Cognitive Radio Communications and Networks

Principles and Practice

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Chapter 16

Public Safety and Cognitive Radio

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16.1 Introduction

In public safety applications, robustness and rock-solid technology are paramount. The communication system of rescue workers should always work, even under extreme conditions. So, at a first glance it may seem that an emergency situation is not something in which one wants to experiment with such a new technology as cognitive radio. There are, however, a number of arguments why the application of cognitive radio in this field may form viable business cases. First, current day communication systems used for public safety lack support for multi-media applications that nowadays come standard with low-budget mass-market cell phones. One of the reasons behind this is that it is not sensible from an economical perspective to permanently reserve the large bandwidths that are required for such applications. Cognitive radio, however, is able to acquire this spectrum on-the-fly only when it is needed. Furthermore, backwards compatibility is very important in the field of professional radio systems because of the large investments in a relatively small market. Therefore, many incompatible standards and new broadband services are one of the main drivers for investigating how cognitive radio can be applied in this field.

One of the most difficult aspects of cognitive radio in general, is that it is not allowed to cause interference to any primary user. This problem also applies to the public safety field, but to a lesser extend. When a large scale emergency occurs, the importance of the situation makes the rescue workers, at least in principle, primary users of the spectrum. The only primary users that must be carefully sensed for are the legacy systems that may play a role in the rescue operation. Because the number of legacy systems is limited and their standards and frequency bands are well known, most issues can be dealt with by careful engineering of the spectrum sensing system.

This chapter addresses the application of cognitive radio to the field of public safety, disaster relief and rescue scenarios. First, we give a description of the requirements for public safety communication networks, and explain how cognitive radio technology can be useful. Next we look at the current systems. We focus on the TETRA standard, and its implementation in the C2000 system in the Netherlands. Next we look at a real world scenario and discuss the main system design aspects, such as spectrum organization, availability of white space and suitability of certain frequency bands for cognitive radio.

16.1.1 Requirements

The next generation communication system for public safety will have very extensive requirements. These requirements are studied and specified by commissions such as SAFECOM [612] in the US and Project MESA [613] in Europe. Most of these requirements deal with the higher layers in the network protocol stack. In this chapter we restrict ourselves to the physical layer.

Communication Structure

A public safety wireless network consists of a backbone network, base stations and handsets. The backbone network is used for inter base station communication. In case the entire public safety network is down, emergency workers should still have the option for direct communication. In a rescue situation, the network consists of different types of network nodes, such as emergency workers, vehicles, helicopters, airplanes, robots, *etc.* Each type of node has different physical layer requirements. For instance, emergency workers carry battery powered handsets that are energy limited. Helicopters and airplanes on the other hand have a very high speed.

Public safety workers are usually embedded in talk groups. The layout of a talk group, or 'fleet map', is mainly determined by the situation at hand, and is coordinated by the central control room. Typical talk groups may be a neighborhood police team, a team of parking attendants, or a special group for low-priority conversation. Moreover, the central control room acts like an info/helpdesk for the rescue workers. If a policeman wants more information about a building, he can ask this to the central control room, because they are members of the talk group. If the situation changes, the central control room can dynamically change the members of the talk group.

In a critical situation, rescue workers don't have time to dial a number before they can communicate. They just press the 'push-to-talk' button. A typical system will setup a call within 350 ms. Voice calls are often monitored by support personnel who are not actively participating in the call, but for whom the information exchanged, the identity of the speakers, their emotional state, and other audio indicators are key to their decisions in support of critical operations [614]. For instance, if there is a hostage at a school, the police unit that has established a perimeter around the school must be able to passively 'listed in' on conversations of the SWAT (Special Weapons And Tactics) team.

Reliability

For emergency networks, reliability is an important issue. There are two kinds of reliability: robustness and security.

Robustness is the ability of a system to avoid total failure despite unforeseen conditions or partial damage. A public safety communication system should always be available, especially during large disasters. The network should have guaranteed coverage in the whole service area, including special coverage locations like tunnels. Handsets should have a ruggedized design and be capable of working under extreme conditions. All base stations have power supply backup batteries, so that the system remains operational for about 4 to 5 hours during a power failure. Directly after a power failure is detected, the maintenance crew installs a portable generator. Also if a base station is destroyed, it is very important that the system should still have coverage in the service area of the destroyed base station. The reason for this is that most communication of the rescue workers is required in this disaster area. Coverage in this area can be obtained by mobile base stations (on a truck) and by over designing the network. So, other neighboring base stations can handle the communication needs. In Section 16.2.1 we describe that cellular networks are interference limited. If the SNR requirements are increased at the border of a cell, neighboring base stations will have also coverage in the service area of the destroyed base station. A third solution is that handsets should be able to communicate directly with other handset (without a base station). See also Section 16.2.1. The backbone of the network should be very robust against failures. The backbone of the network, communication between base stations, consists of optical fiber and/or microwave radio relay links. Robustness can be obtained by having at least two independent backbone connections to each base station.

Security is the ability of a system to withstand malicious attacks. The communication should be secure against eavesdropping, spoofing and jamming. It should also be able to block lost or stolen handsets from using the network. In addition, handsets should not contain information which can help unauthorized users from accessing the network.

Broadband

In an emergency situation a picture could say more than a thousand words. Video is even more powerful in providing a clear impression of a complicated situation. So, although voice will always be the primary mode of communication during an emergency, there is a huge demand for multimedia.

