SATELLITE COMMUNICATIONS IN DISASTER MANAGEMENT

A Degree Thesis
Submitted to the Faculty of the
Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona
Universitat Politècnica de Catalunya
by
Nil Ponsatí Sabé

In partial fulfilment
of the requirements for the degree in TELEMATICS ENGINEERING

Advisor: Marian Marciniak and Jacek Wilk (destination) and Marcos Postigo-Boix (ETSETB)

Kielce, June 2017
Abstract

This work consists on a study of the post disaster, both natural or human made, situations and its main impediments this situations bring. We focus on the collapse of the communications which limits the relief tasks from the different organizations and institutions.

The solution we offer to enable the communications between the affected population and the organizations, family or friends consists on the deployment of a cellular telephony system which uses satellite communications.

The system consists on a combination of LTE technology at 20 MHz, as a reception and distribution system, to and from the mobile telephony users and TES (Transportable Earth Stations), using satellite communications to send the information to the network and the calls to the PSTN (Public Switched Telephone Network).
Aquest treball consisteix en un estudi de les situacions post desastre, tant natural com realitzat per l’ésser humà, i dels principals impediments que aquestes situacions comporten. Ens focalitzem en el col·lapse de les comunicacions que impadeixen o limitien les tasques de socors de les diferents organitzacions i institucions.

La sol·lució que oferim per habilitar la comunicació entre la població afectada i les organitzacions, familiars o amics consisteix en el desplegament d’un sistema de telefonia cel·lular que utilitza les comunicacions per satèl·lit.

El sistema està format per una combinació de tecnologia LTE a 20 MHz, com a sistema de recepció i distribució de cara als usuaris de telefonia i TES (Transportable Earth Stations), utilitzant comunicacions via satèl·lit per l’enviament de la informació a la xarxa i les trucades a la PSTN (Public Switched Telephony Network).
Resumen

Este trabajo consiste en un estudio de las situaciones post desastre, tan natural como realizado por el ser humano, y de los principales impedimentos que estas situaciones suponen. Nos focalizamos en el colapso de las comunicaciones que impiden o limitan las tareas de socorro de las diferentes organizaciones e instituciones.

La solución que ofrecemos para habilitar las comunicaciones entre la población afectada y las organizaciones, familiares o amigos consiste en el desarrollo de un sistema de telefonía celular que utiliza las comunicaciones vía satélite.

El sistema está formado por una combinación de tecnología LTE a 20 MHz, como sistema de recepción y distribución de cara a los usuarios de telefonía, y TES (Transportable Earth Stations), utilizando, así, las comunicaciones vía satélite para el envío de la información a la red y las llamadas a la PSTN (Public Switched Telephony Network).
Acknowledgements

First of all, I want to thank my main project supervisor Prof. Dr. Marian Marciniak with whom I have shared so many mails and has supported me during all my work and stay in Poland. I would like to express my gratitude to Prof. Dr. Marcos Postigo Boix my supervisor in Barcelona for the Universitat Politècnica de Catalunya. Finally, I want to express my gratitude to Prof. Dr. Jacek Wilk who has also been my supervisor in Kielce and has helped me with the study of satellite communications.
### Revision history and approval record

<table>
<thead>
<tr>
<th>Revision</th>
<th>Date</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>06/04/2017</td>
<td>Document creation</td>
</tr>
<tr>
<td>1</td>
<td>14/06/2017</td>
<td>Document revision</td>
</tr>
</tbody>
</table>

### DOCUMENT DISTRIBUTION LIST

<table>
<thead>
<tr>
<th>Name</th>
<th>e-mail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil Ponsatí Sabé</td>
<td><a href="mailto:nilponsati@gmail.com">nilponsati@gmail.com</a></td>
</tr>
<tr>
<td>Marian Marciniak</td>
<td><a href="mailto:m.marciniak@itl.waw.p">m.marciniak@itl.waw.p</a></td>
</tr>
<tr>
<td>Marcos Postigo Boix</td>
<td><a href="mailto:marcos.postigo@entel.upc.edu">marcos.postigo@entel.upc.edu</a></td>
</tr>
</tbody>
</table>

### Written by: Reviewed and approved by:

<table>
<thead>
<tr>
<th>Date</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/04/2017</td>
<td>14/06/2017</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil Ponsatí Sabé</td>
<td>Marian Marciniak</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Author</td>
<td>Project Supervisor</td>
</tr>
</tbody>
</table>
# Table of contents

The table of contents must be detailed. Each chapter and main section in the thesis must be listed in the “Table of Contents” and each must be given a page number for the location of a particular text.

