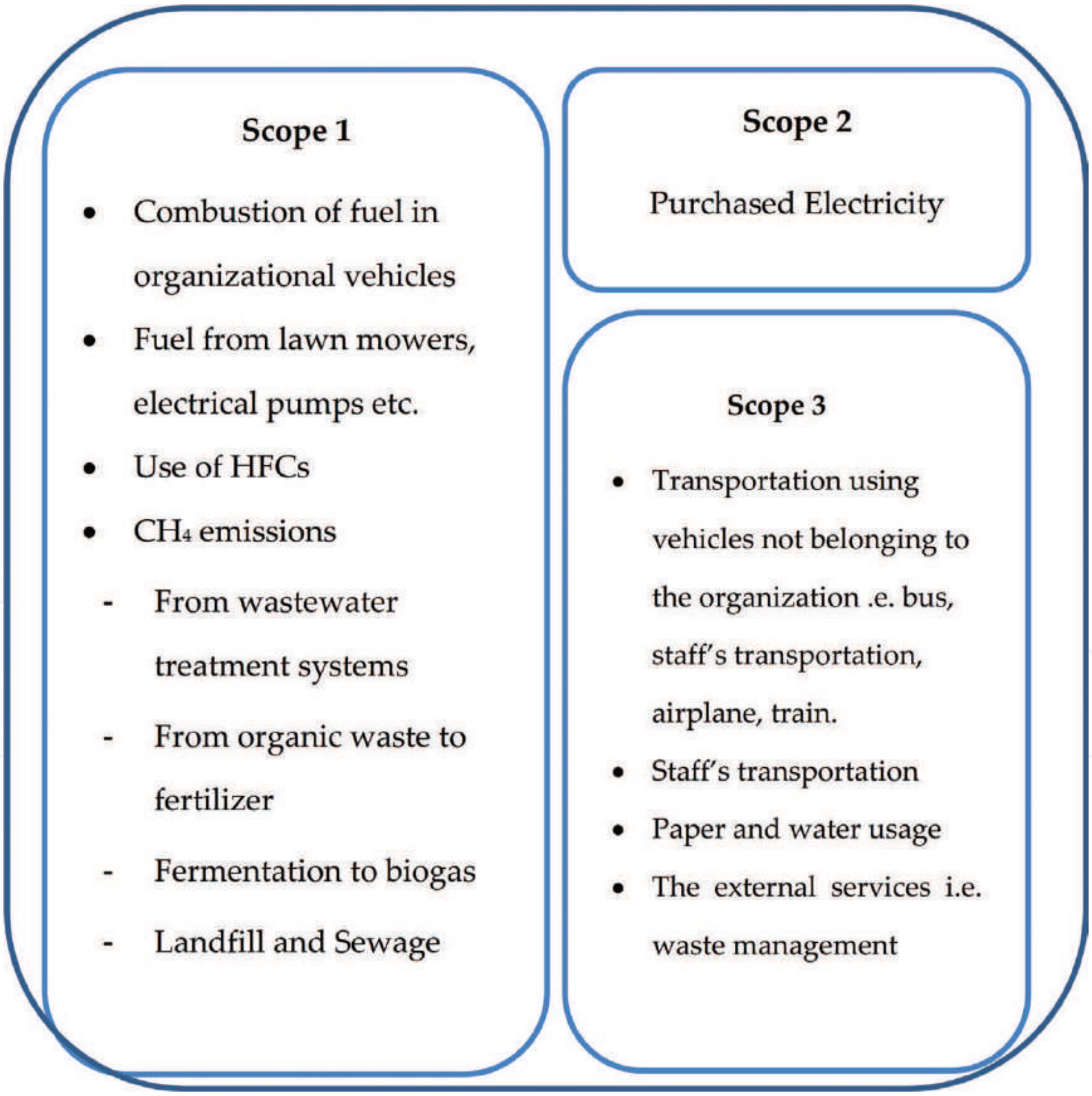


**Figure 4.** The scope of carbon emission sources in local organization [12].

owned by the entity but associated to the entity's activities. Those GHG emission sources are currently required for federal GHG reporting. Additional sources, such as GHG emissions from leased space, outsourced activities, vendor supply chains, and site remediation activities, are presently optional under federal reporting requirements, but they are substantial.

TGO defined the framework for carbon footprint for organizations in terms of three scopes as illustrated in **Figure 4** [12].

### 2.4. Step for GHG accounting and reporting

In order to measure the GHG emission and mitigation, the procedure for GHG calculation and reporting is illustrated in **Figure 5** [13].

### 2.5. Background of Kho-hong municipality

In general, Kho-hong municipality is located on the east of Hatyai municipality as illustrated in **Figure 6**. It is 2.5 km away from Hatyai district office and 30 km away from Songkhla province. The distance from Bangkok is about 1125 km.

The information of Kho-hong municipality could be described as follows:

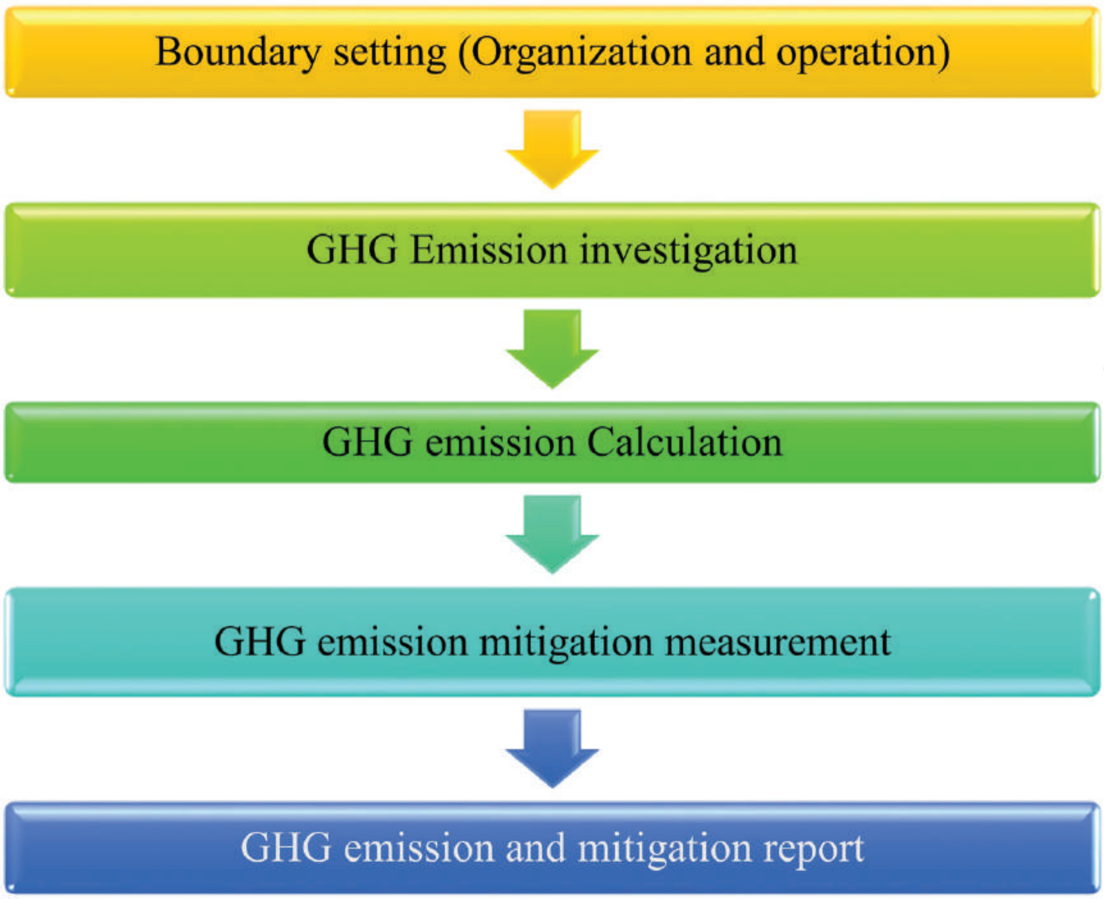


**Figure 5.** Steps for GHG accounting and reporting (modified from [13]).

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### 2.5.1. Boundary

Kho-hong municipality territorial areas are as follows:

- In the north, the municipality borders with the Klong-hae municipality and Nam-noi sub-district.
- In the south, it borders with the Ban-pru municipality and Ban-rai sub-district.
- In the east, it borders with the Sub-district Administration Organization (hereafter SAO) of Thung-yai and Na mom and.
- On the western side, the municipality borders with Hat-yai and Kuan-lung municipalities.

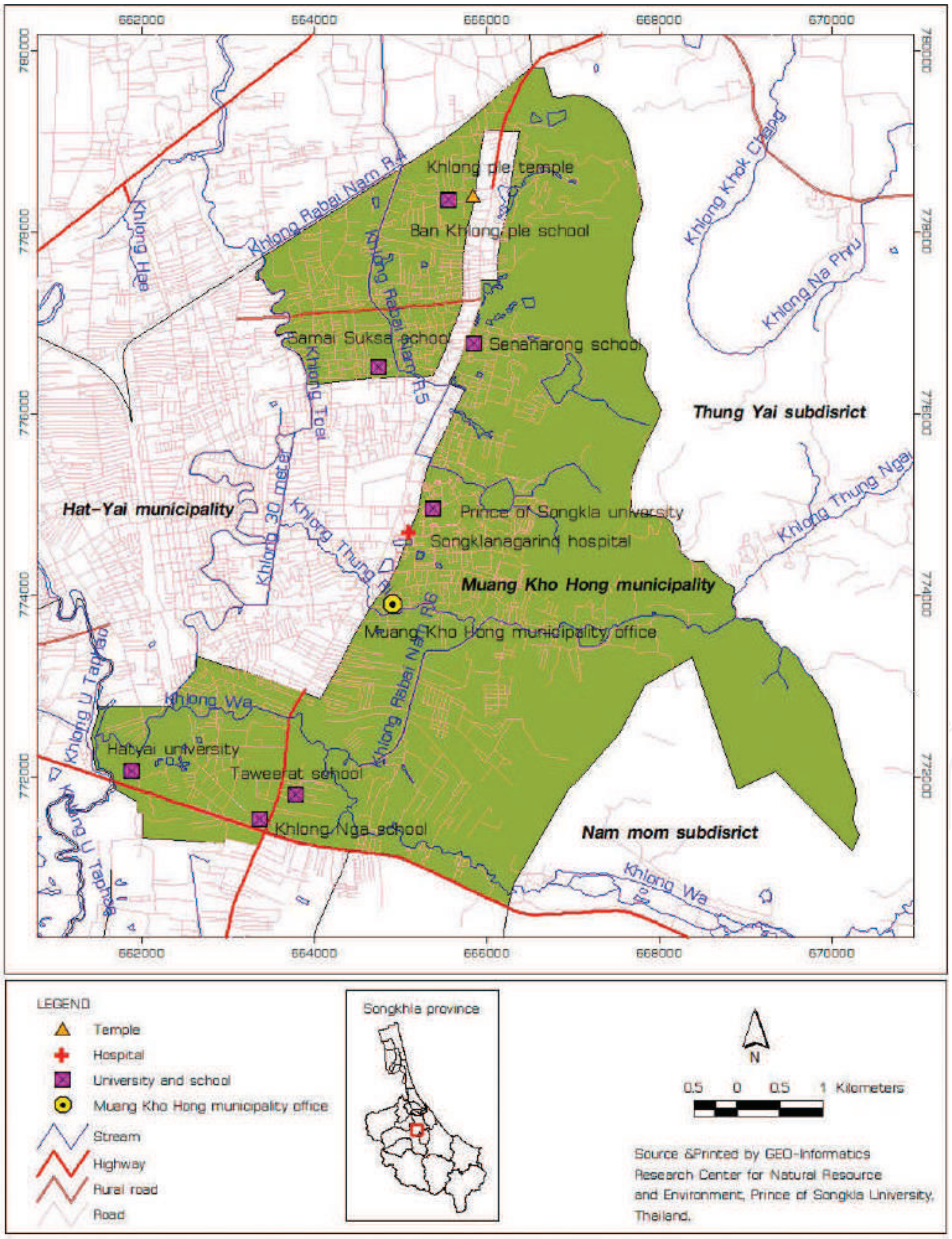


**Figure 6.** Map of Kho-hong municipality [4].

### *2.5.2. Population*

The current population of Kho-hong municipality is about 45,939 persons which are 22,283 males and 23,656 females (February 2018) [14]. The total household in the municipality is 27,739 households, divided into 30 groups [4].

### *2.5.3. Geography*

The area of Kho-hong municipality is approximately 34.57 $km^2$ or 8,542.43 acres (**Figure 6**). The area is generally a flat area near Kho-hong hill slope down to the Au-tapao Canal which is the border line of the Kuan-lang and Kho-hong districts. The predominant soil texture is sandy soil and sandy loam, with isolated portions of clay soil [4].

### *2.5.4. Community settlements*

The municipality is located in the area between the floodplain and highland areas in the eastern part of the district. According to data gathered from the Prince of Songkla University (PSU) also located in Kho-hong municipality, the community was not established many years ago, when compared to other municipalities in the Southern provinces of Thailand. The community type is also educational and residential zone. A much older community is located in the northern end of Kho-hong municipality. This area supported the expansion of the city's residential area. However, frequent floods affected the progression of settlements in the municipality.

### *2.5.5. Climate data*

Kho-hong municipality is located in the tropical monsoon zone: the southwest and the northeast monsoon. The northeast monsoon blows from October to mid-January and the southwest


**Figure 7.** Kho-hong municipality office.

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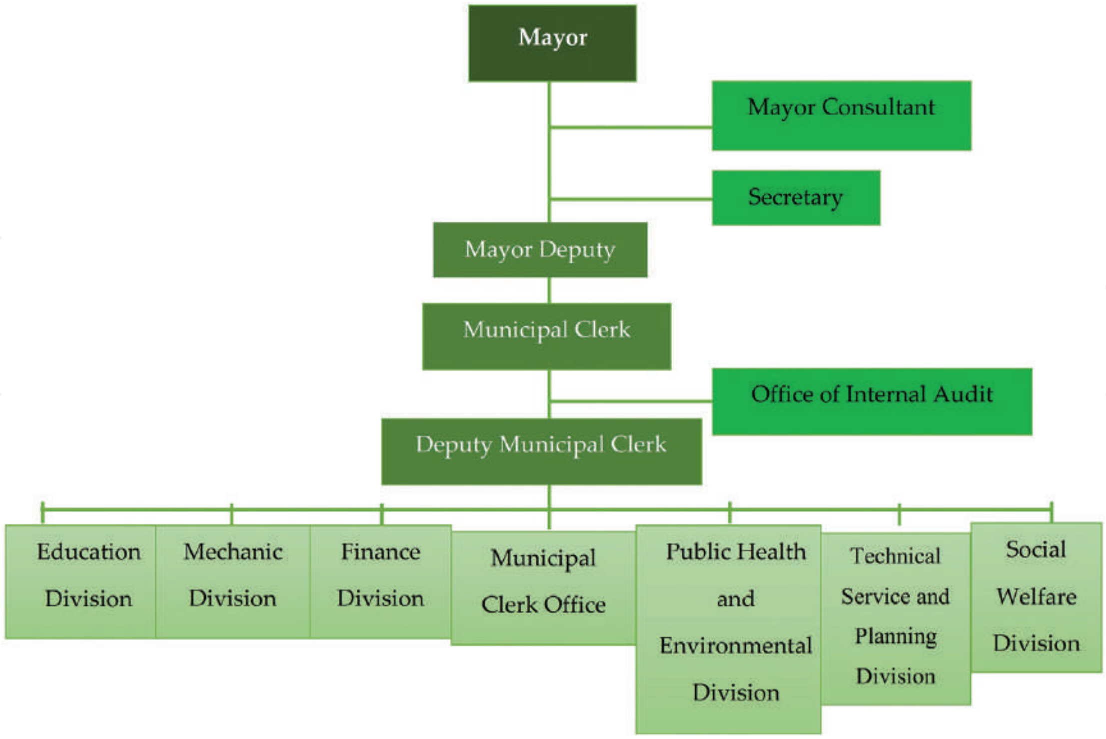


**Figure 8.** Organization chart for Kho-hong municipality **[5]**.

monsoon blows from mid-May to mid-October. Due to the monsoon influence, there are only two seasons: summer which spans from February to July and the rainy season which spans from August to January. The annual rainfall is approximately 1995 mm. The average temperature is 28.1°C. In summer and rainy seasons, the average temperature is about 27.7–29.1°C and the average temperature reduces to 26.7°C in December [15]. The lowest temperature on record was measured at 13.7 on February 4, 2014, at Kho-hong air quality monitoring center. The average minimum and maximum temperatures are 24.8 and 40.3°C, respectively. The relative humidity is 77% [16].