From the control room, maps and floor plans of buildings may be uploaded to the device of a rescue worker. Furthermore, the next generation public safety communication equipment will provide advanced features, like sensors for biomedical and environmental signals.

Paging

In paging communication short predetermined text messages are sent to mobile devices and are very important for public safety applications. Examples are emergency notifications (Evacuate Now!!), arrival on a predetermined position, sensor readings, *etc.* Paging is even more important than voice communication. They are used for instance to alarm fire fighters when there is a fire alarm. The advantage of such predefined messages is that they convey a lot of meaning in very few data bits.

16.1.2 Commercial Wireless Communication Networks

Commercial wireless communication networks like GSM and 3G networks could potentially provide most of the functionality described in the previous section. However, if a disaster occurs there are two important drawbacks of these networks. First, the network gets overloaded, as each person in the vicinity tries to communicate with his or her friends and family. As a result the communication network may collapse. The second reason is that when a disaster occurs a part of the infrastructure may be damaged. For instance, the power may be unavailable in the area of the disaster. Due to economical reasons, commercial networks don't have back up for the power supply and hence the affected network is down. In addition, commercial networks will not have coverage in rural areas where there are very few customers. Moreover, they also don't have coverage in special coverage locations like tunnels, metro stations.

16.1.3 Economical Value of Spectrum

Spectrum is scarce. However, it is very difficult to estimate the value of spectrum, because it depends on many parameters, like population, allowed transmit power *etc.* Take for example the first UMTS auction in the Netherlands in 2000. The area of the Netherlands is about 41.500 km^2 and its population is 16.5 million people. In total there was 155 MHz of spectrum, which was given for 15 years to 5 operators for 2.7 billion euro, *i.e.*, 370 million per MHz [615, 616]. This are only the costs of the license, so without the costs for construction of the network and other operational costs.

Spectral Efficiency

With cognitive radio one of the goals is to use spectrum more efficiently. In order to get insight in the economics of spectrum usage, a good starting point is the Shannon-Hartley theorem for the capacity of an additive white Gaussian noise (AWGN) channel,

$$C = B \cdot \log_2(1 + \mathrm{SNR}) \quad [\mathrm{bit/s}], \tag{16.1}$$

in which C is the channel capacity in bits per second, B the channel bandwidth in Hertz,

$$\mathrm{SNR} = \frac{P_{\mathrm{rx}}}{N_0 B} \tag{16.2}$$

the signal to noise ratio, with P_{rx} the received signal power in Watt and N_0 the power spectral density of the white noise in Watt per Hertz. The noise in a radio link is caused by various sources. The most fundamental source of noise is thermal noise, which originate from all warm matter with a power of

$$S(f) = N_0 = k\ T \quad [\mathrm{W/Hz}], \tag{16.3}$$

in which $k \approx 1.3806504 \cdot 10^{-23}\ J/K$ is the Boltzmann constant. For a temperature of 15.2°C this gives a noise floor of about -174 dBm/Hz.

Based on this Shannon limit, we can identify two 'regimes' of operation of a communication link (see Figure 16.1). First, if the SNR is good ($\approx$ 10 dB and more) we have

$$C \ \approx\ B \cdot \log_2(\mathrm{SNR}) \ \approx\ B \cdot \frac{1}{3} \cdot \mathrm{SNR(dB)}. \tag{16.4}$$

In this regime the capacity depends linearly on the bandwidth, but only logarithmical on the transmit power. Therefore this regime is called 'bandwidth limited' or 'spectrally efficient', since most capacity improvement can be gained by increasing

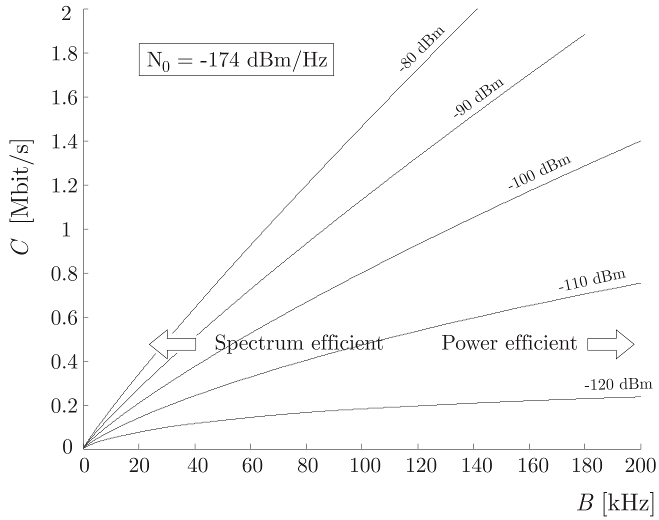

Figure 16.1: Channel capacity as function of channel bandwidth for various received signal power levels.

the bandwidth. If we choose to divide the bandwidth by a factor N and maintain capacity by increasing the transmit power, we see that the required power grows exponentially with N, as

$$B \cdot \log_2(\mathrm{SNR}) \;=\; (\frac{1}{N}B) \cdot \log_2(\mathrm{SNR}^N), \tag{16.5}$$

so the required transmit power for the same capacity is increased by a factor $\mathrm{SNR}^{(N-1)}$. For a low, or even negative SNR we have

$$C \;\approx\; 1.44 \cdot \frac{P_{\mathrm{rx}}}{N_0}\;. \tag{16.6}$$

In such a 'power limited' regime, increasing the bandwidth has almost no effect, but increasing the received signal power gives a proportionally higher capacity.