Abstract ............................................................................................................................ 1
Resum .............................................................................................................................. 2
Resumen .......................................................................................................................... 3
Acknowledgements .......................................................................................................... 4
Revision history and approval record ................................................................................ 5
Table of contents .............................................................................................................. 6
List of Figures ................................................................................................................... 7
List of Tables: ................................................................................................................... 8
1. Introduction ................................................................................................................ 9
   1.1. Statement of puropose ....................................................................................... 9
   1.2. Methods and procedures .................................................................................... 9
   1.3. Work packages, Milestones and Gantt Diagram ............................................... 10
2. State of the art of the technology used or applied in this thesis: ............................... 12
   2.1. Disaster management ...................................................................................... 12
   2.2. Satellite communications .................................................................................. 15
   2.3. Cellular telephony ............................................................................................. 18
   2.4. TETRA ............................................................................................................. 20
3. Methodology / project development: ........................................................................ 21
   3.1. Dimensioning a cellular emergency system in Kielce ........................................ 21
4. Results .................................................................................................................... 28
7. Conclusions and future development: ................................................................. 29
Bibliography: ................................................................................................................... 30
Glossary ......................................................................................................................... 31
List of Figures

Each figure in the thesis must be listed in the “List of Figures” and each must be given a page number for its easy location.

Figure 1 .......................................................................................................................... 12
Figure 2 .......................................................................................................................... 13
Figure 3 .......................................................................................................................... 13
Figure 4 .......................................................................................................................... 14
Figure 5 .......................................................................................................................... 15
Figure 6 .......................................................................................................................... 18
Figure 7 .......................................................................................................................... 21
Figure 8 .......................................................................................................................... 22
Figure 9 .......................................................................................................................... 27
List of Tables:

Each table in the thesis must be listed in the “List of Tables” and each must be given a page number for its easy location.

Table 1 ........................................................................................................................................... 12
Table 2 ........................................................................................................................................... 16
Table 3 ........................................................................................................................................... 18
Table 4 ........................................................................................................................................... 19
Table 5 ........................................................................................................................................... 25
1. **Introduction**

An Introduction that clearly states the rationale of the thesis that includes:

a. Statement of purpose (objectives).

b. Requirements and specifications.

c. Methods and procedures, citing if this work is a continuation of another project or it uses applications, algorithms, software or hardware previously developed by other authors.

d. Work plan with tasks, milestones and a Gantt diagram.

e. Description of the deviations from the initial plan and incidences that may have occurred.

The minimum chapters that this thesis document should have are described below, nevertheless they can have different names and more chapters can be added.

1.1. **Statement of purpose**

The objective of this project is to design a solution for communications in case of natural or human-made disaster, where the terrestrial communication infrastructure crashes. The idea is to create a mobile system formed by a cellular telephony base station, to give coverage to cellular phones, and connected to a transportable earth station which will use satellites to avoid the crashed terrestrial system in order to connect the population with relief organizations.

To develop an efficient solution, we will work on hypothetical disasters in the city of Kielce (South East of Poland), working on the implementation of a cell system in case of emergency. With the intention of working in a realistic situation we will study past disasters to know how these have been managed, as well as this, we will study the operation of satellite communications and how introduced to society it is and the cellular telephony system that is currently implemented in most of the countries around the globe.

1.2. **Methods and procedures**

The realization of this project is composed by two main parts:

The first part is the research and study of satellite communication to get acknowledgement on the transmission of data and calls with the earth terminal that approaches more to the needs of an emergency situation where current cellular communications try to adapt a system with cellular telephony base stations and transportable earth stations to avoid the collapse, enabling the communication between relief organization with affected population.

The second part consists of planning the dimensioning of the cell-to-satellite system to cover all the regions of Kielce in case of disaster from natural hazard.
### 1.3. Work packages, Milestones and Gantt Diagram

<table>
<thead>
<tr>
<th>Major constituent: Disaster management</th>
<th>Planner start date: 07/03/2017</th>
<th>Planned end date: 04/04/2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short description: Study of current disaster management response plans and study of precedents.</td>
<td>Start event: 15/03/2017</td>
<td>End event: 30/04/2017</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Major constituent: Satellite communication</th>
<th>Planned start date: 04/04/2017</th>
<th>Planned end date: 25/04/2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short description: Study of satellite communication operation and components.</td>
<td>Start event: 15/03/2017</td>
<td>End event: 30/04/2017</td>
</tr>
</tbody>
</table>

| Major constituent: Cellular telephony | Planned start date: 04/04/2017 | Planned end date:  |
Project: Satellite Communication in Disasters Management

WP ref: (WP4)

Major constituent: Design of communication method in the field for disaster response

Sheet 1 of 1

Short description:
Design of a method to give coverage to the population of Kielce via satellite communication in a hypothetic emergency situation.