### *2.5.6. Organization information*

Kho-hong municipality office (**Figure 7**) comprises seven divisions based on its function including education service, mechanic, finance, municipal clerk office, public health and environment, technical service and planning, and social welfare. Each division is responsible for municipal council management. According to this classification, **Figure 8** illustrates the organization profiles of Kho-hong municipality which has a service schedule from 8.30 am to 4.30 pm in a full operation mode on weekdays (Monday to Friday). The office closes during weekends and public holidays. The full working time is therefore 8 h a day excluding lunch time break.

## 3. Materials and methodology

To evaluate CFO, Kho-hong municipality has a committee in order to collect and provide data and relevant information in February 2017. The first step to run the project began with in-house training for staff by consultant from the Faculty of Environmental Management, Prince of Songkla University, Hatyai, Songkhla, Thailand.

### 3.1. Scope and boundary

Scope and boundary of collecting data were clarified in terms of the following:

#### *3.1.1. Organization boundary*

Control approach in terms of operational control which account for the activities owned and run by municipality.

#### *3.1.2. Base year*

Single base year approach in fiscal year 2016 started from October 2015 to September 2016.

#### *3.1.3. Geographical operations: Activities*

Prior to set the operational boundary, the organization context was defined in terms of

1. layout
2. organization structure
3. the area and amount of staff
4. organization type: management function of Kho-hong municipality.

#### *3.1.4. Operational boundary*

In order to obtain an effective data collection, a clear determination of emission sources was necessary. Based on TGO greenhouse gas reporting and literature review, the operational boundary can be classified into three scopes as follows:

Scope 1: All direct GHG emissions, with the exception of direct $CO_2$ emissions from biogenic sources.

1. GHG emissions from stationary combustion units
   - **1.1.** Electricity production for organization use
   - **1.2.** Fossil fuel combustion from stationary machines which are controlled or owned by organization
2. GHG emissions from mobile combustion
3. Fugitive GHG emissions.

Scope 2: Indirect GHG emissions associated with the consumption of purchased or acquired electricity, heating, cooling, or steam.

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Scope 3: All other indirect emissions which are not covered in scope 2 including upstream and downstream emissions, emissions resulting from the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting organization, use of sold products and services, outsourced activities, recycling or used products, waste disposal, and so on [9].

#### *3.1.5. GHG from operational activities*

The research is carried out to measure GHG emission from the operation control of Kho-hong municipality for the purposes of consolidating and reporting GHG emissions.

In this study, seven GHGs, which are the target for the first commitment period of the Kyoto Protocol, are included namely carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbon (HFCS), perfluorocarbon (PFCs), sulfur hexafluoride ($SF_6$), and nitrogen trifluoride ($NF_3$) were investigated.

With the TGO's guidelines, all of human activities are taken into account to GHG emission. So the assumption and estimation of the GHG were analyzed baseline annual calculation on Kho-hong municipality in fiscal year 2016.

#### *3.1.6. Facilities for consideration in GHG emissions calculation*

- The facilities include seven divisions of municipality function namely education service, mechanic, finance, municipal clerk office, public health and environment, technical service and planning, and social welfare.
- Excluded facilities:

  1) The outsource performance related to municipality operation and staff own vehicle.

  2) Dry chemical in extinguisher according to its application was not regarded as an impact on GHG emission.

The activity data and source of GHG emission were provided for evaluating carbon performance as presented in **Table 2**.

### 3.2. Data collection

In order to achieve data evaluation, data collection and report are requisite to confirm that the process is following principle guidelines of the GHG protocol by TGO, which provided a guideline GHG protocol corporate concept and the GHG emissions report. Data flow (**Figure 9**) was analyzed and evaluation criteria were established before primary data were collected by means of measurement, evaluation, and interview. Secondary data could be reached from calculation, statistical data, exploration, literature review, and so on.

### 3.3. Data calculation

To achieve the first objective, "Identify and quantify carbon mitigation possibility," all data collected from scopes 1–3 were calculated by Eq. (1). An example of these data and the subsequent carbon footprint calculations has been provided in Appendix A

| Scope | Activity |
|---|---|
| **Scope 1** | 1.1 Stationary combustion |
| | 1.1.1 Gasoline combustion from stationary machine i.e. mower |
| | 1.1.2 Diesel combustion from foggy machine and power supply |
| | 1.2 Mobile combustion |
| | 1.2.1 Gasoline combustion from organization's vehicles |
| | 1.2.2 Diesel combustion from organization's vehicles |
| | 1.3 Septic tank |
| | 1.4 Wastewater |
| | 1.5 Waste recovery - Compost |
| **Scope 2** | Electricity consumption |
| **Scope 3** | 3.1 Paper consumption (A4 and A3) |
| | 3.2 Water consumption |
| | 3.3 Solid waste management |

**Table 2.** Activities data.

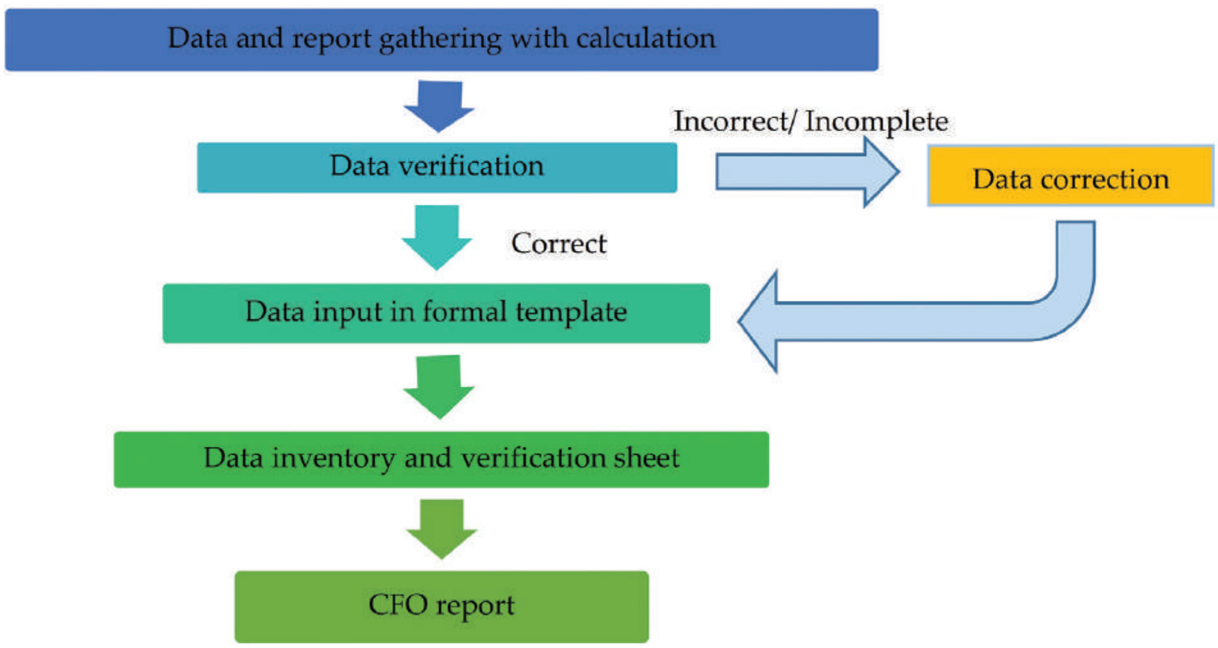


**Figure 9.** Data flow for carbon footprint evaluation.

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$$CO_2\ Emission = Activity\ Data\ x\ Emission\ Factor \quad (1)$$

*3.3.1. Activities data*

Activity data and source of GHG emissions were gathered from each division and summarized following the scope as summarized in **Table 3**.

| Resource | GHG | Pollution Source | Emission Factor (kg GHG/unit) | Emission Factor Source |
|---|---|---|---|---|
| **Scope 1** | | | | |
| Stationary combustion | $CO_2$ | Gasoline Combustion | 2.1816 | IPCC Vol. 2 table 2.2 DEDE |
| | $CH_4$ | | 0.0001 | |
| | $N_2O$ | | 0.0000 | |
| Mobile combustion | $CO_2$ | Gasoline Combustion | 2.1816 | IPCC Vol.2 table 3.2.1, 3.2.2, DEDE |
| | $CH_4$ | | 0.0010 | |
| | $N_2O$ | | 0.0001 | |
| | $CO_2$ | Diesel Combustion | 2.6987 | IPCC Vol.2 table 3.2.1, 3.2.2, DEDE |
| | $CH_4$ | | 0.0001 | |
| | $N_2O$ | | 0.0001 | |
| Septic tank | $CH_4$ | Wastewater from septic tank | 25.00 | IPCC 4th Assessment Report, Climate Change 2007 |
| Wastewater w/o treatment | $CH_4$ | Domestic wastewater | 25.00 | IPCC 4th Assessment Report, Climate Change 2007 |
| Compost | $CH_4$ | Compost waste | 25.00 | IPCC 4th Assessment Report, Climate Change 2007 |
| R-22 refrigerant | $CO_2$ | Fugitive emission from refrigerant R-22 | 1,810 | R-22 (HCFC-22), World Meteorological Org, 2006, Carbon Footprint for Organization (TGO, 2017) |
| **Scope 2** | | | | |
| Electricity | GHG | Electricity appliances | 0.5821 | Thailand Grid Mix Electricity LCI Database 2014, Carbon Footprint for Organization (TGO, 2017) |
| **Scope 3** | | | | |
| Paper consumption | GHG | Working documents, meeting documents | 2.0859 | Thai National LCI Database/MTEC, Carbon Footprint for Product (TGO, 2016) |
| Water consumption | GHG | Faucets, sanitary wares | 0.7043 | Thai National LCI Database/MTEC, Carbon Footprint for Product (TGO, 2016) |
| Sanitary landfill | $CH_4$ | Anaerobic Digestion from Sanitary Landfill | 25.00 | IPCC 4th Assessment Report, Climate Change 2007 |

**Table 3.** Emission source and emission factor.

**Figure 10.** Verification process in Kho-hong municipality office.

*3.3.2. Emission factors*

The emission factors were chosen from reliable data sources, that is, IPCC, Thai LCI Database, DEDE, and TGO as presented in **Table 3**.

### 3.4. Data verification

After the inventory data were compiled by municipality, the verification process began. The collected and analyzed data were verified by a consultancy team from Thaksin University in terms of collection method, data acquisition and accessibility, data correctness, including emission factors and calculations. The meeting was hosted by Kho-hong municipality (**Figure 10**).

## 4. Results and discussion

The GHG emission sources were summarized by scope. The primary data of each emission source were obtained for calculation in different conversion units. The GHG emission sources were presented for each division document and evidence as presented in **Table 4**. GHG emissions were calculated in terms of ton $CO_2$ eq. Total direct GHG emissions from stationary and mobile combustion including fugitive emissions were calculated to be 1129.92 ton $CO_2$ eq. The diesel combustion from mobile source occupies the biggest portion of scope 1 emissions of about 746.92 ton $CO_2$ eq/year. Meanwhile, $CH_4$ emissions generated from waste in sanitary landfill was the major source of alternative indirect emission for scope 3 equal to 15,524 ton $CO_2$ eq./year or 91.75% of total emissions with regard to municipality responsible for Kho-hong waste management. The least proportion emission was from consumed electricity for the municipality (255.24 ton $CO_2$ eq./year). Therefore,

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| Emission Source | Division | Data Source | Unit | Amount |
|---|---|---|---|---|
| **Scope 1** | | | | |
| Gasoline combustion | Mechanic | Petroleum receipt | L | 15,672.63 |
| | Finance | | | 18.00 |
| | Public Health and Environment | | | 6,914.56 |
| Diesel Combustion | Mechanic | Petroleum receipt | L | 150,186.67 |
| | Finance | | | 1,090.00 |
| | Technical Service and Planning | | | 2,371.00 |
| | Social Welfare | | | 1,730.00 |
| | Education | | | 1,480.00 |
| | Clerk office | | | 20,275.36 |
| | Public Health and Environment | | | 95,007.62 |
| $CH_4$ from septic tank | | C | kg $CH_4$ | 1,324.22 |
| $CH_4$ from wastewater without treatment | | C | kg $CH_4$ | 18.13 |
| $CH_4$ from waste compost | | R | kg $CH_4$ | 49,309.50 |
| Fugitive refrigerant R-22 | | R | Kg $CO_2$ | 160.00 |
| **Scope 2** | | | | |
| Electricity consumption | Technical Service and Planning | Electricity bill from Provincial Electricity Authority of Thailand | kWh | 121.00 |
| | Social Welfare | | | 15,459.00 |
| | Education | | | 51,696.38 |
| | Clerk office | | | 348,744.04 |
| | Public Health and Environment | | | 18,202.00 |
| | Mechanic | | | 4,262.00 |
| **Scope 3** | | | | |
| Paper use | | Annual record | kg | 2,227.86 |
| Water consumption | Social Welfare | Water payment bill | $m^3$ | 1,653.00 |
| | Education | | | 3,137.00 |
| | Clerk office | | | 3,671.00 |
| | Mechanic | | | 752.00 |
| $CH_4$ from sanitary landfill | | C | kg $CH_4$ | 620,960 |

Remark: C = Calculation, R = Record

**Table 4.** Summary of carbon emissions for Kho-hong municipality under three scopes.

total emissions from Kho-hong municipality operations were evaluated to be 16,920.29 ton $CO_2$ eq. The carbon footprints under scopes 1, 2, and 3 are 6.67, 1.51, and 91.81% of the total emission, respectively, as presented in **Table 5**. In comparison, scope 3 revealed the highest carbon footprint in this study. Correspondingly, it was found that 75% of an industry sector's carbon footprint is attributed to scope 3 emissions [17]. The emissions for scope 3 increased due to the increasing population and complex nature of activities performed by different kinds of organizations and the varying scales in which they function [18]. Although scope 3 emissions represent the largest proportion of the organizational carbon footprint, they represent the priority in carbon balance strategies [19].

In order to reduce GHGs emission, several strategies were proposed. 3Rs (Reduce, Reuse, and Recycle) are approaches which would effectively reduce waste at source and transfer stations. Waste to energy is another alternative to waste recovery prior to disposal in landfill. However, the cooperation and participation of municipal staff impacts negatively on GHG mitigation efforts through electricity consumption reduction including energy savings through responsible

| Description | Unit | Amount | Emission Factor (kg GHG/unit) | $CO_2$ Emission (ton $CO_2$ eq.) | % |
|---|---|---|---|---|---|
| **Scope 1** | | | | | |
| - Gasoline (Stationary) | L | 1,666.20 | 2.1896 | 3.65 | 0.02 |
| - Gasoline (Mobile) | L | 20,938.99 | 2.2376 | 46.85 | 0.28 |
| - Diesel (Mobile) | L | 272,140.65 | 2.7446 | 746.92 | 4.41 |
| - $CH_4$ from septic tank | kg $CH_4$ | 1,324.22 | 25 | 33.11 | 0.20 |
| - Wastewater w/o Treat | kg $CH_4$ | 18.13 | 25 | 0.45 | 0.00 |
| - Compost | kg $CH_4$ | 49,309.50 | 25 | 9.34 | 0.05 |
| - R-22 refrigerant* | kg $CO_2$ | 160 | 1,810 | 289.60 | 1.71 |
| **Total** | | | | **1,129.92** | **6.67** |
| **Scope 2** | | | | | |
| - Electricity | kWh | 438,484.92 | 0.5821 | 255.24 | 1.51 |
| **Scope 3** | | | | | |
| - Paper | kg | 2,227.86 | 2.0859 | 4.64 | 0.03 |
| - Water consumption | $m^3$ | 9,213.00 | 0.7043 | 6.49 | 0.04 |
| - Sanitary landfill | kg $CH_4$ | 620,960.00 | 25.00 | 15,524.00 | 91.75 |
| **Total** | | | | **15,535.13** | **91.81** |
| **Total** | | | | **16,920.29** | **100** |

Remark: w/o = Without, IPCC, DEDE – Department of Alternative Energy Development and Efficiency, Ministry of Energy, Thailand, R-22 refrigerant is not included in Kyoto Protocol

**Table 5.** Carbon footprint evaluation from Kho-hong municipality in 2016.

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vehicle usage. Incentives for GHG emission mitigation would be optional for increasing motivation for carbon footprint balance [20]. The three most influential constraints to collect data and GHG emissions reduction from upstream and downstream of the organizational activities would be identified in terms of time, cost, and data accessibility. Many organizations have a poor understanding of GHG emissions directly and indirectly associated with their activities. Consequently, this limited reduction for GHGs mitigation in the local municipality is a subject requiring further exploration. The carbon footprint should also be continually evaluated to monitor the GHG reduction and energy conservation measures [21]. The convergent approaches are practically involved in global warming mitigation thoroughly as well.