16.1.4 Benefits of Cognitive Radio

The general meaning of a cognitive radio is a smart device that does all kinds of useful things for its owner, based on sensory input and machine learning. In a more specific meaning, it is a radio that can opportunistically use white space in licensed bands without causing interference. Due to the special requirements of public safety networks, there are several benefits of cognitive radio technology:

Improved Communication Structure

- Communication with other networks: Currently, there exist multiple public safety standards. So, when a large disaster occurs at the border of countries, there will be a huge challenge if those countries use different technologies. Also, in emergency situations where military force is required, the same problem occurs. A cognitive radio with support for military standards and other public safety standards would solve this problem.

- Backwards compatibility: Because of the large investments and the relatively small market, legacy systems are replaced slowly and co-exist with new communication networks for a long time. Also, over time new revisions of standards are released. Cognitive radio allows an upgrade of the existing equipment to this new release without replacing the hardware.

- Introduction of new services: New services could be enabled more easily by cognitive radio as it can adjust its parameters according to the requirements of the new service. It does not have limitations set by existing standards. An example of this is that current day public safety communication systems lack support for multi-media content that nowadays is normal for mass-market cell phones.

Improved Reliability

A cognitive radio always tries to minimize interference to other networks by changing its frequency if other signals are present. The feature automatically makes a cognitive radio more resilient to jamming.

Enabling Broadband

In case of an emergency, public safety networks are heavily used, and there is demand for more capacity. Implementing this capacity beforehand in the whole network would be very costly. A different approach would be to use cognitive radio to sense for empty frequency bands (white space) and use it as a secondary user to set up an auxiliary communication network. The relatively large bandwidths that are required for broadband communication could be provided by secondary spectrum usage.

16.2 Standards for Public Safety Communication

Several communication standards have been developed for public safety applications. The first generation of standards were based on analog modulation (FM/AM) and used an optional speech scrambler to prevent eavesdropping. By the end of the last century, second generation standards emerged based on digital modulation and trunking. The latter are now used in most countries. There are three second generation public safety communication standards: P25 (APCO Project 25), TETRAPOL and TETRA. APCO Project 25 systems are used by the federal, state/province and local public safety agencies in North-America. An important feature is to be backwards compliant with the old analog APCO Project 16 standard. This means that P25 handsets have support for an analog and digital communication mode. More information about P25 can be found in [617]. TETRAPOL [618] was one of the first digital public safety standards, developed in France. Already in 1988 it was used by the French Gendarmerie Nationale. The Terrestrial Trunked mobile Radio (TETRA) [619] communication network was developed almost 10 years later and is now used in most European and other countries.

16.2.1 TETRA

TETRA was formerly known as Trans-European Trunked Radio and standardized by ETSI in 1995. TETRA was specifically designed for use by government agencies, emergency services (police forces, fire departments, ambulance), rail transportation staff, transport services and the military.

Handhelds can communicate in Direct Mode Operation (DMO) in which they work similar to a walkie-talkie, or in Trunked radio Mode Operation (TMO), in which the TETRA base station infrastructure is used. The DMO mode allows direct communications in situations where network coverage has been lost. In addition to voice services, the TETRA system supports several types of data communication: status messages, short data services, packet data and circuit switched data communication.

TETRA uses Time Division Multiple Access (TDMA) with four user channels on one radio carrier and 25 kHz spacing between carriers. Both point-to-point and point-to-multipoint transfer can be used. Digital data transmission is also included in the standard though at a low data rate. All voice and data traffic is protected by encryption, so that it is practically impossible to eavesdrop or spoof the communication. Table 16.1 summarizes the air interface parameters, which can be found in [620].

Trunking

If one would expect a communication system in such way that even in a worst case scenario no call is lost, this would require an enormous amount of capacity. Moreover, most of this capacity will remain unused most of the time. Because such an approach is highly uneconomical, it is almost never used anymore. Instead,

Table 16.1: Air interface parameters of TETRA.

Parameter	*value*
Frequency range	150 to 900 MHz
Channel bandwidth	25 kHz
Modulation	$\pi/4$-QPSK
Bits per symbol	2
Transmit filter	Root Nyquist with 0.35 roll-off
Symbol rate	18000 Symbols/s
Raw data rate	36 kbit/s
Spectral efficiency	1.44 bit/s/Hz
Time slots duration	$85/6 = 14.167$ ms
TDMA frame	4 time slots = 56.656 ms
Bit rate per channel	36 kbit/s per 4 slots = 9 kbit/s
Voice codec	ACELP
Handheld RX sensitivity	-104 dBm
Vehicle RX sensitivity	-107 dBm
Mobile TX power classes	1W, 3W, 10W, 30W

practical systems are designed for an average load with some margin for peak loads. The average load, or *traffic intensity* of a system is defined by

$$A = \frac{\lambda}{\mu} \quad \text{[Erlang]}, \tag{16.7}$$

in which λ [calls/s] is the average *arrival rate* of calls, usually measured during a busy period, and μ [calls/s] the average *service rate*. The unit of average load is named after A. K. Erlang, the originator of traffic engineering and queueing theory. Note that in Equation (16.7) one can recognize Little's theorem, in which μ^{-1} is the average call duration time, or *holding time*. Based on the average load A, the number of channels N has to be chosen. Although in reality λ and μ are random processes that depend on time and other external factors, it is often convenient to regard them as constants. Furthermore, it is convenient to assume that the number of calls per second is Poisson distributed, and the call duration is exponentially distributed. In other words, there is an infinite number of potential callers, which have no memory and no interdependencies, which make random calls with random duration.