Planned start date: 25/04/2017
Planned end date: 03/06/2017

Start event: 01/05/2017
End event: 03/06/2017

Milestones

<table>
<thead>
<tr>
<th>WP#</th>
<th>Task#</th>
<th>Short title</th>
<th>Milestone / deliverable</th>
<th>Date (week)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1</td>
<td></td>
<td>Disaster management</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>WP2</td>
<td></td>
<td>Satellite communication</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>WP3</td>
<td></td>
<td>Cellular telephony</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>WP4</td>
<td></td>
<td>Design method</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

Gantt Diagram
2. **State of the art of the technology used or applied in this thesis:**

A background, comprehensive review of the literature is required. This is known as the Review of Literature and should include relevant, recent research that has been done on the subject matter.

2.1. **Disaster management**

The definition of a disaster given by WHO (World Health Organization) is “events that occur when significant numbers of people are exposed to hazards to which they are vulnerable, with resulting injury and loss of life, often combined with damage to property and livelihoods”.

The definition of an emergency given by WHO (World Health Organization) is “situations that arise out of disasters, in which the affected community’s ability to cope has been overwhelmed, and where rapid and effective action is required to prevent further loss of life and livelihood”.

Historically there have been different natural hazards (which are usually followed by disasters) and human-induced disasters where a part of the population has been affected with material losses and/or human casualties. From 2000 to 2011 disasters affected 2.7 billion people and produced a cost of 1.3 trillion dollars.

Most of the natural hazards can be prevented from becoming disasters with an adequate plan and enough resources. But when the prevention plan fails or society does not prepare for the situation is when emergency plans are launched. That is why organizations and governments from different regions around the world have developed different emergency plans to minimize the damage caused by those situations.

The United Nations (UN) developed a document, which is being updated and reviewed periodically, called *Disaster Preparedness for Effective Response*. It is a document where governments or other organizations can get the guidelines to prevent disasters, minimize damages and manage a response. This document is used by different governments and institutions to elaborate their own emergency plan.
Sahana Foundation (www.sahanafoundation.org) is a non-profit organization that developed an open-source software after the 2004 Tsunami. It is an emergency management program to help coordinate different organizations and governments for disaster response tasks. This software consists on different modules that can support all different phases of the emergency cycle.

Some of the most recent disasters where the ground communications infrastructure collapsed are:

- Haitian Earthquake

  One of the most recent and deadliest disasters was the earthquake of magnitude 7.0 with its epicentre near Port-au-Prince, capital of Haiti, on January 12, 2010. Affecting more than 3 million people and causing 160.000 deaths, apart from millions of dollars in infrastructure damage.

  The fact that communication systems were cut off, some institutional buildings collapsed, like Presidential Palace’s roof, and basic services such as electricity and water were interrupted by the quake and the multiple aftershocks during the next 24 hours made the response slow and inefficient in a situation where time was running out against the population and relief organizations, making the rescue difficult and disorganized.

- Indian Ocean Tsunami

  The deadliest natural disaster on the last 50 years occurred in the Indian Ocean near the coast of Sumatra, Indonesia, on 26 December, 2004. A 9.3 magnitude undersea earthquake unleashed a tsunami which affected 18 countries from Southeast Asia and Southern Africa. It killed more than 250.000 people in one day and left more than 1 million homeless.

  The disaster originated in environmental and medical issues like water pollution and endemic diseases. Terrestrial communications of the most affected countries (Indonesia and Shri Lanka) suffered damages limiting the communications for the relief.
Peru’s floods

The most recent disaster which has claimed 94 deaths and more than 700,000 homeless has occurred in Peru on March, 2017. The rains and thunderstorms have caused floods and overflows the river affecting 12 of the 25 regions of the country.

The floods has impacted the water supply and the power supply leaving uncommunicated some of the affected areas.

When a natural hazard becomes a disaster, the emergency response has to be fast and efficient to minimize damage and the best way to get these goals is assigning different functions to different organizations.

Local or national authorities have to assume the administrative role which consists of assigning different tasks for different NGOs or institutions to do and supervising the security of the base camps deployed in the affected area.

The UN is required to assume the coordination role which consists of working on the strategy to follow, the information management, contingency plan and setting the standards.

Usually a partner NGO and local or national authorities have to assume the management role which consists of coordinating the different organizations and institutions to work in the most efficient way with the others.

Ways in which we could summarize the different roles with the next scheme:

- **Coordination:** Collect information about people who need help or assistance
- **Administrative:** Assign each organizations to relief each of them
- **Management:** Coordinate the different organizations for the relief

Base camps are situated in the different parts of the region in the way they can reach as much people as possible and to the different camps as well. Those camps have to be located in strategic places with power supply, clean water and with infrastructures that allow an easy access.
2.2. **Satellite communications**

A satellite is a radio located in space which has between 24 and 72 transponders, the signal path which data follows through the satellite. Each transponder has a capacity of 155 million bits per second.

![Diagram of a satellite receiving information from USA and sending it to Tanzania (Intelsat)](image)

Satellite communication consists of sending electromagnetic waves signals from earth stations to space stations (satellites) and vice versa. The transmission of information goes from a ground-based antenna to the satellite whose antennas capture the signals, changes the frequency and sends it to another ground-based antenna or broadcasts it to many earth stations. It is called **uplink** when the transmission goes from an earth station to a space station and **downlink** when the signal goes from the satellite’s antenna to the ground’s one.