## 5. Conclusion

A general methodology, which provides a practical, reliable, and transparent inventory for practitioners in assessing the carbon footprint for local organizations, was followed. The total carbon footprint for Kho-hong municipality is 16,920.29 ton $CO_2$eq/year. Carbon footprints under scopes 1, 2, and 3 are 1129.92, 255.24, and 15,535.13 ton $CO_2$eq/year, respectively. The highest carbon footprint was represented by waste to sanitary landfill (15,524 ton $CO_2$eq/year) while the highest emission from activities in municipality was due to diesel combustion from municipality-owned vehicles (746.92 ton $CO_2$eq/year) followed by fugitive emissions from refrigerant (289.60 ton $CO_2$eq/year), and third emissions were electricity consumption (255.24 ton $CO_2$ eq/year). The lowest emissions were due to emissions from wastewater without treatment (0.45 ton $CO_2$ eq/year). Though indirect emissions (scope 3) represent the largest proportion of the organization's carbon footprint, these are seldom the priority in carbon management policies in municipalities. In order to reduce GHGs emission, several strategies were proposed. 3Rs (Reduce, Reuse, and Recycle) are adaptive approaches which would effectively reduce waste at source and transfer stations. Waste to energy is another alternative to waste recovery prior to disposal in landfill. However, the cooperation and participation of municipal staff impacts negatively on GHG mitigation efforts through electricity consumption reduction including energy savings through responsible vehicle usage. Incentives for GHG emission mitigation would be optional for increasing motivation for carbon footprint balance. The carbon mitigation with cost reduction should not only be one's task responsibility but public participation is also required to provide sustainable workplace [22]. Convergent approaches would be a good alternative for GHGs mitigation for local organizations. However, limitations in time, cost, and human behavior (negatively impacting on public cooperation) were some of the most important barriers identified.

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## Appendix.A. Example of scope 2 carbon emission from electricity consumption

| Division | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Total (kWh) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TSP | 0.00 | 0.00 | 12.00 | 13.00 | 11.00 | 12.00 | 12.00 | 12.00 | 3.00 | 13.00 | 20.00 | 13.00 | 121.00 |
| SW | 1,969.00 | 2,052.00 | 2,334.00 | 2,483.00 | 2,118.00 | 2,581.00 | 1,308.00 | 240.00 | 17.00 | 28.00 | 47.00 | 282.00 | 15,459.00 |
| Education | 2,490.70 | 4,442.80 | 4,591.80 | 4,780.20 | 4,103.90 | 5,347.80 | 2,731.00 | 4,393.90 | 2,653.80 | 4,910.60 | 5,499.70 | 5,750.18 | 51,696.38 |
| Clerk Office | 26,049.68 | 27,119.08 | 26,904.08 | 25,900.84 | 24,281.32 | 31,626.36 | 28,570.84 | 29,183.52 | 30,021.04 | 29,485.32 | 36,292.24 | 33,309.72 | 348,744.04 |
| PHE | 1,191.00 | 1,494.00 | 1,516.00 | 1,459.00 | 1,271.00 | 1,424.00 | 1,452.00 | 1,720.00 | 1,554.00 | 1,685.00 | 1,729.00 | 1,707.00 | 18,202.00 |
| Mechanic | 40.00 | 55.00 | 261.00 | 299.00 | 319.00 | 459.00 | 266.00 | 845.00 | 337.00 | 460.00 | 921.00 | 0.00 | 4,262.00 |
| **Total** | **31,740.38** | **35,162.88** | **35,618.88** | **34,935.04** | **32,104.22** | **41,450.16** | **34,339.84** | **36,394.42** | **34,585.84** | **36,581.92** | **44,508.94** | **41,061.90** | **438,484.42** |

Remark: TSP = Technical Service and Planning Division, PHE = Public Health and Environment Division

**Calculation steps**

$$GHG\ emissions\ electricity(kg\ CO\,2\,eq.yr\,-1)\ =\ E\ x\ EF\ e \tag{A1}$$

*where E* = Electricity consumption (kWh/year).

EFe = $CO_2$ emission factor for electricity consumption which, is 0.5821 kg $CO_2$/kWh (Thailand Grid Mix Electricity LCI Database 2014_Update 1 Jan 2017, **Table 3**).

From the data above, the total electricity consumption = 438,484.42 kWh

$GHG\ emissions_{electricity}$ = 438,484.42 × 0.582

= 255,241.78 kg $CO_2$ eq/year

**= 255.24 ton $CO_2$ eq/year**

**Table A1.** Electricity consumption of Kho-hong municipality in 2016 [4].

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Chapter 1

# Introductory Chapter: Next Generation of Broadband Networks as Core for the Future Internet Societies

Abdelfatteh Haidine and Abdelhak Aqqal

Additional information is available at the end of the chapter

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## 1. Introduction: evolution of the needs for “broadband”

The Internet traffic is an ongoing explosive increasing from year to year, so that the annual global IP traffic surpassed the zettabytes threshold in 2016. Furthermore, it is predicted that the overall IP traffic will grow at a compound annual growth rate (CAGR) of 24% from 2016 to 2021 [1]. Different factors are alimenting this growth, such as the increasing number of connected devices from different types, as illustrated by **Figure 1**. This continuous growth has a big impact on different level of networking, such as the wide area network, metro (metropolitan) network, access networks and the home (in-house/in-home) networks. Along the evolution of telecom networks, the access networks were always the “weak point” of the infrastructure and therefore referred to as “the bottleneck”. Consequently, one of the first challenges in the era of Internet is the realisation of high-speed “broadband access networks”. Basically, the concept and the term “Broadband Communications Networks” refers to any type of networks/access technologies used by Internet Service Providers (ISP) to provide a broadband Internet access for a multimedia content delivery/distribution according to technical considerations and requirements such as guaranteed Quality of Service (QoS). So many technologies were/are developed to support Broadband Communications in different connection forms such as Dial-up, Digital Subscriber Line (DSL), Optical fibre, cable, Broadband over Powerline, Mobile and wireless Internet access and satellite Internet. There are also quite a few other broadband options available for the Internet connection. Both wired and wireless broadband solutions exist, but none is universally considered optimal for all use cases and products configuration. In fact, the quantification of the meaning of “broadband access” in Mbps is evolving with the time depending on user-experiences in using or consuming the offered data services. With the apparition of the notion “broadband” access, systems had to guarantee at least a capacity of 2 Mbps. This was achieved in a first stage through the successful rollout of Asymmetric Digital

Subscriber Line (ADSL). With the increasing data traffic, the fastest version of DSL, Very high bit rate DSL—VDSL, has partially fulfilled the requirements of intensive data traffic by offering 25 Mbps, but it is limited by the weak coverage of its signal transmission, which does not go over 300 m. Currently, it is expected that the speed of broadband access will merely double by 2021, so that the global fixed broadband speed will reach 53 Mbps, up from 27.5 Mbps in 2016 [1].

The classical paradigm requiring the high speed for downlink connection, which was the reason for the success of ADSL, is not valid anymore for the current broadband access networks. For the cloud services, the end-users also need high-speed uplink to be able to upload their data to the cloud server(s). Furthermore, services and businesses based on big data are nourished by huge data volumes, which are collected in different forms (video, location information, sensing information, software logs, etc.). These two aspects concern both wired as well wireless network access.

The realisation of broadband for downlink and uplink can always be achieved by using optical fibres in the access domain guaranteeing very high speeds. However, it remains in most case economically unfeasible/unprofitable. Thus, the deployment of fibre in access networks, either as fibre-to-the-home (FTTH) or through fibre-to-the-building (FTTB) remains low and extremely different from one country to another, even in the industrial western countries. For example, according to most recent statistics from FTTH Council Europe, fibre access penetration in France does not go over 14.9% of households (with 3% through FTTH and remaining 11.9% through FTTB); while in Germany, this rate reaches 2.3% of households (with 1% FTTH plus 1.3% using FTTB) [2].

Beside the high speeds, the mobility is the second major key requirements of today's society, which makes from the "Broadband Mobile Internet" the headache for mobile operators. The age of Mobile Internet has started with the Universal Mobile Telecommunications System (UMTS), i.e. the third generation of mobile communications—3G. However, this start did not reach the expected success. Among the main causes for this start failure, two facts can be cited:

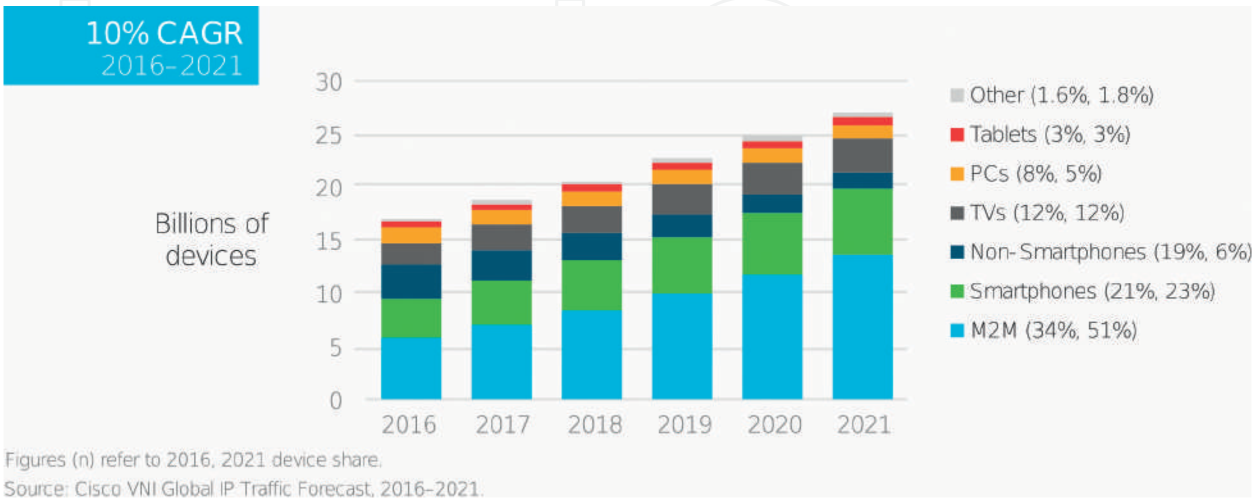


**Figure 1.** Global devices and connections [1].

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Technically, UMTS was designed to offer up to 2 Mbps for the end-users; however, in the field only about 300 kbps were possible. From the economical aspect, the fees of spectrum licences have reached some astronomical levels that bring strong imbalance in the business model.

The failed targets of 3G were partially corrected through the new versions of UMTS, like the High-Speed packet Access (HSAP or 3G+, some references use 3.5G). However, the real breakthrough of mobile broadband has been brought by the fourth generation of mobile technology based on 3GPP Long Term Evolution (LTE) that allows capacities up to 300 Mbps. This speed increased significantly with the extension to LTE-Advanced and LTE-Advanced Pro (referred to as 4.5G). With the successful rollout of 4G around the world (except in some developing countries), the mobile broadband data traffic grew 70% between Q1 2016 and Q1 2017 and a further stronger increase in number of mobile/wireless connected device at their generated traffic is foreseen for the next years [3].

Mobile communications are experiencing a major revolution catalysed by the change in the way our today's society creates, shares and consumes information. While the preparation for massive deployment of 5G by 2020 is still ongoing, researchers are already talking about the "Beyond 5G" (B5G) mobile communications era. It is widely agreed that B5G network should achieve greater system capacity (<1000 times) in terms of data rate (terabits per second) and user density (the Internet-of-things and nano-things) [4]. Accordingly, three ways are considered to realise several orders of increase in throughput gain: the extreme densification of infrastructure, large quantities of new bandwidth and a large number of antennas, allowing a throughput gain in the spatial dimension.

## 2. Changing applications landscape

The telecommunications operators, especially the mobile services providers, have experienced one of the main mutation in the telecom markets, as the voice-dominated services are no longer making the main revenue for their business. In fact, in the period between 2006 and 2008 the operators' revenues were data dominated. At that period, the data traffic started its exponential growth, while the price stagnated accompanied with the economic recession. To balance their business model, operators started to converge their infrastructure to all-over-IP services, by the elimination of the circuit-switched infrastructure, which requires high OPEX and a wasting resources/bandwidth per excellence [5]. This was triggered by the adoption of 3GPP LTE as fourth generation mobile technology that transmits the voice service over IP packets (VoIP). The rollout of 4G has solved the main challenges that were facing the operators, but in the after-4G era, new challenges and requirements must be met such as more bandwidth, shorter latency and ultra-high reliable (UHR) communications. This is resulting either from new services/businesses or caused by a change in user or societal behaviour. As major pillars in new services or applications, we can cite the video, smart cities, big data and Mobile Big data (MBD), Internet-of-things (IoT), Car-to-X communications or Internet-of-vehicles (IoV), etc.

According to the mobile traffic analysis by application, the increased viewing of video on mobile devices, embedded video and emerging video formats will extremely drive data consumption; as stated in the recent Mobility Report [3]. As stated in this report, mobile video traffic is forecast to grow by around 50% annually through 2023 to account for 75% of all mobile data traffic. Social networking is also expected to grow—increasing by 34% annually over the next 6 years. However, its relative share of traffic will decline from 12% in 2017 to around 8% in 2023, as a result of the stronger growth of video traffic. The position of video in mobile data consumption is illustrated in **Figure 2**. Furthermore, streaming videos are available in different resolutions to increase the user experience and satisfaction by using more high-resolution videos, which will certainly affect data traffic consumption to a high degree. Accordingly, watching HD video (1080p) rather than video at a standard resolution (480p) typically increases the data traffic volume by around 4 times. An emerging trend with increased streaming of immersive video formats, such as 360-degree video, would also impact data traffic consumption. For example, a YouTube 360° video consumes 4–5 times as much bandwidth as a normal YouTube video at the same resolution [3]. In addition, the emergence of new applications and changes in consumer behaviour can shift the forecast relative traffic volumes.