In a trunking system, all channels are kept in a *pool* from which they are dynamically assigned to users. A user can request for a channel via a *control channel*. After the call is finished the channel is placed back in the pool. On average there will be enough free channels available in the pool to handle all incoming requests. However, since the tail of the Poison distribution extends to infinity, there is always a chance that a large numbers of calls are made simultaneously, so that the pool is exhausted. When that happens there are a number of scenarios. The simplest of them is that the call is is just dropped and lost forever. The chance that this happens is given by the Erlang-B equation

$$\Pr\{\text{blocking}\} \; = \; B(A,N) \; = \; \frac{A^N/N!}{\left(\sum_{n=0}^{N} A^n/n!\right)} \; . \tag{16.8}$$

Spatial Reuse

Modern mobile radio communication networks are usually bases on a cellular architecture. In a cellular system a large geographical area is partitioned into cells. Each cell has its own base station that works with a specific set of frequency channels.

Conceptually it is convenient to model the cell shape as a hexagon because of its nice geometrical properties. If R is the radius of a hexagon then its width is $W = \sqrt{3}R$ and its area is $A = 1.5\sqrt{3}R^2$. Cells are grouped in clusters of size K, and each cell in the cluster is given a different set of frequencies in such a way that neighboring cells have different frequencies. From the geometrical properties of the hexagonal cell shape, it is straightforward to derive that the number of cells in a cluster must be a number $K \in \{1, 3, 4, 7, 9, 12, 13, ...\}$ for which $K = i^2 + j^2 + ij$ holds with i and j positive integers including zero. Furthermore, the distance between two clusters can be shown to be $D = \sqrt{3K}R$.

In a cellular system, the dominant noise contribution in the downlink is not from thermal noise, but from interference from neighboring cells that use the same frequency. This interference is called co-channel interference (CCI). The system is called *interference limited* rather than *noise limited*. The worst case CCI occurs if the mobile is in a corner of a cell, because then it is at the largest distance from its base station. The mobile will receive most of its interference from the six nearest surrounding cells that work on the same frequency. The interference from these *first tier* cells gives

$$\text{SNR} \; = \; \frac{P_{\text{tx}} \cdot (R)^{-\gamma}}{\sum_{n=1}^{6} P_{\text{tx}} \cdot (d_n)^{-\gamma}} \; = \; \left(\sum_{n=1}^{6} \left(\frac{R}{d_n}\right)^{\gamma}\right)^{-1} , \tag{16.9}$$

in which γ is the path loss exponent, and d_n the exact distance between the corner of a cell to the n-th interfering base station. If we approximate d_n by D this simplifies to

$$\text{SNR} \approx \frac{1}{6}(3K)^{\gamma/2}. \quad (16.10)$$

From this we get the somewhat counterintuitive result that the SNR, and thus the capacity, is independent of the transmitted power and cell size, and becomes better with a higher path loss. Furthermore, increasing the number of cells in a cluster will increase the SNR, but it will decrease the total system capacity. This is because each cell needs a unique channel, which can not be used by the other cells in the cluster. However, from Equation (16.5) we have seen that in a bandwidth limited system, we could better give all the cells more bandwidth, at the cost of a lower SNR.

16.2.2 C2000

TETRA is only a standard, and manufacturers only make generic base stations and handsets that implement the standard. To build a complete operational network is still a huge effort. The specification of a communication system for public safety depends on the exact situation in a country, and therefore there are no off-the-shelf solutions. The public safety communication network in the Netherlands is called C2000. It consists of three components:

- **T2000:** A TETRA-based network for voice and low-rate data communication. It uses the frequency band 380 - 385 MHz for uplink and 390 - 395 MHz for downlink communication. The network uses around 400 masts and is designed for at least 95% outdoor coverage. It uses both direct mode and trucked radio mode. For special coverage locations, like tunnels and stadiums, the system has additional low power base stations. To facilitate helicopters and airplanes, a separate overlay network, TETRA AGA (Air - Ground - Air services) has been constructed. In this overlay network the distance of the base stations is increased to 83 km.

- **P2000:** Paging is a very important communication application in public safety where short predetermined texts are transmitted and displayed on pager devices. For instance, they are used to alarm fire fighters. C2000 uses a different network for paging. This network is called P2000 based on the FLEX protocol in the 169.650 MHz band. TETRA has also support for paging, but the current outdoor coverage is too low for this application. In fact, no message should be lost in the system. So, it was more cost-effective to construct a separate pager network than increasing the coverage of the T2000 network.

- **M2000:** M2000 is a software system used in the *public safety answering point (PSAP)*. A PSAP is a call center responsible for answering calls to an emergency telephone number for police, fire fighting, and ambulance services. M2000 is a software system that helps the employees in the PSAP to identify the scale of the emergency and which resources should be allocated to the emergency. Moreover, it facilitates the communication between the different PSAPs. Another important task of the PSAP is to act as an info/helpdesk in talk groups. So, for instance a policeman can ask the PSAP for more details about a registration plate. Also, the PSAP can be actively monitoring the talk groups. The M2000 system facilitates these tasks. Finally, it is also used for network management and network planning. Once a network has been built, it not finished. New residential areas are developed, new high buildings are constructed that block the radio signal, *etc.* So, every year several base stations have to be moved or have to be added to the network.