Different frequency bands are used by different satellites: first bandwidths historically used are the C-Bands, which are still in use by some systems, using an uplink band of 6 GHz and a downlink of 4 GHz. The so-called X-Bands, which are used by the military and governmental systems, are the 8 GHz for uplink and 7 GHz for downlink band. New systems, and the one we are interested in, are using the Ku-Bands which operate around the 14 GHz for uplink and 11-12 GHz for downlink. These bands are getting saturated, so the Ka-Bands will be more and more implemented with the time, this band works on 30 GHz uplink and 20 GHz downlink, giving much more bandwidth for different satellite systems that will be implemented.

Nowadays different kinds of satellite communications networks exist depending on their orbits or functionality. The type of satellites we will study depending on its orbits are the GEO and the LEO satellite which are those we are interested in for our necessities in this project.
GEO (Geostationary Earth Orbit) satellites are located 36,000 km above the Earth fixed in the same point providing service to the same region all the time so they are coordinated with the Earth’s rotation (24 hours’ period). One satellite can give coverage almost to one third of the Earth because of the altitude, but it also implies a delay >250ms. There are approximately 300 GEO satellites in orbit and they can provide voice, video and broadband data. GEO satellites are used by VSAT (Very Small Aperture Terminal) antennas to send information to other terminals.

MEO (Medium Earth Orbit) satellites are located higher than 10,000 km above the Earth with a period of 6 hours approximately needing tracking systems to be able to connect to the different satellites (between 12 and 24 devices are needed to cover the whole globe) that provide a continuous coverage. These satellites have an acceptable delay of 40ms because of the lower distance to earth, not like GEOs, for voice conversations between users.

LEO (Low Earth Orbit) satellites that are located between 800 and 1,200 km above the Earth following a circular orbit with a, respectively, 1.6 and 1.9 hours’ period. These satellites are covering the same cell (designated areas all around the globe) for 15-20 minutes per round, this fact, as with MEOs, makes the need of tracking systems. Because of its altitude it can cover a 2,800 km radius zone of the Earth, needing between 50 and 150 devices to provide continuous service to the whole globe. These satellites can provide voice and low speed data communications with small delays of several milliseconds being compatible with small antennas and handheld user terminals.

LEO satellites are distinguished in 3 types depending on what are them used for: Little LEO for low bit rate data (paging). Big LEO for mobile telephony (cellular telephony). Broadband LEO for high bit rate data (fibre).

Depending on the functionality we can differentiate between two types of satellites, on one hand, *Feeders*, these are the ones that are linking the communication to a gateway of earth stations carrying trunk or network traffic. On the other hand, *Services*, which are linking to the end-users carrying traffic intended for them.

TESs (Transportable Earth Stations) are used for emergency communications in disasters due to low weight and ease of carry with vehicles as vans, helicopters, etc. as can be seen in the table. These antennas work in the 14/12 GHz band being able to send and receive data to satellites from almost every part of the globe and have enough capacity to transmit voice, data and video to any kind of satellite system.

<table>
<thead>
<tr>
<th>Type of transportation</th>
<th>Air transportable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna diameter (m)</td>
<td>1.2–21.8</td>
</tr>
<tr>
<td>e.i.r.p. (dBW)</td>
<td>62.5–72</td>
</tr>
<tr>
<td>RF bandwidth (MHz)</td>
<td>20–30</td>
</tr>
<tr>
<td>Total weight (kg)</td>
<td>200–275</td>
</tr>
<tr>
<td>Package:</td>
<td></td>
</tr>
<tr>
<td>· Total dimensions (m)</td>
<td>&lt;2</td>
</tr>
<tr>
<td>· Total number</td>
<td>8–13</td>
</tr>
<tr>
<td>· Max. weight (kg)</td>
<td>20–45</td>
</tr>
<tr>
<td>Capacity of engine generator (kW)</td>
<td>0.9–9.3</td>
</tr>
</tbody>
</table>

*Table 2. Transportable earth station technical specifications*

In appropriate conditions the capacity of TES can reach the 1.5 Gbps, being enough - there is not a cellular telephony antenna that can achieve such capacity - for the data transmission and communications from and to the population located in the affected area with the relief institutions.
Multiple access

FDMA (Frequency Division Multiple Access) separates the different carriers in the transponder by frequency so, on the uplink the transponder can process the different signals from different terminals at the same time, on the downlink the full FDMA spectrum is transmitted and terminals listen only to their own part of the broadband. FDMA can effect either analogic and digital communications or a combination of them.