The world knows currently a strong urbanisation of today's societies, where more people are living in cities than in rural areas. This generates a pressure on different resources, which are always available or generated in limited volumes and/or capacity, such as energy, water, road, spaces, transport means, hospitals, etc. Therefore, the decision-makers developed roadmaps for building smart cities, with the goal of an optimal generation and utilisation/consumption of these resources. The roadmaps differ from one country to another, but they all agree that the Information and Communications Technologies (ICTs) platforms will constitute the core of these smart cities. In some visions, smart cities consists in developing different smart domains, such as smart grid, smart parking, smart building/homes, smart education,

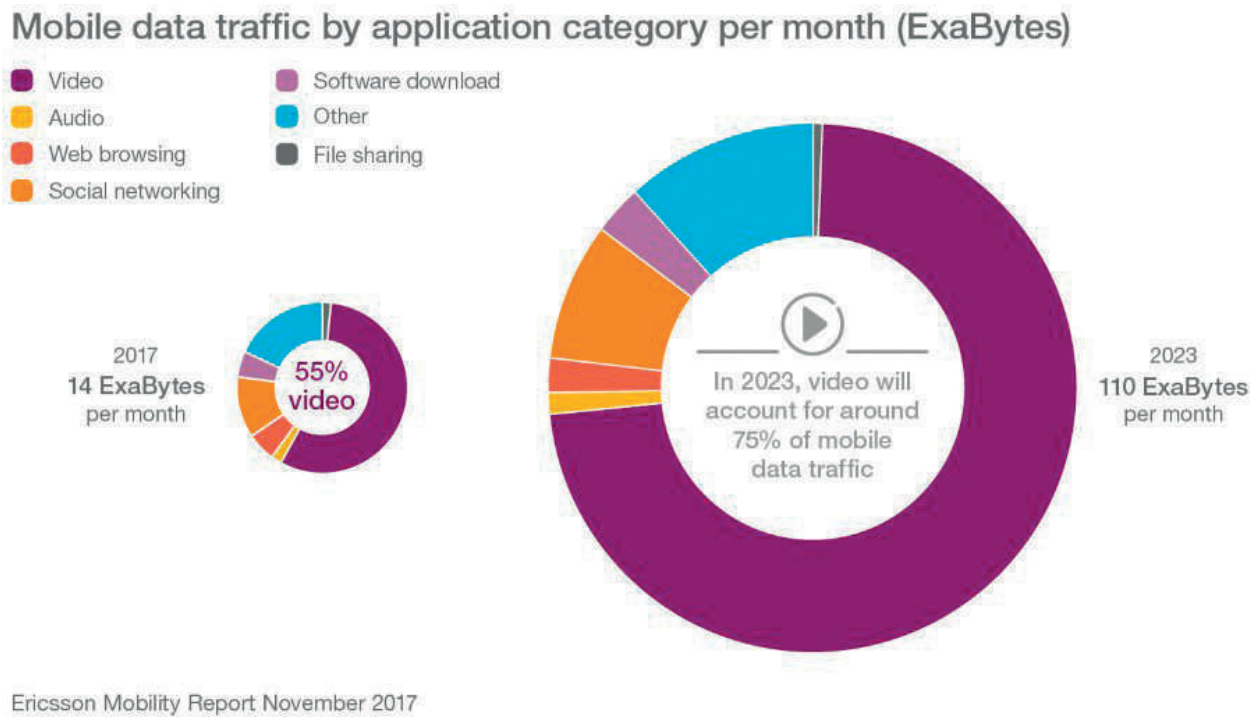


**Figure 2.** Increasing dominance of video content in mobile data [3].

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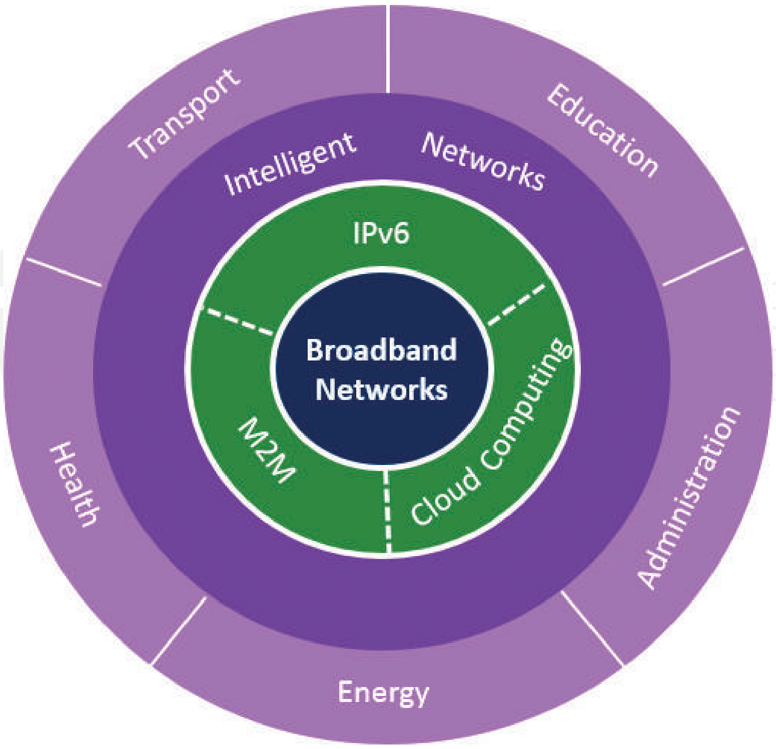


**Figure 3.** Broadband networks as core of future smart cities – German government's point of view [6].

e-administrations, etc. One of the visions is depicted in **Figure 3**, representing an early version of the smart cities from the German government's point of view, where broadband networks are the cornerstone in the ICT infrastructure [6]. A more complex and detailed recent version of this structure, which includes security and big data, can be found in [7].

## 3. Technologies to build the next generation of broadband networks

In spite of the above-cited challenges, the future mobile generation (5G) has found new emerging technologies to overcome all the boundaries, as explained in different chapters of this book. As key technologies of 5G, we can cite massive multiple-input multiple-output (massive-MIMO), network densification (or Ultra Network Densification), Cloud-based Radio Access Network (C-RAN), virtualisation, improved energy efficiency by energy-aware communication and energy harvesting, etc. However, mobile/wireless communications alone cannot be successful without the support from optical fibre, especially for the backhauling. This later is one of major parts of 5G as well as new spectrum parts, among others. The issues related to backhauling in 5G are discussed in Chapter 4 "5G Backhaul: Requirements, Challenges, and Emerging Technologies" and Chapter 5 "Radio Access Network Backhauling Using Power Line Communications", while spectrum issues are discussed in Chapter 3 "Spectrum usage for 5G mobile communication systems and electromagnetic compatibility with existent technologies".

One of the key success factors of next mobile broadband networks is the finding of new locations in the spectrum (Unlicensed, mmWave and THz). In a first step, operators have started to restructure their network to offload their traffic in the unlicensed bands. The 3GPP new technologies of Licenced Assisted Access (LAA) and LTE in unlicensed band (LTE-U) employ an unlicensed radio interface that operates over the 5 GHz unlicensed band to leverage the radio resources for operators' transmission [8, 9]. In a second step, to overcome the increase demand for wireless communication and scarcity of the spectrum bands, new land or parts of the spectrum are currently under exploration. Specifically, millimetre-wave (mmWave) communications systems (30–300 GHz) have been officially adopted in the fifth generation (5G) cellular systems, and several mmWave sub-bands have been allocated for licenced communications. However, the total consecutive available bandwidth for mmWave systems is still less than 10 GHz, which makes it difficult to go to the next step of the evolution and support data rates of the terabit per second. This pushes the researchers' community to explore the terahertz band (0.1–10 THz) communication, which is now envisioned as a key wireless technology to fulfil the future demands within 5G and beyond. Detailed discussion of this topic is given in Chapter 9 "Atmospheric attenuation of the terahertz wireless networks".

Optical fibre is forcing its way to go beyond the backhauling domain and FTTB, since so many countries have recognised the importance of high-speed broadband networks. The passive version of optical access network had a big part in lowering the deployment costs, besides the utilisation of software defined network (SN) technology. Discussion of the aspects related to "how to force the way for fibre" near to the end-user can be found in Part 2 of the book.

## 4. Conclusion

Broadband communication networks are currently a real need for today's society, and not more just a trend or luxury. In general, there is a lot of conferences and documentation in the literature about Broadband Communications Networks, but only few are interested in making it very transparent and accessible to others according to a broad perspective, cutting across wired/wireless technologies and Internet sectors. For example, what kind of Internet access do we need to have when moving to new Internet-driven applications of business and/or for specific computing contexts/smart environments? High Speed? Broadband? Wireless connection? Satellite? Optical Fibre? Mobile networks? What are the lessons we need to know about the practice in order to get fresh innovative ideas to speed up business operations and to improve every aspect of the human life? What are recent advances and notable emerging technologies, which will make us look beyond the horizon? Providing answers to these questions, based on the latest research and developments of the broadband communications technologies, is the focus of the following chapters.

With all this in mind, drawing on research experiences and lessons from over the globe, this book explores the latest research and developments of the broadband communications technologies associated with broadband communications network architectures in support of many emerging paradigms/applications of the global Internet from the traditional architecture to the incorporation of smart applications.

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# Spectrum Usage for 5G Mobile Communication Systems and Electromagnetic Compatibility with Existent Technologies

Guntis Ancans and Vjaceslavs Bobrovs

Additional information is available at the end of the chapter

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**Abstract**

The increased demand of consumers on services in the mobile broadband environment with high data rate and developed mobile broadband communication systems will require more spectrum to be available in the future. New technologies as well as the existing services require frequencies for their development. In this chapter, we investigate the available and potential future mobile terrestrial radio frequency bands (5G)—worldwide and in Europe. An insight into the mobile spectrum estimate is provided. Characteristics and requirements of IMT-2020, future possible IMT frequency bands, and examples of 5G usage scenarios are also addressed in the chapter. Electromagnetic compatibility evaluation methods are provided mainly focusing on existent mobile technologies below 1 GHz where also 5G technologies will be developed in the future. It is stressed that the radio frequency spectrum is a limited national resource that will become increasingly precious in the future.

**Keywords:** 4G mobile communication, 5G, electromagnetic compatibility, frequency band, international mobile telecommunications (IMT), IoT, international telecommunication union (ITU), M2M, mobile service, radio wave propagation, spectrum planning, WRC-19

## 1. Introduction

5G referred to as IMT-2020 in ITU-R terms is the next generation of mobile communication technologies. IMT systems are now being evolved to provide diverse usage scenarios and applications such as enhanced mobile broadband (eMBB) communication, massive machine-type communication (mMTC), and ultrareliable and low-latency communication (URLLC) requiring larger contiguous blocks of spectrum than currently available bandwidth to realize those applications.

5G aims to provide high data rates, low latency, seamless coverage, low power, and highly reliable communications. Used cases under consideration include enhanced mobile broadband communications, but also machine-to-machine (M2M), Internet of Things (IoT), home and industrial automation and applications, etc. expected to respond to requirements from vertical sectors (e.g., utilities, automotive, railways, public protection). 5G is planned to be deployed around the world by 2020.

The potential usage scenarios shown in **Figure 1** have different operational and technological requirements.

Different players from various verticals, i.e., different industries, can be brought together using the 5G concept. The network capabilities are intended to match the requirements of the different vertical players.

The first 5G specification in 3GPP Release 15 is planned to be available by the end of 2018 and will address the more pressing commercial needs. The second release, 3GPP Release 16, planned for March 2020, will address all used cases and requirements. There is an ongoing work on development of new radio access technology targeted for completion by the end of 2017.

3GPP has been working to standardize the 5G-NR (New Radio) specification. In March 2017, 3GPP decided to accelerate the timescale in order to finalize the *non-stand-alone* mode by March 2018. This mode will operate in parallel with 4G long-term evolution (LTE) to provide boosted data rates. The *stand-alone* 5G mode is planned for completion in September 2018. This accelerated timescale will facilitate 5G network trials in the early 2018.

In general, 5G technologies will describe the following characteristics: high-frequency operation, very wide bandwidth, massive beam forming, and interworking with LTE. ITU will complete its work for standardization of IMT-2020 no later than the year 2020 [2].

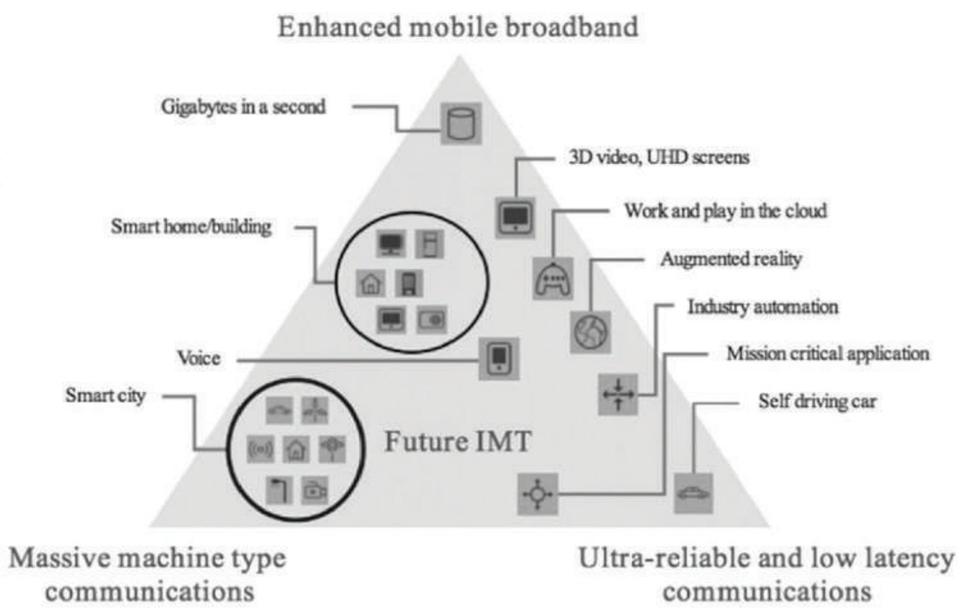


**Figure 1.** 5G usage scenarios according to ITU-R Recommendation M.2083-0 [1].

From a spectrum management's point of view, one of the main innovations brought by 5G is its capacity not only to handle broadband mobile communications as in the previous generations but also to cover the needs from a range of sectors, the so-called "verticals."

## 2. Mobile spectrum estimate for terrestrial IMT

The ITU terms for 3G and 4G are IMT-2000 and IMT-Advanced accordingly. The term IMT-2020 is adopted for 5G. Collectively, they are known as IMT [3]. IMT systems have contributed to global economic and social development.

With the mobile data traffic, increasing more spectrum resources will be necessary for the future mobile broadband communication systems. The Report ITU-R M.2290-0 provides a global perspective on spectrum requirement estimate for terrestrial IMT in the year 2020. The predicted total spectrum requirement for both low and high user density scenarios was calculated to be 1340 and 1960 MHz (including the spectrum already in use or planned to be used) at least by the year 2020 [4]. In some countries, national spectrum requirement can be lower than the estimate derived by lower user density settings, and in some other countries, national spectrum requirement can be higher than the estimate derived by higher user density settings. The mobile traffic forecast is presented in **Figure 2**.

It is assumed that for the year 2020, the median traffic growth will fall in between the lowest and highest growths, anticipating at least 25-fold traffic growth ratio in 2020 compared to 2010. Other estimates [1] anticipate that global IMT traffic will grow in the range of 10–100 times from 2020 to 2030.

An option for increasing data rates is the development of small cells and the combination of the capacity of unlicensed bands (e.g., 2.4 GHz, 5 GHz) with the capacity of a licensed

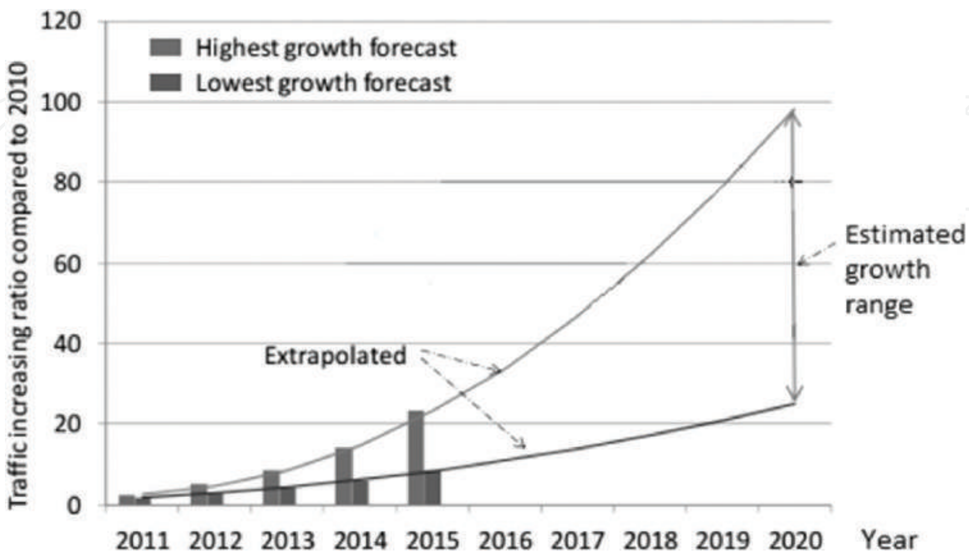


**Figure 2.** Mobile traffic forecasts toward 2020 by extrapolation according to the Report ITU-R M.2290-0.

frequency block [5]. Another option is carrier aggregation, which enables to increase data rates, but its complexity is exponential with the number of possible combinations of frequency bands used; spectrum sharing is also possible as a solution.

Another option is to develop and introduce the next generation of broadband communication technologies (5G) [6]. Authors presume that 5G base stations in the future will be connected by fiber optical lines or microwave backhaul links as an alternative solution. Huge investment in fiber is needed in order to realize the 5G vision.

## 3. Characteristics and requirements of IMT-2020

According to the Ericsson paper [7], LTE will evolve in a way that recognizes its role in providing ubiquitous wide area coverage for mobile users, and 5G networks will incorporate LTE radio access, based on orthogonal frequency division multiplexing (OFDM), along with new air interfaces.