The C2000 network fulfills all important public safety requirements, but lacks support for multimedia/broadband internet communication. In the frequency band in which C2000 operates, the inflexible and fragmented licensing scheme made it difficult to find more static allocated spectrum. On the other hand, there is always a huge amount of this spectrum that is temporarily unused. But traditional radio equipment does not have the technology to find this free spectrum, and there is not yet a legal system that allows ad-hoc secondary usage.

16.3 Application of Cognitive Radio

In the previous section we looked at public safety communication as it is done today. The requirements for the next generation system include features that require broadband communication. Cognitive radio may in the feature provide a means to find the required bandwidth. In this section we give an example of how a cognitive radio could fit in with existing systems.

16.3.1 The Firework Disaster in the Netherlands

What does a typical disaster look like? This question is difficult to answer, because each disaster is unique and unforeseen. But we can learn from examples from the past. At May 13th 2000, a large disaster took place in the city of *Enschede*, the Netherlands[1]. On a nice warm Saturday afternoon, a crowd gathers to witness a small fire in their neighborhood, at what they thought was a paper recycling depot. Only the firemen and police knew that it was actually a firework storage that was burning. What they didn't know, was that the safety regulations were violated, and much more and much heavier firework was stored than was allowed. After

[1] Exact GPS location: 52° 13' 49" N, 6° 53' 41" E

about twenty minutes a first big explosion occurs, shortly followed by a detonation that ruins the whole area. The result was that an area of 1 km^2 was destroyed (400 houses), 23 people were killed and about 950 injured [621].

Even before the explosions, the central control post and PSAP were flooded with calls. Soon after the final explosion all communication systems collapsed because everyone started calling. Most calls over the GSM network involved people notifying their friends and families. Many calls over the public safety network where made by police men who offered their help after they heard the explosion. However, the first responders that survived the explosion could not reach the control center, because the network was overloaded. Even hours after the explosion, communication remained difficult. For example, much time was wasted because experts could not get reliable information about the risks of explosion of an ammonia cylinder in the refrigeration system of the nearby Grolsch factory, that also caught fire.

From May 13th till May 25th in total 141 ambulances and 15 helicopters (680 rescue workers), 7980 police men and 1675 fire workers were active [621] in the area of the disaster. From these numbers, we estimate that around 2500 rescue workers were active during May 13th in area of several km^2. For normal tasks like house fires, surveillance only up to 25 rescue workers would be working in this area. So, a large disaster increases the regional/local demand for a public safety communication network with a factor of approximately 100.

16.3.2 Bandwidth Requirements

In this section, we derive the spectral requirements in case that a cognitive radio system would have been used during this disaster. In the previous section, we estimated that at maximum 2500 rescue workers were present at the disaster location. The primary disaster region was 1 km^2, but rescue workers are of course active in a larger area, so the extended disaster region would be 10 km^2. In this area, we estimate that 25 video streams of 256 kbit/s each (MPEG-4 streams) should be uploaded to the central command. Moreover, 25 photos of 1 Mbit each are taken per second and should also be uploaded. In total, this results in a gross 31.4 Mbit/s stream to the central command.

The cognitive radio network consists of vehicles and rescue workers. We assume that the vehicles can act as relay stations for the rescue workers to communicate with the central command. So, this is similar to normal 2G and 3G networks; the vehicles are base stations and the rescue workers are modeled as mobile terminals. Between the vehicles there exists a high-bandwidth backbone network for which also cognitive radio may be used.

The noise-limited communication is from rescue worker to vehicle and therefore the most challenging task to achieve. For this type of communication, a frequency band has to be selected that has both good propagation conditions and have small antennas suited to be mounted on handheld terminals. Frequency bands from 400 MHz to 1 GHz are appropriate bands. On the other hand communication from vehicle to central command is not limited by power and therefore higher frequency bands can be selected, which are less optimal.

So, for the rescue worker to vehicle communication, we have to derive how much spectrum is required. We assume that the average distance between rescue worker to vehicle is 100 m, a spectral efficiency of 1.3 bit/s/Hz and an overhead of 50% (encryption, protocol overhead, *etc.*). Finally, we assume that 70% of the rescue workers can communicate directly with the vehicle and 30% requires another rescue worker as relay. The core of the firework disaster would be the 1 km^2 and the other 9 km^2 are surroundings were less rescue workers are active. So, the frequency demands are highest in the core of the disaster. If 50% of the 2500 workers are in this area, a total of: $31.4 \times 0.5 \times 1.5 \times 1.3 = 30.6$ MHz is needed. If the network can distinguish between primary users and its own network[2], frequencies can be reused more efficiently. In Section 16.2.1 we introduced a cluster radius D, which determines the number of times a frequency can be used in a km^2. In our case the cluster[3] area is 0.165 km^2. So, frequencies can be reused 6 times in a km^2. This makes our spectral requirement in the core of the disaster 5 MHz. So, for this scenario a cognitive radio network has to find 5 MHz of empty space.

16.3.3 Spectrum Organization

In this chapter, we propose to use the cognitive radio as an add-on system to the existing TETRA/C2000 system. The C2000 system uses frequencies around 400 MHz. For easy integration of the cognitive radio add-on, it is beneficial to use frequencies near 400 MHz. In this section we review frequencies from 100 to 800 MHz.