TDMA (Time Division Multiple Access) the different carriers access to the transponder in different periods of time so, on the uplink each terminal is using the whole bandwidth during their time slot, on the downlink the burst is interleaved set of all packets. A reference station is needed to establish the synchronization reference clock and burst time management data. With TDMA only one carrier is at any time to the transponder allowing the final amplifier in the satellite transponder to operate with a saturated power output being the most efficient method on using the power available.

CDMA (Code Division Multiple Access) is the most complex method because requires synchronization at both transmission and reception levels. It consists on a combination between both FDMA and TDMA, for the uplink each ground terminal has been assigned with a time slot and a frequency band in coded sequence and for the downlink the receiver must know a code to detect the appropriate packets. CDMA is practical for digital formatted data only, and offers the highest power and spectral efficiency operation.
2.3. **Cellular telephony**

Nowadays, society has a really close link with communication technology, so much so 64.5% (2017) of the world’s population have a mobile phone, they are called cell phones because of the cells its network is divided in.

![Figure 6. Cell system diagram](image)

The cell system consists on dividing a region in several hexagonal cells covered by an antenna with a number of radio channels that connects terminals in its area to the PSTN (public switched telephone network). Each cell has a base station which consists of three sectorial antennas, each one facing to a different direction, which cover the 360° of a circular area with their beam widths.

As can be seen in the table, there are different types of cells depending on the radius of the area their base station covers. The largest cells are implemented in rural zones where the density of population is low and the smallest cells are allocated in places where there’s a lot of people like offices or tourist buildings.

The cells we will be more interested in during this project are microcells which can have a radius area between 200 m and 2 km in function of the power it is powered with.

<table>
<thead>
<tr>
<th>Kind of cell</th>
<th>Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrocell</td>
<td>&lt; 35 km</td>
</tr>
<tr>
<td>Microcell</td>
<td>&lt; 2 km</td>
</tr>
<tr>
<td>Picocell</td>
<td>&lt; 200m</td>
</tr>
<tr>
<td>Femtocell</td>
<td>10m</td>
</tr>
</tbody>
</table>

Table 3. Type of mobile phone cells

With the evolution of the technology from the beginning of the mobile telephony until now, base stations have gone through 5 different generations, as can be seen in the table below, from 1G to 4G, each one implementing new experiences for the users.
To transmit and receive information of different users at the same time, base stations use the TDMA, CDMA or FDMA.

<table>
<thead>
<tr>
<th>Generation</th>
<th>Technology</th>
<th>What does it allow</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>PTT</td>
<td>Analogic voice transmission</td>
<td></td>
</tr>
<tr>
<td>2G</td>
<td>GSM</td>
<td>Digital voice and low speed data transmission.</td>
<td>9.6 kbit/s</td>
</tr>
</tbody>
</table>
| 2.5G       | GPRS       | Dynamic and interactive, multimedia data transmission and better data transmission. | GPRS: 56 kbit/s – 114 kbps  
EDGE: 384 kbit/s |
| 3G         | UMTS       | Global data itinerancy, videoconference, TV and broadband (internet). | 144 kbit/s - 7.2 Mbit/s |
| 4G         | LTE        | Voice over IP and considerable higher speed. | 100MB/s moving - 1GB/s quiet |

Table 4. Cellular technology evolution
2.4. **TETRA**

A trunked radio system is a two-way radio system that allows communications one-to-one, many-to-one and many-to-many by using a control channel to automatically direct the traffic. Trunked radio differs from a conventional system on how users occupy the channels available. When there is a group of users with a conventional radio it has a dedicated channel, having as many channels as groups of users. Meanwhile, with a trunked radio system has a pool of channels which are shared by the different talk-groups. In a trunked system, groups of users are called talk-groups. This system allows a larger number of user group can fit in a number of channels.

TETRA (Trans-European Trunked Radio) is a European standard of trunked radio system used in emergency situations by relief organizations and government agencies. TETRA terminals can communicate with a full-duplex direct connection to other TETRA terminals or to the PSTN. Multiple access is managed by TDMA with 4 user channels per radio carrier and, after coding, has a data transfer speed up to 7.2 kbit/s per timeslot in a one-to-one communication and 3.5 kbit/s in case of IP encapsulation, being a very slow transfer speed nowadays. TETRA Mobile Stations can also communicate using DMO (Direct-Mode Operation) enabling communication in situations where network coverage is not available or using other TETRA terminals as relays.

TETRA systems are being used in 144 countries (2009) around the globe, including most of European countries’ public services like Catalunya mainly police, Mossos d’Esquadra, provided by EADS.
3. **Methodology / project development:**

The Methodology is included in this chapter and should include all relevant methods that were utilized as well as research methods and measurements, software and hardware development...

3.1. **Dimensioning a cellular emergency system in Kielce**

The number of mobile phone SIM cards in Poland in 2015 was 56.6 million, being it a penetration of 147.2%, as can be seen in the Figure 7. We can also appreciate a decreasing of 3 points from year 2014 which comes from the adjustment that mobile companies did deleting the unused numbers.