Millimeter wave cells are very small, and they could be deployed mainly in dense urban areas or indoors delivering greater capacity. In the long term, it is expected that all devices that benefit from network connectivity eventually will become connected through M2M communications in the future.

According to Recommendation ITU-R M.2083-0, goals of future development of 5G capabilities are summarized in **Table 1**, which include IMT-2020 capability eight key parameters [1].

Performance requirements must be met but at the same time depend particularly on the used cases or scenario. The key capabilities of IMT-2020 are presented in **Figure 3** compared with those of IMT-Advanced.

In the enhanced mobile broadband scenario, peak data rate, user-experienced data rate, area traffic capacity, mobility, energy efficiency, and spectrum efficiency all have high importance in comparison to connection density and latency.

| **Parameter** | **Key value for 5G** |
|---|---|
| Peak data rate | 10–20 Gbit/s |
| User-experienced data rate | 100 Mbit/s (for wide area coverage, e.g., in urban and suburban areas) and 1 Gbit/s (for hotspots, e.g., indoor) |
| Latency | 1 ms |
| Mobility | 500 km/h (e.g., for high-speed trains) |
| Connection density | 106 devices/km$^2$ |
| Energy efficiency | 100x more than IMT-Advanced |
| Spectrum efficiency | 3x more than IMT-Advanced |
| Area traffic capacity | 10 Mbit/s/m$^2$ |

**Table 1.** 5G target capabilities.

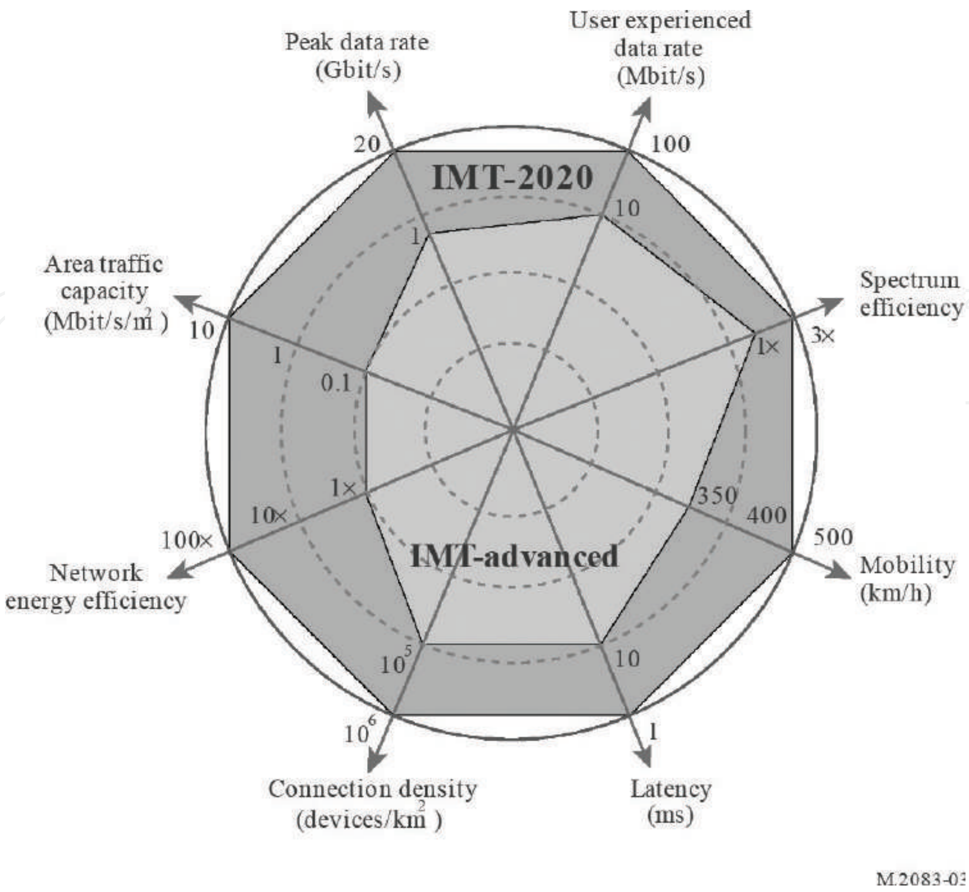


**Figure 3.** Enhancement of key capabilities from IMT-Advanced to IMT-2020.

In some low-latency communications and ultrareliable scenarios, low latency is of the highest importance, e.g., in order to enable the safety critical applications. Such capability would be required for some high mobility uses as well, e.g., in transportation safety, while, e.g., high data rates, might be less important.

The high connection density is needed in the massive machine-type communication scenario to support large number of devices in the network that, e.g., may transmit only occasionally at low bit rate and with zero or very low mobility. A low-cost radio device with long operational lifetime is of great significance for this usage scenario.

## 4. Future possible IMT frequency bands

In order to encourage increased data traffic capacity and to enable the transmission bandwidths needed to encourage very high data rates, 5G will extend the range of frequency bands used for mobile communications. This includes new radio spectrum below 6 GHz, as well as spectrum in higher frequencies.

For wireless communications, lower frequencies provide better coverage. Currently, almost all countries use spectrum below 6 GHz for IMT systems. Spectrum relevant for 5G wireless access therefore ranges from below 1 GHz up to approximately 100 GHz.

| Frequency bands identified for IMT in the RR (MHz) | World Radiocommunication Conference (WRC) | Licensed mobile frequency bands in CEPT countries (MHz) |
|---|---|---|
| 450–470 | WRC-07 | 450–457.5 / 460–467.5 |
| 470–608 | WRC-15 | — |
| 614–698 | WRC-15 | — |
| 694–960 | WRC-2000, WRC-07, WRC-12 | 694–790 |
| | | 790–862 |
| | | 880–915 / 925–960 |
| 1427–1518 | WRC-15 | 1427–1518 |
| 1710–2025 | WARC-92, WRC-2000 | 1710–1785 / 1805–1880 |
| | | 1900–1920 |
| | | 1920–1980 / 2110–2170 |
| | | 2010–2025 |
| 2110–2200 | WARC-92 | 1920–1980 / 2110–2170 |
| 2300–2400 | WRC-07 | 2300–2400 |
| 2500–2690 | WRC-2000 | 2500–2690 |
| 3300–3400 | WRC-15 | — |
| 3400–3600 | WRC-07 | 3400–3600 |
| 3600–3700 | WRC-15 | 3600–3800 |
| 4800–4990 | WRC-15 | — |

**Table 2.** Spectrum already identified for IMT.

High frequencies, e.g., those above 10 GHz, can only serve as a complement to lower frequencies and will mainly provide additional system capacity with very wide transmission bandwidths for extreme data rates for dense deployments. Spectrum use at lower-frequency bands will remain the backbone for mobile radio communication networks in the 5G era, providing excellent ubiquitous wide area connectivity.

### 4.1. Spectrum below 6 GHz

Besides achieving high data rates, it is also necessary to guarantee wide area coverage and outdoor to indoor coverage in 5G. Therefore, spectrum below 6 GHz forms a very important part of the 5G spectrum solution. Until now in Europe, more than 1200 MHz of spectrum for mobile broadband in the frequency range from 694 to 3800 MHz was harmonized.

For providing ubiquitous coverage in next-generation (5G) or pre-5G networks, the important role will be of LTE (4G) bands already harmonized below 1 GHz, including particularly the 700 and 800 MHz band, in order to enable nationwide and indoor 5G coverage. The 450 MHz band, which harmonized conditions for LTE use in the band currently is under development in the European Conference of Postal and Telecommunications Administrations

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| Frequencies to be studied until WRC-19 for possible identification to IMT (GHz) | Primary allocations to radiocommunication services in RR in ITU regions (including WRC-15 results) | Comments |
|---|---|---|
| 24.25–27.5 | Earth exploration-satellite (space-to Earth), fixed, fixed-satellite (Earth-to-space), inter-satellite, mobile, radionavigation, space research (space-to-Earth) | Frequencies have already allocation to the mobile service on a primary basis in RR |
| 37–40.5 | Earth exploration-satellite (Earth-to-space), fixed, fixed-satellite (space-to-Earth), mobile, mobile except aeronautical mobile, mobile-satellite (space-to-Earth), space research (Earth-to-space), space research (space-to-Earth) | |
| 42.5–43.5 | Fixed, fixed-satellite (Earth-to-space), mobile except aeronautical mobile, radio astronomy | |
| 45.5–47 | Mobile, mobile-satellite, radionavigation, radionavigation-satellite | |
| 47.2–50.2 | Fixed, fixed-satellite (Earth-to-space), fixed-satellite (space-to-Earth), mobile | |
| 50.4–52.6 | Fixed, fixed-satellite (Earth-to-space), mobile | |
| 66–76 | Broadcasting, broadcasting-satellite, fixed, fixed-satellite (space-to-Earth), inter-satellite, mobile, mobile-satellite (space-to-Earth), radionavigation, radionavigation-satellite | |
| 81–86 | Fixed, fixed-satellite (Earth-to-space), mobile, mobile-satellite (Earth-to-space), radio astronomy | |
| 31.8–33.4 | Fixed, inter-satellite, radionavigation, space research (deep space) (space-to-Earth) | Frequencies may require additional allocation to the mobile service on a primary basis in RR |
| 40.5–42.5 | Broadcasting, broadcasting-satellite, fixed, fixed-satellite (space-to-Earth) | |
| 47–47.2 | Amateur, amateur-satellite | |

**Table 3.** Possible new spectrum for IMT in frequencies above 24 GHz.

(CEPT), in author's opinion will also play a significant role for enabling wide coverage for services of next-generation mobile networks in Europe. Frequency bands currently identified for IMT in the ITU Radio Regulations (RR) are presented in **Table 2**.

The *priority* frequency band suitable for the introduction of 5G use in Europe even before 2020 with wide channel bandwidths (50–100 MHz and more) could be 3400–3800 MHz band, noting that this band is already harmonized for mobile networks in Europe. This frequency band has the ability to put Europe at the forefront of the 5G or *pre*-5G deployment.

### 4.2. Spectrum above 6 GHz

5G envisages very high data rates, which will need much larger bandwidths than ever before. Those very high data rates may only be found in higher frequency bands (above 6 GHz). To deliver higher data rates and lower latency, there is an expectation that new wireless solutions at higher frequencies—millimeter wave (*mmWave*) bands—will be deployed. Therefore, implementation of frequency bands even above 24 GHz remains needed to ensure all the performance targets of 5G, e.g., multi-gigabit per second data rates. Implications of very low-latency drive to millimeter wave deployments with their highly directive antennas and small cell sizes.

The 2015 World Radiocommunication Conference (WRC-15) decided the following frequency bands 24.25–27.5 GHz, 31.8–33.4 GHz, 37–43.5 GHz, 45.5–50.2 GHz, 50.4–52.6 GHz, 66–76 GHz, and 81–86 GHz as presented in **Table 3** to study for possible identification to IMT (aimed for 5G) at WRC-19.

Europe identified 26 GHz as a *pioneer* frequency band for early European harmonization, as it provides over 3 GHz of contiguous spectrum and has the greatest potential to be a globally harmonized band.

The 31.8–33.4 GHz (referred to as 32 GHz) and 40.5–43.5 GHz (referred to as 40 GHz) bands were also identified as priority bands for study in the CEPT.

## 5. Examples of 5G usage scenarios

According to the recent ITU theoretical assessment, simulations, measurements, technology development, and prototyping described in the Report ITU-R M.2376-0, utilization of bands between 6 and 100 GHz is feasible for studied IMT deployment scenarios and could be considered for the development of IMT for 2020 and beyond [6].

It is expected that LTE will develop in a way of providing wide area coverage for mobile users. 5G networks will include LTE access based on OFDM along with new radio interfaces using possibly new techniques, e.g., filter bank multicarrier (FBMC) transmission technique.

### 5.1. IMT-2020 architecture

Deployment architecture of IMT-2020 can be classified into two architecture types: *stand-alone* or *overlay*. The stand-alone architecture refers to the network deployment consisting of millimeter wave (*mmWave*) small cells. The overlay architecture refers to the network deployment of mmWave small cells developed on top of the existing macro-cell networks (LTE, etc.). In overlay architecture case, the macro-cell layer of the existing 4G mobile communication serves mainly for providing coverage, whereas the mmWave small cell layer should be used to provide capacity [6] as shown in **Figure 4**.

For mmWave small cells explicated using cellular technologies, the typical service range is expected to be around 10 to 200 m under non-line-of-sight (NLOS) circumstances, which is a lot shorter than the range of a cellular macro-cell that can provide several kilometers. The small cells can be deployed both indoors (e.g., femto cells) and outdoors. When deployed outdoors, mmWave small cells are typically deployed at a lower antenna height than a macro-cell (on street lamp posts, on building walls, in parks, etc.) and with lower transmit power to cover a targeted area. For mmWave small cell deployment, scenarios can be identified three categories: indoor, hotspot, and outdoor [6].

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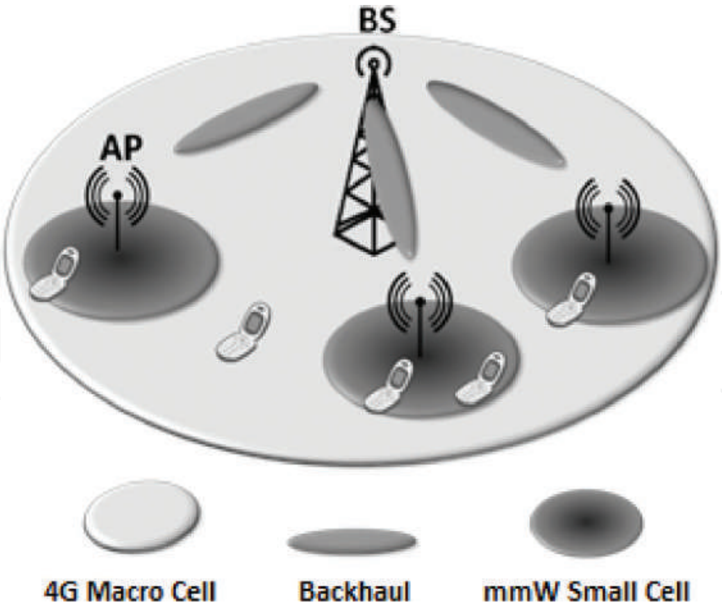


**Figure 4.** System deployment architecture proposed for 5G.

### 5.2. Channel bandwidth

For single-input/single-output (SISO) scenario, the maximum capacity of a radio channel can be described by Shannon-Hartley formula. This formula relates the maximum capacity (transmission bit rate) that can be achieved over a given channel to certain noise characteristics and bandwidth. For an *additive white Gaussian noise* of power the $N$, the maximum capacity can be calculated by

$$C = B \cdot \log_2\left(1 + \frac{S}{N}\right), \tag{1}$$

where $C$ is the maximum capacity of the channel (bits(s)) otherwise known as *Shannon's capacity limit for the given channel*, $B$ is the bandwidth of the channel (Hz), $S$ is the signal power (W), and $N$ is the noise power (W). The ratio $S/N$ is named *signal-to-noise ratio* (SNR) [8].

It can be perceived that the maximum transmission data rate, at which the information can be transmitted without any error, is limited by the bandwidth, the signal level, and the noise level. With the increase in bandwidth, the noise power also increases; that is why the channel capacity does not become infinite. By using wider channels, increasing the number of antennas, and reducing interference, it is possible to increase the capacity.

One of the benefits of higher-frequency adaptation for mobile communications is system capability to implement wide channels.

In the authors' opinion, to achieve objectives set for future IMT-2020 systems, it is necessary to provide contiguous, broad, and harmonized frequency bands, which will minimize 5G device complexity and possible interference issues.

In the 5G era, FDD will remain the main duplex scheme for lower-frequency bands. However, for higher-frequency bands—especially above 10 GHz—targeting very dense deployments, TDD will play a more important role.

In author's opinion, 5G wireless access may be realized by the improved LTE systems for existing spectrum in combination with new radio access technologies that primarily target new spectrum [2].

### 5.3. Antenna technology

Antennas that can operate well enough in distant frequencies at the same time, e.g., at between 450 MHz, 700 MHz, and 26 GHz, are a difficult task. Therefore, most likely two separate antennas, each operating at the specific frequency band, will be required. The wavelengths above 24 GHz provide a possibility to put more antenna elements in the restricted area. The antenna technology with the increased number of particular antenna elements can be used to provide high beamforming gain. The incremented path loss of above 24 GHz frequency bands can be mitigated by beamforming techniques with exact pointing direction. The phased array beamforming is used to raise the received signal power by using beamforming gain. Greater antenna gains may be achieved applying narrower beams [4].