What kind of neighbors and primary users can we expect? Between the FM-radio and the UHF-television broadcasting band lies a region of the spectrum that is ideal for digital land mobile communication. Below the FM band, is becomes difficult to find a reasonable amount of bandwidth, and above the TV band indoor coverage becomes difficult unless a lot of base stations are used. The FM band lies world wide between 88 and 108 MHz, and the television band lies in Europe between 470 and 846 MHz. In the US the actual UHF television band starts at 512 MHz, but the numbering of the channels also starts at 470 MHz.

Figure 16.2 shows a simplified overview of the band plan (allocation chart) in the Netherlands between the FM and TV band. Directly above the FM band one

[2]This is possible as each vehicle knows which frequencies are used and the backbone network between vehicles can be used to distribute this information.

[3]We assume in our example that the number of cells in a clusters is 7, which is also used by GSM networks.

Figure 16.2: A simplified spectrum band plan of the Netherlands between the FM and TV broadcasting bands.

finds the aviation band, which in utilization measurements appears much quieter than the FM band. However, since the signals in this band are used to guide airplanes, the risk of interference is much too large, so that it is unsuitable for cognitive radio, or every other type of spectrum sharing.

The band between 137 and 174 MHz is typically used by private mobile radio (PMR) networks used by private security personnel, public transportation, taxies, *etc.* Typical equipment in use in this band are analog FM radios that use in a 12.5 kHz raster without trunking. Because of this old-fashioned technology, there is a lot of white space in this band, which potentially can be harvested by a cognitive radio.

The band between 174 and 240 MHz was traditionally used for television (VHF Band III) but is now used for various purposes and for Digital Audio Broadcasting (DAB). Directly after VHF band III, a large international NATO military band follows. The upper part of this band is shared with C2000 system.

Between 400 and 470 MHz we find a second band for various applications. Typical usage is for Public Access Mobile Radio (PAMR). A PAMR network is a trunked radio system that is operated by a telecom service provider that licenses capacity to its, usually professional, customers. Digital PAMR systems often use TETRA and older networks often use the analog MPT1327 standard. Because PAMR is only deployed in the area of its customers, there is a lot of white space in this band, that potentially can be harvested by a cognitive radio.

Above 470 MHz (up to 862 MHz), we find television band IV (UHF). The frequencies in this band are internationally coordinated. This means in each area, a part of this spectrum is used by terrestrial TV. Neighboring areas use different frequencies to avoid interference. At this moment there is a transition of analogue terrestrial TV to digital terrestrial TV. Digital terrestrial TV uses lower transmission power and allow the use of multiple transmitters at the same frequency (single frequency networks). Basically this means that the spectrum is used more efficiently. In this band a cognitive radio could also harvest a lot of spectrum. The reason for this is that outside the service area, there is a large surrounding area where this frequency cannot be used by another terrestrial TV transmission due to interference. So, cognitive radio can use these frequencies for local communication. Because this frequency band is used for broadcasting, its transmitters are fixed. So, a cognitive radio would only require its own GPS coordinates and a database of TV transmitters. Spectrum sensing is then only necessary for detecting wireless microphones.

16.3.4 Propagation Conditions

The propagation conditions determine how far a radio wave propagates. It seems beneficial to have good propagation conditions, *i.e.*, low path loss. However, for spatial re-use (Section 16.2.1) it is beneficial to have a large path loss. A high path loss will allow more spectrum re-use and this means that the spectrum usage increases. Also, for cognitive radio a high path loss is better, because it reduces the area in which interference can be caused.

At UHF frequencies ionospheric reflections only play a small role in the propagation of radio waves. Therefore we can assume that the range of a signal is in principle limited to the horizon. The distance to the horizon is approximately given by

$$d \approx \sqrt{2 \text{ k } r \; h} \; , \tag{16.11}$$

in which k is a factor that corrects for the bending of RF waves around the earth which is about 4/3, r is the radius of the earth, which is about 6371 km, and h the sum of the heights of the transmit and receive antennas. So the signal of a 30 m high base station can not be detected beyond about 23 km, and the signal from a handheld cognitive radio can not cause interference to another handheld radio much farther than 5 km.

A simple path loss model that is often used in for land mobile radio is the plane earth model, which predicts a path loss exponent $\gamma = 40$ dB,

$$P_{\text{rx}} \;=\; P_{\text{tx}} \, G_{\text{tx}} \, G_{\text{rx}} \left(\frac{c}{4\pi f d} \right)^2 \cdot 4 \; sin^2 \left(\frac{2\pi \; f \; h_{\text{tx}} \; h_{\text{tx}}}{c \; d} \right) . \tag{16.12}$$

The first part of Equation (16.12) is just the free space path loss, which is the dominant factor close the transmitter. The second factor is caused by the interference between the direct path and the ground reflection. Figure 16.3 compares the path loss predicted by the free space model with that of the plane earth model for a frequency of 400 MHz and antenna heights of 1.5 m. As can be seen from this

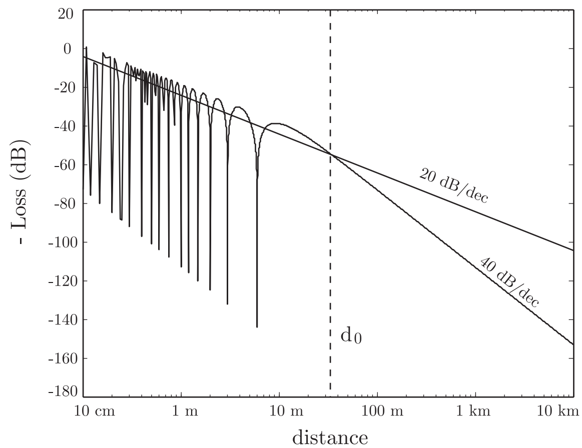

Figure 16.3: Negative of the path Loss (dB) as function of the distance for a carrier frequency of 400 MHz with antenna height $h_{\mathrm{tx}} = 1.5$ and $h_{\mathrm{rx}} = 1.5$.