We will consider the data provided before, which is an average of whole Poland, to work in the city of Kielce. This city is located in the south center of Poland, in the middle of the Świętokrzyskie Mountains (Holly Cross mountains) occupying an area of about 109.65km$^2$ and has a population of 198,046 inhabitants\(^1\), knowing that we can get the average density of population in the city, that is approximately 1,806 inhab./km$^2$.

In a conventional cellular system the consumption by users is mostly stable with some peaks everyday, but now we are considering an emergency situation after a disaster, this fact makes the cellular system we want to deploy an unusual system that will have to work with an initial huge peak just after the disaster and will decrease gradually as relief institutions bring the situation under control.

To dimensionate the cellular system in a way all inhabitants with a cellular phone line have coverage, trying to minimize the costs of the system and not overdimensionate it, we will consider certain initial considerations.

First considerations will be that all the users with more than one line will only use one of the terminals at the same time, so we will consider the number of inhabitants without considering the lines which actually exists, ignoring the penetration of phone telephony. In that way we will consider 198,046 lines, one per inhabitant, not 291,524 as we should use considering the penetration of mobile telephony.

The second consideration consists on removing a 13.18% the lines that matches with the percentage of population of children between 0 and 14 years old, which we will consider they don’t have any terminal. So we will consider 171,944 lines to give coverage in the region.

The third and the last consideration will be considering a 70% of working time which means that the maximum capacity of the system will be about 120,361 lines working at

---

\(^1\) Population of Kielce in 2015
the same time. This consideration corresponds to the situation where groups of cellular telephony users will be in group so only one of them will call the emergency services and not each one of the users that are together in that moment. Finally, after all considerations we will have to provide coverage to a total number of 120,361 SIM cards at the highest peak of use after the disaster, which is a 60.77% of the penetration.

After knowing the penetration we will consider in the emergency situation we will need to know how people is distributed around the city of Kielce to differentiate between dense locations like Rynek (center of the city) or sparse locations like the fields or woods that can also be found in its territory. We will differentiate between Urban (Blue), Industrial (Orange) or Rural (remaining) areas to optimize the resources of the dimensioning. Population in urban areas is about 173,667 inhabitants and a density of population about 3,136.66 inhabitants/km\(^2\). In industrial areas there are 23,369 inhabitants and a density of 448.07 inhabitants/km\(^2\). And population in rural areas is 3,090 with a density of 44.79 inhabitants/km\(^2\).
With the penetration of cellular telephony we have calculated before and the population divided by areas we have, we can calculate the number of users to give coverage during the emergency situation in the different areas.

In the urban areas the number of users will be $173,667 \times 0.6077 = 105,538$ users.

In the industrial areas will be $23,369 \times 0.6077 = 14,201$ users.

In the rural areas will be $3,090 \times 0.6077 = 1,878$ users.

Considering that the number of users that we have calculated will all call the emergency services, the number of calls just after the emergency situation will be 1 call/user (charged hour) and the average call duration will be about 3.5 minutes\(^2\).

Each Base Station will have a configuration of 3 sectorial antennas with 4 carriers each one and 32 slots. 1 slot for signage and 2 slots for control will be reserved in each antenna so, 32-1-2 = 29 slots per BS will be for voice circuits.

To determine the situation, size and type of BS we will use we will consider a BP<2%.

**Urban areas:**

Offered traffic per user = 1 call/user * 3.5 min/call * 1 h / 60 min = 58.33 mErl user.

Offered traffic per cell = 58.33 mErl * Nusers

Erb (OTcell\(^3\), 29) < 2% \quad OTcell <= 69 Erlangs.

Number of users per cell <= 69 / 0.05833 = 1,183 users/BS.

Number inhabitants per cell = 1,183 / 0.6077 = 1,947 inhabitants/BS.

Density = 3,136.66 inhabitants/km\(^2\)

Cell size = 1,947 inhab. / 3,136.66 inhab. / km\(^2\) = 0.621 km\(^2\).

Radius of the cell = \sqrt{(0.621 \times 10^6) / \pi) = 445 m.}

We will need microcells of 445 m of radius to cover the urban areas.

**Industrial areas:**

Offered traffic per user = 1 call/user * 3.5 min/call * 1 h / 60 min = 58.33 mErl user.

Offered traffic per cell = 58.33 mErl * Nusers

Erb (OTcell, 29) < 2% \quad OTcell <= 69 Erlangs.

Number of users per cell <= 69 / 0.05833 = 1,183 users/BS.

Number inhabitants per cell = 1,183 / 0.6077 = 1,947 inhabitants/BS.

Density = 448.07 inhabitants/km\(^2\)

Cell size = 1,947 inhab. / 448.07 inhab. / km\(^2\) = 4.345 km\(^2\).

\(^2\) Data extracted from the EENA, European Emergency Number Association

\(^3\) Offered Traffic per cell
Radius of the cell = sqrt \( \frac{4.345 \times 10^6}{\pi} \) = **1,177 m**.