For 5G communication systems, massive MIMO (*multiple-input and multiple-output*) solutions would be used to compensate additional propagation loss in higher frequencies [2] and to minimize interference. Array antennas should be integrated in the terminals or user equipment. In this case, it should be possible since the transmission wavelengths would become smaller.

### 5.4. 5G development scenarios

The 5G radio access is based on the evolution of LTE and the other one on New Radio (NR) access. In the LTE-5G, enhancements will continue to enable it to support as many 5G requirements and used cases as possible. Unlike the LTE-5G, the NR-5G is free from backward compatibility requirements and thereby able to introduce more fundamental changes, such as targeting spectrum at high (mmWave) frequencies. However, NR is being designed in a scalable manner so it could eventually be migrated to frequencies that are currently served by LTE.

The process of making LTE-5G involves a variety of enhancements and new features in 3GPP Release 14 and Release 15. The most significant ones are enhancements to user data rates and system capacity with FD MIMO (*full-dimension multiple-input multiple-output*), improved support for unlicensed operations, and latency reduction in both control and user planes. FD MIMO is a technology that arranges the signals transmitted to antennas in the form of virtual beams that are able to power multiple receivers in three dimensions. It is expected that this technology significantly will increase spectrum efficiency.

In authors' opinion, LTE along with NR-5G will continue to play a major role in mobile communications for many years to come.

## 6. Electromagnetic compatibility studies with existent technologies

The 2019 World Radiocommunication Conference (WRC-19) will take place over 4 weeks, from 28 October to 22 November 2019. The Conference will address a number of questions

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within the radiocommunication sector, and consideration of spectrum for 5G above 24 GHz is expected to feature heavily through the Resolution of WRC-19 Agenda Item 1.13.

In the framework of WRC-19 Agenda Item 1.13, identification of frequency bands 24.25–27.5 GHz, 31.8–33.4 GHz, 37–43.5 GHz, 45.5–50.2 GHz, 50.4–52.6 GHz, 66–76 GHz, and 81–86 GHz for the future development of IMT will be considered, including possible additional allocations to the mobile service on a primary basis, in accordance with Resolution 238 (WRC-15) [9].

Compatibility studies must be carried out in each frequency band, and each band must balance with the requirement of other existing services and allocations. Any identification of frequency bands for IMT should take into account the use of the bands by other services (to protect existing services) and the evolving needs of these services. WRC-19 Agenda Item 1.13 states to conduct and complete in time for WRC-19 the appropriate sharing and compatibility studies, taking into account the protection of services to which the band is allocated on a primary basis.

Spectrum sharing will be an important element to facilitate the requirements of 5G, and the development of new technological solutions in higher-frequency ranges, such as the more extensive use of MIMO technique, may provide more opportunities for sharing but also challenges for National Regulatory Authorities (NRAs).

In the future, there may be a need to adapt the harmonized regulatory framework for 5G in the existing mobile frequency bands in Europe (700 MHz, 800 MHz, 900 MHz, 1500 MHz, 1800 MHz, 2.1 GHz, 2.3 GHz, 2.6 GHz).

## 7. Electromagnetic compatibility evaluation methods

Congestion of the radio spectrum is growing with an ongoing rise in the demand for more wireless services. National communications regulators are faced with the challenge of identifying new frequencies for new uses while preventing interference to existing users of the spectrum.

### 7.1. Radio frequency interference

Interference occurs when a transmission from one system disrupts the reception of signals at the receiver of another nearby system. It can occur between systems operating on the same frequency known as co-channel interference or between systems in frequencies that are close known as adjacent channel or adjacent band interference. It is worth noting that there are also other types of interference such as intermodulation [10].

Co-channel interference is a result of the stronger interfering signal, which affects the victim signal. In adjacent channel interference, there are two main causes of interference: *unwanted emissions* and *blocking* or *receiver selectivity* as presented in **Figure 5**.

Unwanted emissions are any off-channel noise of the interfering equipment falling within the receive band of the victim receiver and thus acting as co-channel interference to the wanted signal. This sort of interference can only be removed at the source.

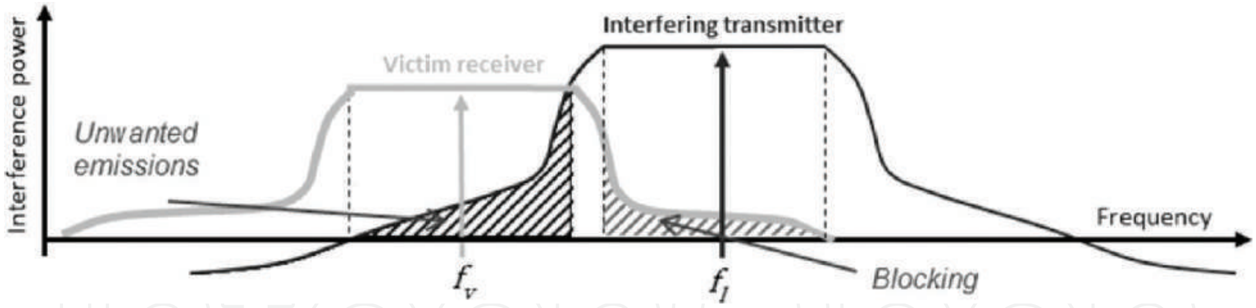


**Figure 5.** Causes of interference: unwanted emissions and blocking.

Blocking, i.e., a strong signal off the receive band of a victim receiver, desensitizes its reception. This sort of interference can only be removed at the victim. In most cases, adoption of power control for the interferer and efficient site engineering can improve the situation.

In practice, both of these can occur simultaneously. Sometimes, it is necessary to improve the design of both the transmitter and receiver to prevent interference, which is becoming increasingly important as the spectrum becomes more congested [10].

### 7.2. Interference prediction methods

Interference prediction typically is done through theoretical calculations known as sharing studies, which usually refer to in-band studies, and compatibility studies, which refer to adjacent band studies. Theoretical studies are necessary because it is not always possible to perform measurements on real systems, particularly in cases where the systems are still under development. Two types of studies are commonly used:

*Deterministic* studies based on fixed parameters, using the *minimum coupling loss* (MCL) method. This is a worst-case assessment of interference. The results usually determine the minimum required separation distance (in space or in frequency) between two systems to avoid interference. The MCL approach is relatively straightforward, modeling only a single interferer-victim pair. It provides a result that is spectrally inefficient.

*Statistical* studies based on variable parameters, using the *Monte Carlo* method. This is a more realistic assessment, which takes into account the real-world variation and randomization of certain parameters such as the relative positioning of systems. The result of a Monte Carlo simulation is a measure of system performance—it is commonly a probability of interference for the scenario under investigation, which can be compared against a relevant threshold to determine if the level of interference is considered to be a problem or not. Care must be taken when interpreting a probability of interference. A mobile system operator specifies that a system can provide a system availability of 95%. It is capable of modeling highly complex systems including LTE networks. The result is spectrally efficient but requires careful interpretation.

A mobile system operator specifies that a system can provide a system availability of 95%.

These studies can be performed using a range of software tools, for example, SEAMCAT for Monte Carlo analysis, which is an open-source software tool. In order to compare both methods, the same radiowave propagation prediction model should be adopted for all three methods.

In some cases, the assumptions used in the studies can be validated through laboratory measurements of real systems or through field measurements [10].

If the results of studies show that interference may occur, it may be necessary to investigate different mitigation techniques to minimize the risk of interference. This could include specification of additional filtering to be applied to the transmitter or receiver, additional frequency separation between both systems, and restrictions on the usage of the new system such as limits on maximum transmit power or geographical restrictions on where the new system can be used. In addition, with the emergence of new technologies, new and innovative sharing solutions are being explored, for example, techniques such as geolocation and licensed shared access (LSA).

This overall process, including the prevention of interference by quantifying the risk through studies and the cure through identifying suitable mitigation, is known as spectrum engineering [10].

Sharing studies need to have accurate input assumptions in order to produce meaningful and reliable results. Spectrum engineers are working with future technologies where not all the parameters can be defined in advance of the deployment of the new technology. Spectrum engineering results can be used to optimize frequency planning.

### 7.3. Protection criteria for mobile service

Different interference criteria can be used for interference assessment to the mobile service stations or other services, e.g., C/I, C/(N + I), (N + I)/N, or I/N.

The protection criterion for use in sharing and compatibility studies between IMT-Advanced and IMT-2020 and other systems and services irrespective of the number of cells and independent of the number of interferers is I/N value of −6 dB. This criterion applies to interference from a single source or to the aggregate interference from multiple sources of interference. The same protection criterion should be used for both co-channel and adjacent band studies [11, 12].

For the assessment of the interference of LTE and other services in 700 MHz band [13, 14], authors used both of these methods, namely, MCL and Monte Carlo method, and the criterion of $I/N = -6$ dB was used for interference assessment to the mobile service. In this assessment the predetermined trigger field strength values also was used. Additionally, some field measurements were also performed.

## 8. Conclusion

Global harmonization of IMT spectrum will be essential for developing 5G. The benefits of spectrum harmonization include facilitating economies of scale, enabling global roaming, reducing equipment design complexity, improving spectrum efficiency, and potentially reducing cross border interference. 5G mobile communication systems will require frequencies for their development and usage. Frequencies below 6 GHz are very valuable because of its optimum radio wave propagation, especially frequencies below 1 GHz. The results of the present study have shown that implementation of frequency bands even above 24 GHz remains needed to ensure all the performance targets of 5G, e.g., multigigabit per second data rates. In the authors' opinion, for the deliberative development of IMT systems, it is necessary to timely provide wide and contiguous spectrum resources for implementation of new technologies and services.

It is important to note that the properties of higher-frequency bands, such as shorter wavelength, would better enable the use of advanced antenna systems including MIMO and beamforming techniques in supporting enhanced broadband.

The electromagnetic compatibility between LTE and different existent technologies in 700 MHz band authors was evaluated with different methods: MCL method, Monte Carlo method, and predetermined trigger field strength values; some field measurements were also done. According to results of electromagnetic evaluation, additional mitigation techniques were proposed in order to assure the compatibility between considered radio systems. Similar electromagnetic compatibility evaluation methods and approach can be also applied for IMT-2020 studies in frequencies above 24 GHz.

The results obtained within the framework of the research can be used by National Regulatory Authorities, equipment manufacturers, mobile operators, researchers, and other interested parties when planning 4G and 5G mobile services.

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Chapter 4

# 5G Backhaul: Requirements, Challenges, and Emerging Technologies

Md Maruf Ahamed and Saleh Faruque

Additional information is available at the end of the chapter

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**Abstract**

5G is the next generation cellular networks which is expected to quench the ever-ending thirst of data rates and interconnect billions of smart devices to support not only human centric traffic, but also machine centric traffic. Recent research and standardization work have been addressing requirements and challenges from radio perspective (e.g., new spectrum allocation, network densification, massive multiple-input-multiple-output antenna, carrier aggregation, inter-cell interference mitigation techniques, and coordinated multipoint processing). In addition, a new network bottleneck has emerged: the backhaul network which will allow to interconnect and support billions of devices from the core network. Up to 4G cellular networks, the major challenges to meet the backhaul requirements were capacity, availability, deployment cost, and long-distance reach. However, as 5G network capabilities and services added to 4G cellular networks, the backhaul network would face two additional challenges that include ultralow latency (i.e., 1 ms) requirements and ultradense nature of the network. Due to the dense small cell deployment and heavy traffic cells in 5G, 5G backhaul network will need to support hundreds of gigabits of traffic from the core network and today's cellular backhaul networks are infeasible to meet these requirements in terms of capacity, availability, latency, energy, and cost efficiency. This book chapter first introduce the mobile backhaul network perspective for 2G, 3G, and 4G networks. Then, outlines the backhaul requirements of 5G networks, and describes the impact on current mobile backhaul networks.

**Keywords:** 5G, mobile backhaul network, wired backhaul, wireless backhaul, microwave, millimeter wave, free space optics

## 1. Introduction

During the last few decades, mobile communication has evolved significantly from early wireless voice systems to today's intelligent communication systems [1, 2]. With the advancement of each generation, the mobile communication systems become more sophisticated and unleashed new consumer services that support countless mobile applications used by billions of people around the world, shown in **Figure 1** [1–3]. In 2000, when 3G brought us the wireless data, the consumers got access to the internet anytime and anywhere they go [2]. This mobile broadband network with a combination of the innovation of smartphone technologies brought a significant change of mobile internet experience where users can access their email, social media, music, high definition video streaming, online gaming, and many more, which we see today as the app-centric interface [4].

Due to the advancement of technologies, mobile devices getting smarter every day in terms of advanced computing and multimedia capabilities that supports a wide range of applications and services (e.g., high quality image transfer, ultrahigh definition video streaming, live video games, and cloud resources) [5, 6]. Therefore, more and more users are expecting to have the same quality of internet experience anytime, and everywhere they go. These trends will even more pronounced when 5G network becomes available with intelligent network capabilities and numerous services. 5G network will extend the wireless connectivity beyond the people, to support the connectivity for everything that may benefit from being connected that might include everything from personal belongings, household appliances, to medical equipment, and everything in between [1]. Numerous 5G network use cases, services and network

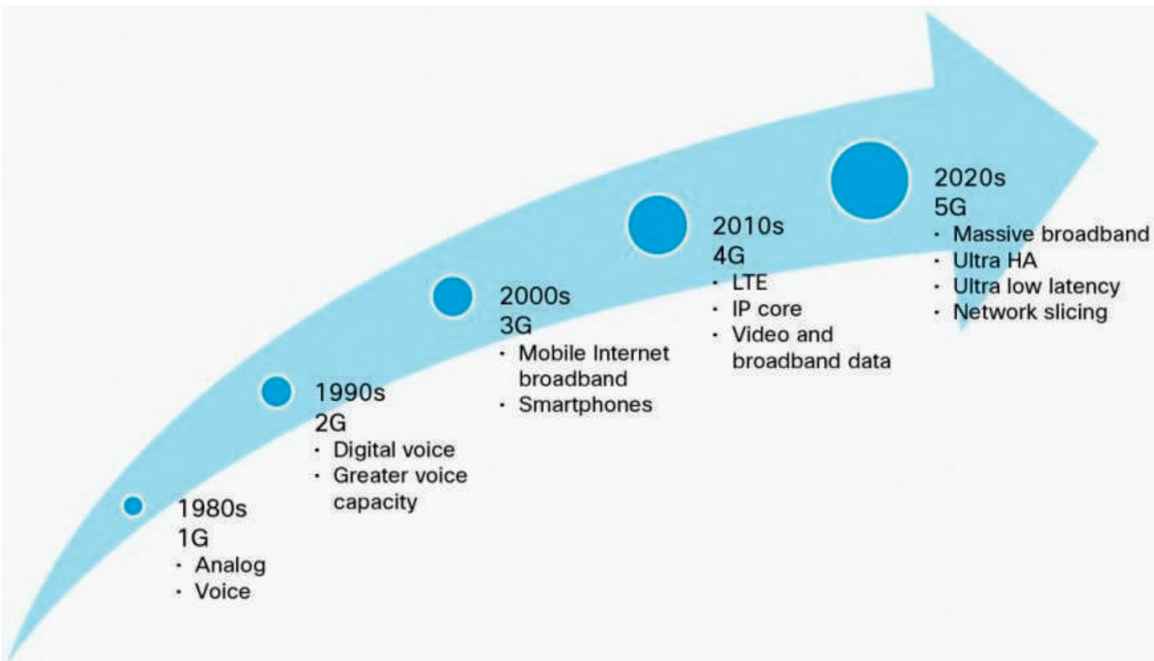


**Figure 1.** The evolution of mobile standards [3].

requirements are discussed in [7]. Here are the two most significant trends of 5G services are discussed below [6]:

- Everything will be connected to the mobile network wirelessly that will enable the billions of smart devices interconnected autonomously while ensuring the security and privacy [8]. 5G network will enable emerging services that include remote monitoring and real-time control of a diverse range of smart devices, which will support machine-to-machine (M2M) services and Internet of Things (IoT), such as connected cars, connected homes, moving robots and sensors [6, 8–10]. According to Cisco VNI Mobile 2017, the most noticeable growth will occur in M2M connections. The number of M2M connection will reach 3.3 billion by 2021, which is 29% of the total devices and connections and it was only 10% in 2016 [5]. Another mobile traffic forecast by UMTS presented that the total number of connected IoT devices will reach to 50 billion by 2020 which was only 12.5 billion in 2010 [5].
- 5G networks will deliver richer content in real time ensuring the safety and security that will make the wireless services more extensive in our everyday life. Some example of emerging services may include high resolution video streaming (4K), media rich social network services, augmented reality, and road safety [6]. According to Cisco mobile data traffic forecast, the maximum mobile data traffic will be generated by video-based mobile application, which is going to be 72% of mobile data traffic by 2019 compared to 55% in 2014 [5, 11].