figure, the plane earth model has two regions, that are separated by the 'Fresnel breakpoint distance' d_0 which is given by

$$d_0 = \frac{4\ \pi\ f\ h_{\mathrm{tx}}\ h_{\mathrm{rx}}}{c}\ , \tag{16.13}$$

which in this example is about 37 m. Before this distance the path loss varies wildly around the 20 dB/decade line, and after this distance it falls off smoothly with 40 dB/decade. The last deep fading dip occurs at $d_0/2\pi$, which in this example is exactly at 6 meter.

Note that the equation for the breakpoint distance is somewhat counter intuitive, because it scales inversely with the wavelength, whereas normally dimensions scale proportionally with the wavelength.

16.3.5 White Space Assessment

In order to get permission from spectrum regulators to apply cognitive radio in a certain band, one has to convince them the spectrum in this band is structurally under utilized. This can be done with a spectrum survey. Figure 16.4 shows an overview spectrogram over a full day of a large portion of the UHF spectrum. This spectrogram was recorded by the Dutch radio spectrum authority *Agentschap Telecom* in October 2005, in the city of *Eindhoven* in the Netherlands[4].

[4]Exact GPS location: 51° 27' 13" N, 5° 28' 44.8" E, at 50 m height.

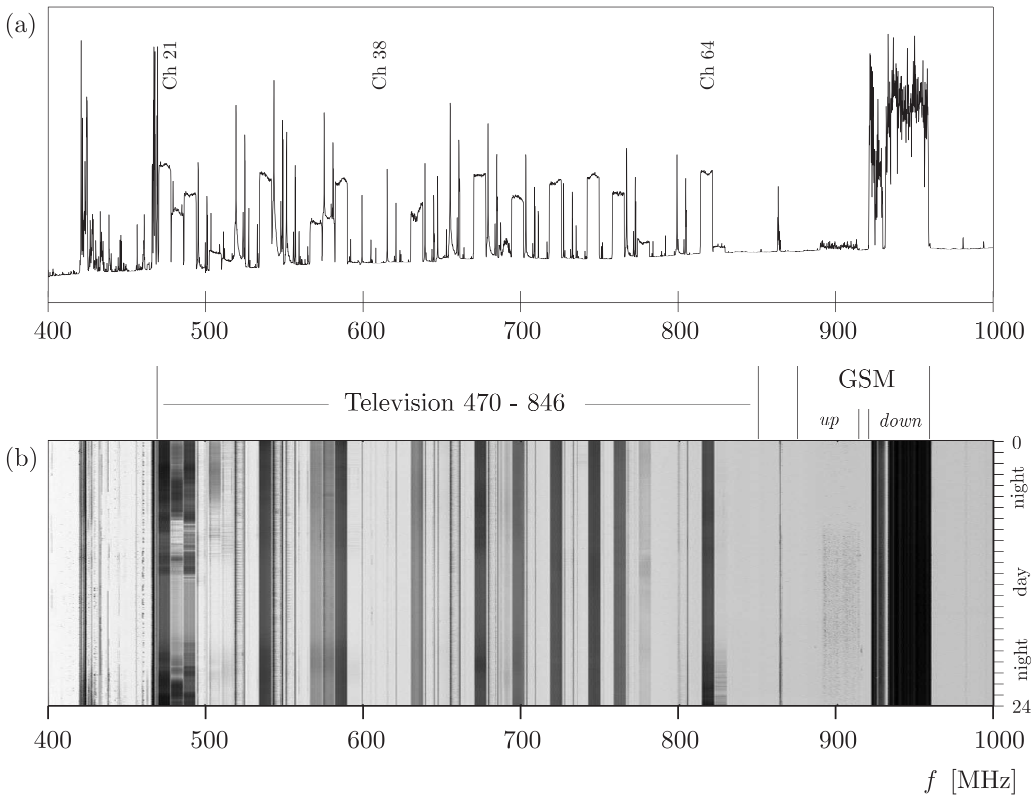

Figure 16.4: Overview of the UHF spectrum in the Netherlands. (a) Spectrum averaged over 24 hours. (b) Spectrogram over 24 hours.

At first sight, there appears to be quite some white space in this spectrogram, especially between the TV channels. However, we must be careful not to draw premature conclusions. For example TV channel 38 (channel 37 in the US channel numbering), just above 600 MHz, is always empty because it is world-wide assigned to radio astronomy. Also the region around 900 MHz seems far less busy than the region around 950 MHz. However, both regions belong to the GSM system, and the uplink frequencies on 900 MHz are in fact paired with the downlink frequencies 45 MHz higher. The uplink channels appear much weaker because the a cell phone uses its transmit power much more sparingly than a base station. But because of the symmetry in typical phone conversations, the occupance in the uplink and downlink must be about equal.

Figure 16.5(a) shows a close-up of Figure 16.4 in the 400 to 470 MHz band.