We will need macrocells of 1,177 m of radius to cover the industrial areas.

**Rural areas:**

- Offered traffic per user = 1 call/user * 3.5 min/call * 1 h / 60 min = 58.33 mErl user.
- Offered traffic per cell = 58.33 mErl * Nusers
- \( \text{Erb (OTcell, 29)} < 2\% \) \( \Rightarrow \) OTcell <= 69 Erlangs.
- Number of users per cell <= 69 / 0.05833 = **1,183 users/BS**.
- Number inhabitants per cell = 1,183 / 0.6077 = 1,947 inhabitants/BS.
- Density = 44.79 inhabitants/km\(^2\)
- Cell size = 1,947 inhab. / 44.79 inhab. / km\(^2\) = **43.47 km\(^2\)**.
- Radius of the cell = \( \sqrt{\frac{43.47 \times 10^6}{\pi}} \) = **3,720 m**.

We will need macrocells of 3,720 m of radius to cover the urban areas.

Once we have the radius of the cells and the area they have to occupy to provide enough capacity to the people in the zone we can calculate that we will need **79 cells:**

- 6 macrocells of 3,720 m radius.
- 10 macrocells of 1,177 m radius.
- 63 microcells of 445 m radius.

The penetration of mobile broadband in Poland is 65.3\%\(^4\). In our region of study, Kielce, we will consider 198,046 * 0.653 = 129,325 mobile broadband consumers which will consume, in average, 10 MB\(^5\) of web browsing + 2 MB\(^5\) for file downloading = 12 MB/user (form fullfilling for possible relief cooperation) per user immediately after the disaster.

Considering the 70\% of the data consumed for downlink, the speed needed per one user will be \( 12 \text{ MB/user} * 0.7 * 1 \text{h} / 3600 \text{ s} * 8 \text{ bits} / 1 \text{ Byte} = 18.67 \text{ Kbps/user} \).

And the 30\% of the data for uplink, needing a speed per user of \( 12 \text{ MB/user} * 0.3 * 1 \text{h} / 3600 \text{ s} * 8 \text{ bits} / 1 \text{ Byte} = 8 \text{ Kbps/user} \).

So each user consumes 18.67 Kbps + 8 Kbps = 26.67 Kbps.

We will consider a working point of the system of 100\% trying to be able to provide all the people that need it to contact with familiars, ask for help or look for information to get over the situation.

As we can see in the table, depending on the frequency we will be working at, we can have different speeds with LTE technology. Further technologies as UMTS or GPRS cannot provide enough capacity to cover the quantity of users we are considering.

\(^4\) OECD, June, 2016

\(^5\) https://www.broadbandchoices.co.uk/guides/broadband/guide-to-internet-data-usage
Table 5. Capacity of a LTE cell

<table>
<thead>
<tr>
<th>Channel Bandwidth</th>
<th>Close</th>
<th>Medium</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>5MHz</td>
<td>17 / 5.6</td>
<td>11 / 3.7</td>
<td>5.6 / 1.8</td>
</tr>
<tr>
<td>(FDD typical) 10MHz</td>
<td>43 / 14.4</td>
<td>28 / 9.5</td>
<td>14 / 4.8</td>
</tr>
<tr>
<td>20MHz</td>
<td>85 / 28</td>
<td>56 / 18</td>
<td>28 / 9.5</td>
</tr>
</tbody>
</table>

If we consider an LTE cell working at 5 MHz channel Bandwith the medium capacity all arround the cell area will be 11 Mbps. The number of users that one cell will provide coverage for will be about 11 Mbps / 26.67 Kbps = 412 users/cell so 412 / 0.653 = 630 inhabitants/cell which is less than the 2,507 inhabitants that each cell of the area of Kielce will have to support.

If we consider an LTE cell working at 10 MHz channel Bandwith, which is the typical frequency, the medium capacity all arround the cell area will be 28 Mbps. The number of users that one cell will can provide coverage will be about 28 Mbps / 26.67 Kbps = 1,049 users/cell so 1,049 / 0.653 = 1,607 inhabitants/cell which is less than the 2,507 inhabitants that each cell of the area of Kielce will have to handle with.

If we consider an LTE cell working at 20 MHz channel Bandwith the medium capacity all arround the cell area will be 56 Mbps. The number of users that one cell will can provide coverage will be about 56 Mbps / 26.67 Kbps = 2,099 users/cell so 2,099 / 0.653 = 3,215 inhabitants/cell which is more than the 2,507 inhabitants that each cell of the area of Kielce will have to handle with.

So, finally we will need to use 79 cells using LTE technology at 20 MHz to provide coverage to the 198,046 inhabitants all arround the city of Kielce after a situation of emergency.

We will consider one location area for the whole city which will be formed by the 79 cells:
63 microcells of 0.621 km² + 10 macrocells of 4.345 km² + 6 macrocells of 43.47 km²
A total area of 343.393 km².