It is clear that the future mobile network (i.e., 5G) will no longer human centric, it will be more on machine centric which will interconnect billions of smart devices to the mobile network. According to Cisco, smart devices are those that have advanced computing and multimedia capabilities with a minimum of 3G network connectivity [5]. Globally the growth of smart devices will reach 82% by 2021 and some regions it will reach 99% by 2021 (e.g., North America). The main impact of this growth will be on mobile data traffic because a smart device generates much higher traffic compared to non-smart device. According to Cisco forecast, a smart device generated 13 times more traffic compared to non-smart device in 2016 and by 2021 a smart device will be able to generate 21 times more traffic [5]. According to another mobile traffic forecast by Cisco, the expected growth will reach 24.3 Exabytes per month by 2019 which was only 2.5 Exabytes in 2014 [12]. This ever-increasing traffic growth becomes the key driver for the evolution of next generation mobile networks, called 5G, envisioned for the year 2020 [13, 14]. The key requirements of 5G network include, extreme broadband delivery, ultrarobust network, ultralow latency (i.e., less than 1 ms latency) connectivity, and support massive smart devices for the human and for the IoT services [15].

To bring the 5G network in reality, a simple upgrade of mobile network will not be enough where we just add new spectrum and enhance the capacity or use advanced radio technology. It will need to upgrade from the system and architecture levels down to the physical layer [15]. Although some research and standardization work addressing the corresponding challenges from radio perspective (e.g., new spectrum exploration, carrier aggregation, network densification, massive multiple-input-multiple-output, and inter-cell interference mitigation techniques) but there is a new challenge has emerged: the backhaul [16–18]. Because in 5G networks, the ultradense and heavy traffic cells will need to support hundreds of gigabits of traffic from the core network through backhaul and today's cellular system architecture is infeasible to meet this extreme requirement in terms of capacity, availability, latency, energy, and cost efficiency [16, 19].

A details survey about the evolution of mobile backhaul solution from 2G to 3G networks and from 3G to 4G networks are presented in [20, 21], respectively. The hybrid of millimeter wave and optical backhaul solution is proposed in [22] where the software-defined backhaul resource manager is proposed as a novel software defined networking (SDN) approach for realizing high utilization of the backhaul network capacity in a fair and dynamic way, while providing better end-to-end user quality of experience (QoE). Also, [23] provides another hybrid solution that combines an optical laser (through free space) and millimeter-wave radio to provide a combination of guaranteed high capacity, extended reach, and high availability with affordable cost.

If given a choice, fiber always remains the first backhaul choice for service provider due to its inhibitive bandwidths more than 10 Gbps and allowed maximum latency of hundreds of microseconds [16, 23]. But, laying fiber to connect all the cells to the core is not possible in some cases due to the availability problem and the deployment cost is high as well. In addition, fiber deployment, even when it is feasible can take several months [4, 23]. Since the massive deployment of small cells will be the key techniques for 5G networks and the backhaul requirements of the small cells can significantly vary with the small cell location, the fiber cannot be the optimal approach for 5G backhaul solution [23–25]. On the other hand wireless backhauling (e.g., microwave and millimeter wave) becomes popular due to its availability, deployment time and cost-effective approach [24]. But the weather condition and multipath propagation have significant impact on microwave and millimeter-wave radio systems which can affect the transmission performance. So it is obvious that there will no unique backhaul solution for 5G networks. The backhaul evolution for 5G networks will include both wired and wireless backhaul solution [23].

The contributions of this book chapter are listed below:

- First, this chapter provides a brief introduction of mobile backhaul network and the evolution of mobile backhaul network.
- Second, provides a comprehensive overview of backhaul requirements of 5G networks and highlight the potential challenges.
- Finally, it outlines the existing mobile backhaul solutions (i.e., wired and wireless) and list their features, benefits, drawbacks, application areas and deployment challenges.

## 2. Introduction to mobile backhaul network and evolution

The mobile backhaul network connects radio access network air interfaces at the cell sites to the inner core network which ensures the network connectivity of the end user (e.g., mobile phone user) with the mobile networks (shown in **Figure 2**). In **Figure 2**, UE refers to end user, eNodeB refers to cell or cell site or base stations. Each user data is added with other components of the backhaul traffic (shown in **Figure 3**), to calculate the single eNodeB transport provisioning and then aggregate with all other eNodeB's traffic before it connects with the core network.

It is found that the capacity requirements on the transmission network to support the backhaul traffic from the core network is raises with the evolution of mobile/cellular networks [23]. Cost and reliability always been a concern and major challenges for cellular network operators and there is no magic solution to the demand [19]. This section describes, how the mobile backhaul network evolve with the evolution of each mobile network (e.g., 2G, 3G, and LTE).

### 2.1. Typical GSM, 3G, and LTE Network Overview

A typical GSM (Global System for Mobile Communications) network architecture is shown in **Figure 4**, where the BTS (base station transceivers) are located at the cell site and provide the control and radio air interface for each cell. The BSC (Base station controllers) provides control

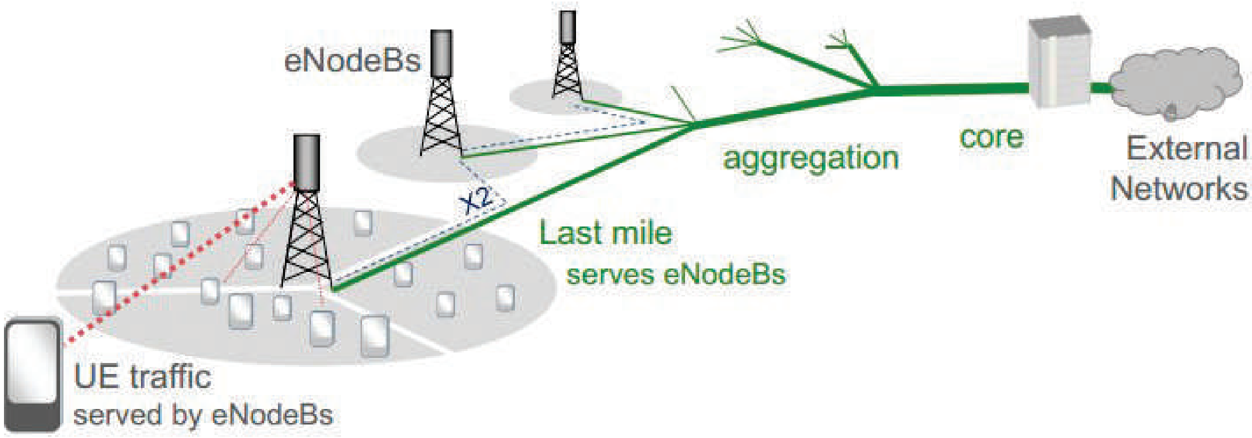


**Figure 2.** Mobile backhaul network of LTE (long-term evolution) [26].

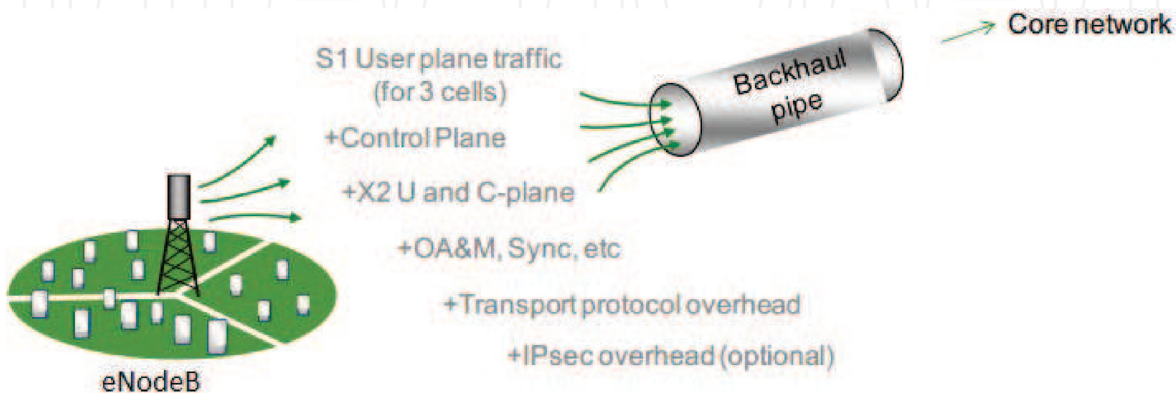


**Figure 3.** Components of backhaul traffic [26].

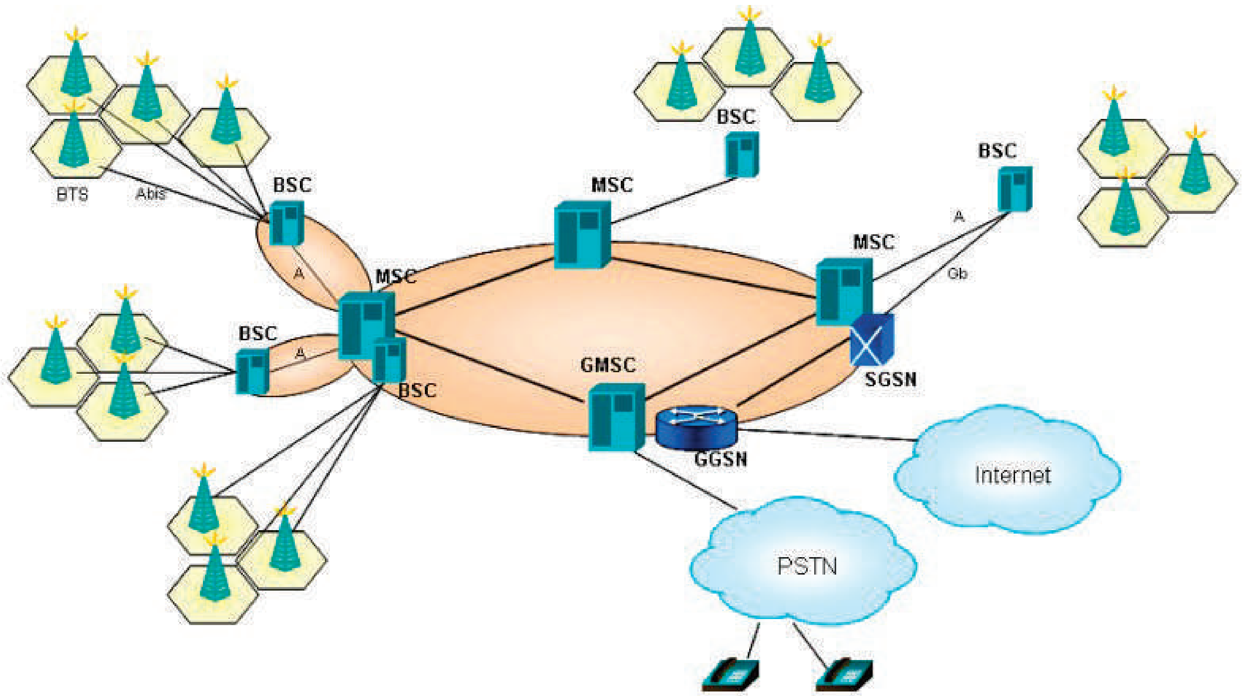


**Figure 4.** Typical GSM network with wireless interface requirements [27].

over multiple cell sites and multiple base station transceivers. The base station controllers can be located in a separate office or co-located at the mobile switching center (MSC).

There are standard interfaces developed by the wireless industry for interconnecting these devices, so they could deploy interoperable systems from multiple vendors. These physical interfaces define the wireless backhaul transport services and requirements. Thus, a basic understanding of these interfaces is very important. Some standard interfaces for GSM network are listed below [27]:

- Abis: the Abis interface connects the base station transceivers to base station controllers.
- A: the A interface in **Figure 2** connects the base station controller to the mobile switching center.
- Gb: voice services continue over the A interface, while data services are handled over the Gb interface.

Although the functions of these devices are similar, the 3GPP wireless standards body adopted slightly different names for the functional nodes and logical interfaces for UMTS (3G) networks, shown in **Figure 5**. But, historically the 2G/3G wireless standards were based on T1 (TDM) physical interfaces for interconnection between these devices because of the wide availability of T1 copper, fiber, and microwave services [28].

T1 physical interfaces has driven mobile backhaul transport requirements for 2G/3G wireless standards, but 4G wireless standards (i.e., LTE: Long-Term Evolution) are based on entirely new packet-based architecture, including the use of Ethernet physical interfaces for interconnection between the various functional elements, shown in **Figure 6**.

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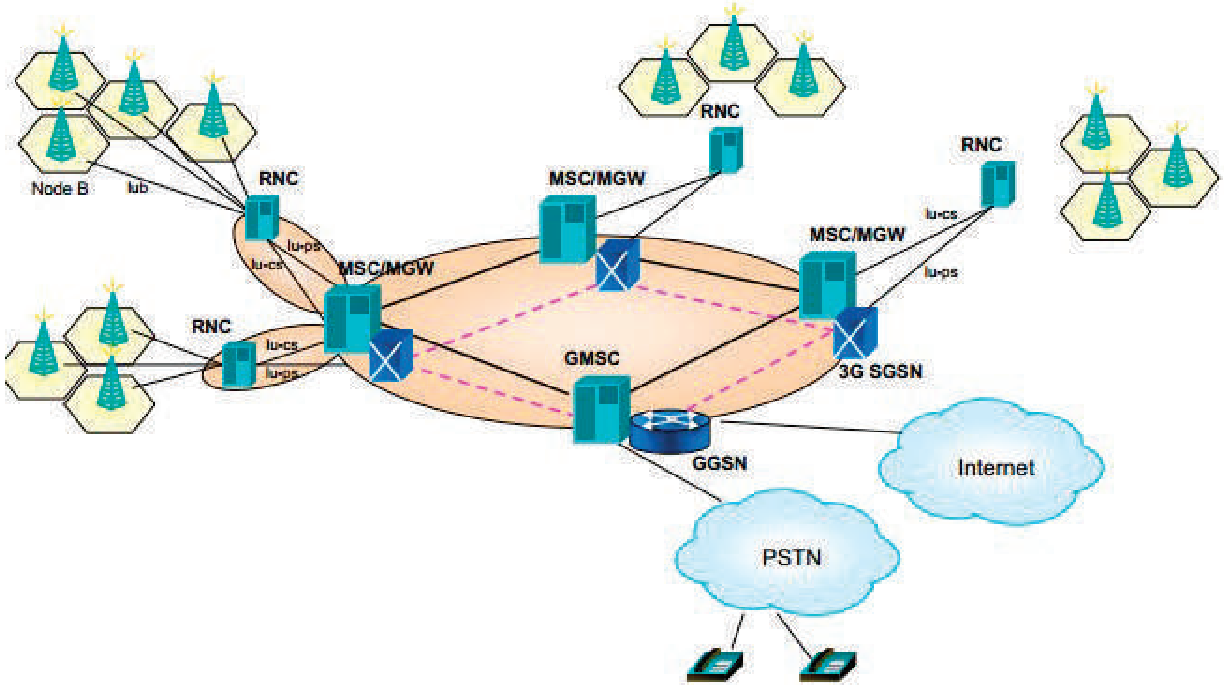


**Figure 5.** Typical 3G network with wireless interface requirements [27].

Another objective of the LTE standards was to flatten and simplify the network architecture. This resulted in pushing more intelligence into the radios (eNodeB) and elimination of the radio controllers as a separate device. In effect, the radio controller function has been distributed into

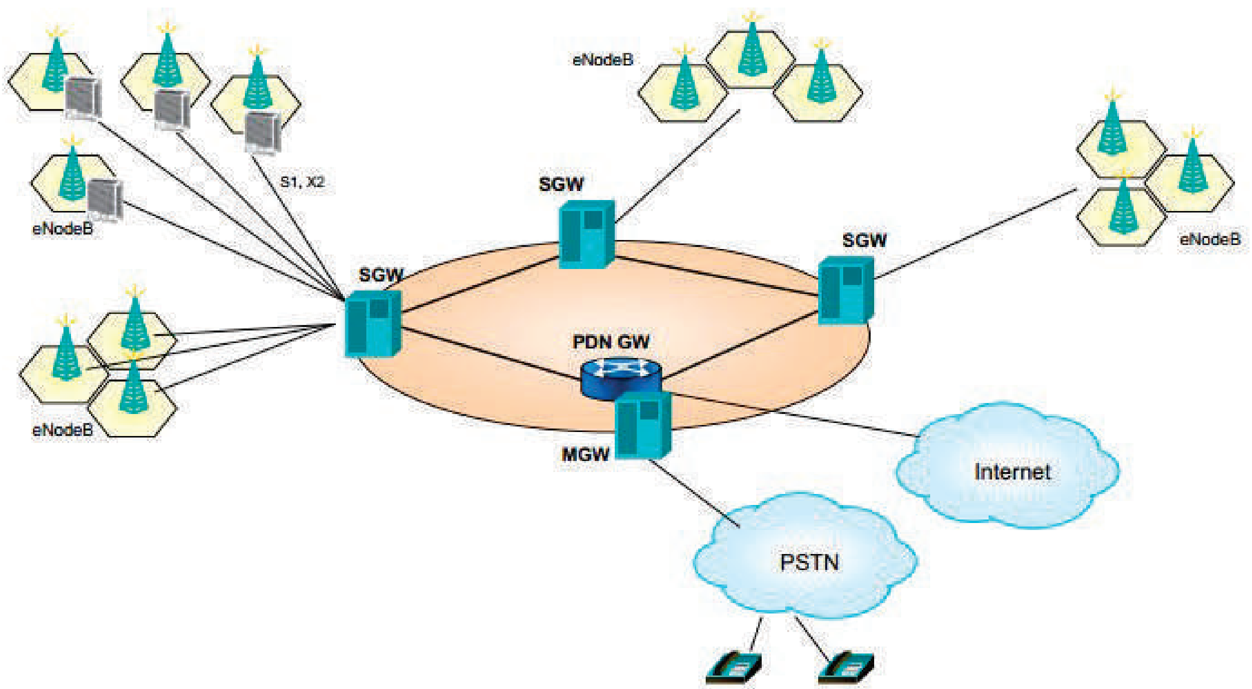


**Figure 6.** Typical LTE network with wireless interface requirements [28].

| Standards | Voice spectrum (MHZ) | Data spectrum (MHZ) | Voice spectral efficiency (bits/Hz) | Data efficiency (bits/Hz) | # Sectors | Total bandwidth (Mbps) | # T1 s |
|---|---|---|---|---|---|---|---|
| GSM 2G | 1.2 | | 0.52 | | 3 | 1.3 | 1 |
| GSM/ EDGE 2.75G | 1.2 | 2.3 | 0.52 | 1 | 3 | 6.1 | 4 |
| HSDPA 3G | | 5 | 0 | 2 | 3 | 21.0 | 14 |
| LTE 4G | | 5 | 0 | 3.8 | 3 | 39.9 | n/a |
| LTE 4G | | 10 | 0 | 3.8 | 3 | 79.8 | n/a |

**Table 1.** Wireless capacity requirements for 2G, 3G and LTE [27, 28].

each eNodeB radio. So, the resultant network is indeed much simpler and flatter, with far fewer functional devices.

From a mobile backhaul perspective: most cell sites will continue to support GSM 2G and UMTS 3G networks for many years, the addition of LTE means backhaul transport carriers need to implement systems that can support both native T1 TDM services and Ethernet services. But, the major changes are the higher capacities required by LTE cell sites. A detail comparison of wireless capacity requirements for 2G, 3G, and LTE networks are shown in **Table 1**.

## 3. 5G backhaul requirements and challenges

Enhance the network reliability and reduce the cost efficiency always been a major challenge for the cellular network operator and there is no magic solution to that demand [19]. With the evolution of mobile network, the capacity requirement of the transport network from the core raises significantly [23]. The major backhaul challenges that mobile network operator had to deal with up to 4G network includes capacity, availability, deployment cost, and long distance reach [16]. But, 5G network will interconnect billions of new start devices with the numerous use cases and services, which will support machine-to-machine (M2M) services and Internet of Things (IoT) to the mobile network [6, 8]. These new smart devices will not only enhance the backhaul capacity requirement, but it will also add two additional challenges in the backhaul network: (a) ultralow latency of ~1 ms (round trip) connectivity requirements, and (b) denser small cell deployment. This section describes the 5G backhaul requirements and potential challenges.

### 3.1. Capacity

The evolution of 5G cellular network is positioned to address new services and demands for business contexts of 2020 and beyond [29]. It is expected that 5G network will enable a fully mobile and connected society that empower socio-economic transformation in many ways and even some of which are unimagined today. To fulfill the demand of fully mobile and connected society can be characterized by the tremendous increase in the number of connectivity and traffic volume density [29]. According to Nokia, the number of connecting devices per mobile users will be ten to one hundred that includes, mobile phone, laptop, tablet, smart watch to smart shirts [11]. In addition, the number of connected machines and sensor devices in the industry and public infrastructure will increase. According to Ceragon, the forecasted capacity increase could be ×1000 compared to the capacity density in current 4G/4.5G networks [30, 31]. So, it is obvious that the evolution of 5G networks from LTE/LTE-A will need higher capacity backhaul links per cell site: while LTE/LTE-A networks need hundreds of Mbps, 5G network will need to support tens of Gbps, shown in **Figure 1**.

### 3.2. Availability

Availability is the major consideration for any backhaul networks, if the backhaul services are not in operation the system performance are negatively affected. In case of fiber systems, if there is any interruption of current path, the systems will automatically switch to the protection path within <50 ms [23]. Even in the wireless backhaul (e.g., microwave and millimeter wave), the backhaul link can be affected by multipath propagation and bad weaher condition. To overcome this, adaptive modulation technique is used that lowers the line rates to maintain the availability. Although the 5G network requirements is not standard yet, but to provide the expected new services such as autonomous vehicle/autonomous driving, tactile internet, and many machine to machine applications need high availability and very low latency [30].

### 3.3. Deployment cost requirements

Cellular network provider has to spend billions of dollars each year to acquire wireless spectrum for building excellent network coverage [23]. Since dense small cell deployment will be the key for 5G networks to support 1000 times more capacity, the cost efficient backhaul solution for the small will be a major challenge. An application specific traffic-engineering model needs to be formulated so that both customers and service providers can be happy.

### 3.4. Long distance reach requirements

Reach defines how far a cell site can get backhaul support from the core network with the required quality of service. Long distance reach is always a big issue for the backhaul network in terms of cost and additional equipment (e.g., total deployment cost of fiber backhaul will increase with the distance) [23]. Typically, cell sites are interconnected in a hierarchical mesh and all the traffics are transported back to an aggregation point (sometimes-called super cell) where all the traffics are aggregated and transport to the core network. Due to the dense small cell deployment in the 5G networks, massive backhaul traffic will be aggregated at the super cell that can create congestion and can even collapse the backhaul networks [19]. Therefore, long distance reach will be a big challenge for the 5G backhaul network.

### 3.5. Ultralow latency requirements

One of the major requirements of 5G network is ultralow latency ∼1 ms (round trip) [31]. Some 5G use cases and services, such as real-time monitoring and remote control, autonomous driving, tactile internet, and M2M applications need to support by mission-critical network because this type of services will need high availability, ultralow latency and tight security. In addition, the risks of network failure are too high [30]. Therefore, it will be a big challenge for 5G backhaul to support massive traffic and maintain the required quality of service with lower latency requirement. Since propagation delay is inherent, a solution has to be formulated based on physical layer.

### 3.6. Ultradense network

Since, 5G will use higher RAN frequencies, the cell site coverage will become very small compared to today's cell site (i.e., macro or micro cell). It is also not feasible to increase the cell site capacity by 1000 times. Therefore, dense small cell deployment is the only efficient way to support 1000 time more capacity in 5G network [30]. This dense nature of the small cell grid will present the following challenges for 5G backhaul:

- Denser backhaul link due to the denser small cell grid will highly limit the frequency reuse, which will require better utilization of wireless backhaul spectrum [30].
- There will be some set to unprecedented requirements for cell site synchronization. According to the forecast, 5G network will need three times stricter accuracy requirements than LTE-A (i.e., 1.5 μs to approx. 0.5 μs) [17].

## 4. Available mobile backhaul solutions and key challenges

Small cell backhaul requirements (e.g., traffic load intensity, latency, target quality of service, and cost of implementing backhaul connections) can vary significantly depending on the locations of the small cells [24]. Besides, the available backhaul scenarios can greatly vary, for example, some places fiber connection may be available but it may not be available for other places. Some places may be good line of sight microwave connectivity but it may not be available for every places. So, there is no single technology that can dominate backhaul technology [25]. There are many options, and the operators have to decide which backhaul solution will be most economical for any particular deployment scenarios. This section describes available backhaul solution that can be used for 5G networks.

### 4.1. Wired backhaul solution

A compressive study of wired backhaul solution is presented in [16]. So this subsection describes the fiber backhaul connection only. Fiber is the most popular backhaul solution that can provides highest capacity with low bit error rate and it allowed highest reach before any signal needs to be retransmitted. That's why fiber is always remains as the first choice for backhaul if it is available. Unfortunately, fiber is not available for most of the places. For example, one study conducted in 2014 present a fact that the fiber backhaul is not available nationwide in Europe and the alternative microwave backhaul solution will not sustain the traffic growth of LTE/LTE-A beyond 2017–2018 [16]. There are some other instances as well, such as nearby backbone fiber does not exist and there is no right of way available, or there are some obstructions (e.g., highways or rivers or buildings) that will make the fiber connection impossible. In addition, the deployment of new fiber connection will take several months compared with wireless deployments that can be completed within a week. Initial deployment cost of fiber connection is also high that includes cable costs, splicing, trenching, right of way, etc., plus the cost of equipment's for the optical transport and aggregation [23]. So, it is obvious that the fiber connection will be first choice for backhaul if it is available otherwise we have to look for other backhaul solution that meets the requirements of 5G networks.

### 4.2. Wireless backhaul solutions

Support the backhaul traffic from radio switch to cell site wirelessly (i.e., wireless backhaul) becomes popular due to the viability, and cost-efficiency. Wireless backhaul (e.g., microwave, millimeter wave) allows operator to have end-to-end control of their network instead of leasing third party wired backhaul (e.g., fiber) connections. However, the optimal selection among wireless backhaul solution depends on several factors that includes cell site location, propagation environment, desired traffic volume, interference conditions, cost efficiency, energy efficiency, hardware requirements, and the availability of spectrum [24]. This subsection describes the available wireless backhaul solution that can be used for small cell backhaul in 5G networks.

#### *4.2.1. Microwave*

Wireless backhaul technology supports approximately 50% of mobile traffic globally where, microwave RF technology has the vast majority [23]. It typically operates in the 6, 11, 18, 23, and 28 GHz frequency bands. The deployment of microwave radio requires one-time capital cost and there is some other costs that includes space/power rental and maintenance. So, microwave RF can be deployed at a much lower cost and the deployment time is much faster compared to fiber connection. However, the performance of microwave RF backhaul solution significantly varies with the propagation environment and bad weather condition. Often the system need to lower the transmission rate to maintain the availability requirements. Typically microwave RF can support up to 500 Mbps capacity and the maximum reach could be 30 miles which may also vary with the applications. For examples, if we use lower frequency band we can achieve longer reach but lower frequency bands are congested and may not be available for backhaul solution. On the other hand, if we use higher frequency we can have higher date rate but the system has to sacrifice the long reach. Microwave RF system capacity can be increased up to 10 Gbps for long and medium distance connectivity by utilizing wider channel spacing (e.g., 112 MHz for traditional microwave bands 4–42 GHz), higher order modulation schemes (e.g., 4096 QAM and up), and the use of ultrahigh spectral-efficiency technique (e.g., line of sight MIMO) [30].

#### 4.2.2. Millimeter wave

According to International Telecommunication Union (ITU), millimeter wave operates in Extremely High Frequency (EHF) which is range in 30–300GHz. So the millimeter wave RF can become prominent for small cell backhaul solution due its enormous spectrum [32]. Besides, smaller wavelengths will enable the integration of large number of antennas in a simple configuration and small cell can take this advantage of massive MIMO for LOS or non-LOS backhaul solutions. Typically, millimeter wave RF can support high data rate up to 1–2 Gbps range but the reach is shorter compared to Microwave RF due to the high propagation loss at millimeter wave [16]. The major factor that causes propagation loss includes, absorption, rain fading, and multipath propagation. Typically, the millimeter wave beams are much narrower compared to microwave beams that creates a major constraint which is line of sight (LOS) backhaul solution. Narrow beam can also create alignment problem and to avoid this problem, millimeter wave RF equipment's need to be installed in a solid structure [23].

#### 4.2.3. Free space optics (FSO)

Free space optics (FSO) is a line of sight backhaul technology which is similar as fiber optics except FSO uses invisible beam of light (e.g., LED, LASR) for data transmission instead fiber cable [33, 34]. FSO has enormous spectrum in the range of 300 GHz to 1 THz and the maximum data rate can support up to 10 Gbps (both upstream and downstream) [16]. The

| Technology | Deployment cost | Latency | Reach | Upstream throughput | Downstream throughput | Options |
|---|---|---|---|---|---|---|
| Satellite | High | 300 ms one-way latency | ~Ubiquitous | 15 Mbps | 50 Mbps | LOS |
| TVWS | Medium | 10 ms | 1–5 km | 18 Mbps/ch | 18 Mbps/ch | NLOS |
| Microwave PtP | Medium | <1 ms/hop | 2–4 km | 1 Gbps | 1 Gbps | PtP |
| Microwave PtmP | Medium | <1 ms/hop | 2–4 km | 1 Gbps | 1 Gbps | PtmP |
| Sub-6 GHz 800 MHz–6 GHz | Medium | 5 ms single-hop one way | 1.5–2.5 km urban, 10 km rural | 170 Mbps | 170 Mbps | NLOS |
| Sub-6 GHz 2.4, 3.5, 5 GHz | Medium | 2–20 ms | 250 m | 150–450 Mbps | 150–450 Mbps | NLOS |
| MmWave 60 GHz | Medium | 200 μs | 1 km | 1 Gbps | 1 Gbps | LOS |
| MmWave 70–80 GHz | Medium | 65–350 μs | 3 km | 10 Gbps | 10 Gbps | LOS |
| FSO | Low | Low | 1–3 km | 10 Gbps | 10 Gbps | LOS |

**Table 2.** Wireless backhaul solutions [16, 23, 33].

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major advantage of FSO is low power consumption compared to microwave or millimeter wave RF. But FSO system has number of constraints that includes LOS communication, fading due to fog, interference due to ambient light, scattering and physical obstructions. However, FSO technology can be one of the possible solution for 5G backhaul due to its scalability and flexibility [33].

Although there are some other wireless backhaul solutions (e.g., Satellite and TV White Spaces (TVWS)), but maximum data rate can support is less than 1Gbps and the latency requirement is also high. This is the main reason not to add much details about this two backhaul technologies. The available features (e.g., latency, reach, and throughput) of all wireless backhaul technologies are summarized in **Table 2**.

As it is seen from **Table 2**, FSO provides highest throughput with lowest latency which is the basic requirements of 5G backhaul. This is the main motivation of this paper where FSO is used for 5G backhaul networks with addition of ambient light cancelation technique at the receiver, described in Section 4.

## 5. Conclusions

According to the use cases, services, and network requirements of 5G, the next generation mobile network will not only human centric. This network will allow to connect new type of devices that support machine-to-machine (M2M) services and Internet of Things (IoT). Therefore, the backhaul network must meet diverse network requirements based on the type of user traffic, such as, some user traffic may care more about the maximum network speed not latency and on the contrary the users may care about the low latency not the speed. So, it is obvious that there will be no unique backhaul solution for 5G networks. Based on the deployment area and user traffic, the 5G backhaul network will be a combination of wired (e.g., fiber) and wireless backhaul (millimeter wave, and free space optics). Thus, understanding the basic backhaul network requirements is the key to choose the right technology and type of network. In an effort, this book chapter first introduce the backhaul network perspective for 2G, 3G, and 4G networks and then outlines the backhaul requirements of 5G networks. This chapter also describes the available backhaul solutions and describes the key challenges.

## Author details

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