The outcoming calls will be about 60%, most of them asking for help or information and the incoming calls will be about 40% (familiars or friends and relief organizations).

Considering again 1 call/user (charged hour) we will have:
Urban area: 1 call/user * 0.4 = 0.4 entering calls/user (charged hour). 105,538 users.
Industrial area: 1 call/user * 0.4 = 0.4 entering calls/user (charged hour). 14,201 users.
Rural area: 1 call/user * 0.4 = 0.4 entering calls/user (charged hour). 1,878 users.
445 meters cell (urban area) from one sectorial BS (63 in total)

\[
\frac{0.4 \times 105.538}{63} = 671 \text{ incoming calls / cell (charged hour)}
\]

1,177 meters cell (urban area) from one sectorial BS (10 in total)

\[
\frac{0.4 \times 14201}{10} = 569 \text{ incoming calls / cell (charged hour)}
\]

3,720 meters cell (urban area) from one sectorial BS (6 in total)

\[
\frac{0.4 \times 1087.8}{6} = 126 \text{ incoming calls / cell (charged hour)}
\]

As we said, the system will be working at 100% of its capacity, so we look for a \( \rho < 1 \).

We have \( \rho = \frac{(\lambda \times Tmf51)}{i} \), being \( i \) the number of blocks used, \( Tmf51 = 235.38 \text{ ms} \) and \( \lambda = \frac{(671 \times 63 + 569 \times 10 + 126 \times 6)}{3600} = 13.53 \).

\[
I = \frac{\lambda \times Tmf51}{\rho} = \frac{13.53 \times 235.38 \times 10^{-3}}{1} = 3.19 = 4 \text{ blocks}.
\]

For one paging sub-channel we have a delay of \( \rho = 1 / 4 = 0.25 \) so the delay will be:

\[
T = \frac{\rho^2}{2\lambda(1-\rho)} = \frac{0.25^2}{2 \times 13.53 \times (1-0.25)} = 3.08 \text{ ms}.
\]
4. Results

Summarizing the results we obtained on our study we can see that we will need 79 cells: 63 microcells with 445 m of radius to cover the urban zones, 10 macrocells with 1,177 m of radius to cover the industrial areas and 6 macrocells of 3,720 m of radius to cover the rural areas of the city of Kielce.

Those cells will be fed by sectorial antennas (three sectors) that will use LTE technology at 20 Mhz frequency to have enough capacity to support the density of population of the region. About the paging channel for the incoming calls we calculated a reasonable delay of 3.08 ms being enough with 4 blocks to localize any user in any of the cells all around the city.

Figure 9. Distribution of the cells on the city of Kielce.
To allow communication in a post-disaster situation where current facilities were damaged, the best solution we found was using Transportable Earth Stations to send and receive the data and the calls between the affected population with the emergency relief and the familiars or friends. This TES has a capacity of 1.5 Gbps which is more than the 85 Mbps that an LTE antenna can provide in the best conditions.

The multiple access in both telephony antennas and TES will be FDMA for ingoing and outgoing calls and TDMA for data to minimize the power used by the antennas.
5. **Conclusions and future development:**

**Conclusions**
This was a project that allowed us to get a little insight into harmful consequences that can cause a natural or human-made disaster for any region around the world. In this project we focused on how to minimize the absence of communications, implementing a cellular emergency system which uses, unlike conventional systems, satellite communications antennas to connect to the truncal network, in case of a collapse of local facilities.

Despite the high cost that can represent the submitted solution, we must also consider the advantages it permits. Allowing the rescue and aid that can provide relief organizations to be as effective as possible in a situation where time goes against them. Using facilities that have not been damaged (as antennas already installed) to minimize costs so we will only need to install the TES to the cellular antennas.

**Future development**
Possible future developments can be added to the project. The implementation of different cities with different necessities or telephony demands being the main one. Depending on the country and region of said country, the cellular telephony system dimensioning must cover other necessities, in some cases it would make no sense to develop a cellular emergency system where most of the population are not using mobile telephony.
Bibliography:


**Glossary**

WHO (World Health Organization)
UN (United Nations)
NGO (Non-Governmental Organisation)
GEO (Geostationary Earth Orbit)
MEO (Medium Earth Orbit)
LEO (Low Earth Orbit)
TES (Transportable Earth Station)
FDMA (Frequency Division Multiple Access)
TDMA (Time Division Multiple Access)
CDMA (Code Division Multiple Access)
TETRA (Trans-European Trunked Radio)
PSTN (Public Switched Telephone Network)
DMO (Direct-Mode Operation)
SIM (Subscriber Identity Module)
BS (Base Station)
BP (Block Probability)
OT (Offered Traffic)
LTE (Long Term Evolution)
UMTS (Universal Mobile Telecommunications System)
GPRS (General Packet Radio Service)