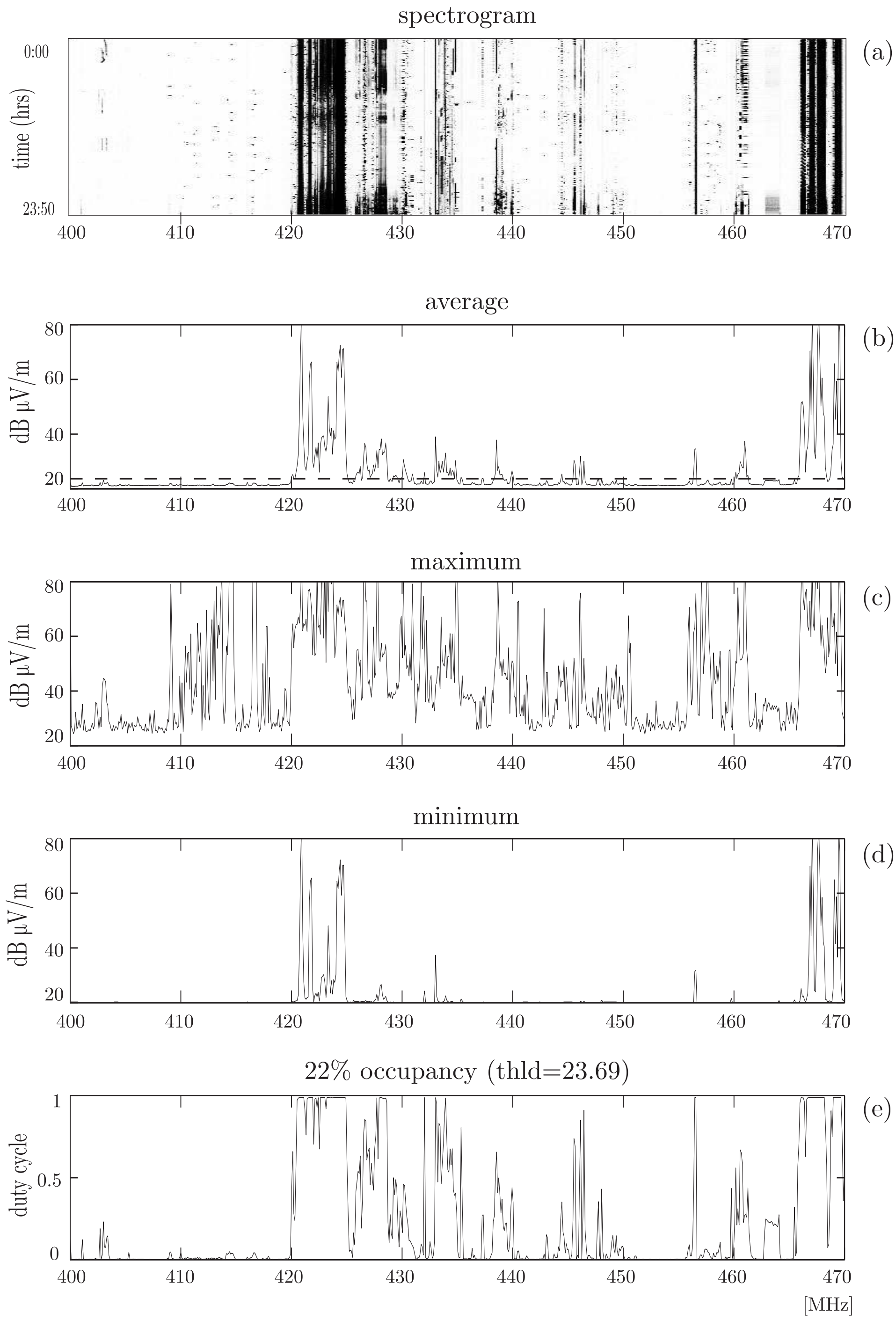

Figure 16.5: Overview of the UHF spectrum in the Netherlands; Close-up of the 400 to 470 MHz band.

Again, we see a remarkable amount of white space. Figure 16.5(b) shows the average over a full day, and Figures 16.5(c) and (d) show the maximum and minimum respectively. If we compare the average and maximum plot, we see that most of the signals have a fairly large peak-to-average ratio, except for the band between 420 and 425 MHz, and 465 and 470 MHz. These two bands are likely downlinks from cellular networks. The dashed line in Figure 16.5(b) indicates a threshold level, which was set 2 dB above the median power level. Figure 16.5(e) shows the duty-cycle obtained by using this threshold. As we can see, a bandwidth of 5 MHz can be found as a contiguous block of spectrum. If our cognitive radio can use non-contiguous spectrum, much more bandwidth can be found.

Why is the 400 MHz to 1 GHz Band Optimal for Mobile Communication?

Below the 240 MHz, the antenna will be too large for mobile communication (*i.e.*, larger than 30 cm). One well-known trick to make an antenna shorter is to roll it up, but this will make it too selective for only one narrow frequency band. Frequencies from 240 to about 400 MHz are used by military communication and the frequency range from 1 to 1.4 GHz is in use by aeronautical radio navigation and radio astronomy. Therefore these bands are also not suitable for cognitive radio. Frequencies below the 1 GHz have less indoor penetration loss, less body loss, and bend better around obstacles (less shadowing) compared to frequencies above 1.4 GHz. In [622], the indoor penetration loss and body loss for DAB, band III (225 MHz) and the L-band (1465 MHz), are reported. Band III had 3.5 dB less indoor penetration loss and 10 dB less body loss compared to the L-band. So, frequencies from 400 MHz to 1 GHz are from a power budget point of view the optimal frequencies.

16.3.6 System Spectral Efficiency

A wireless communication system should use the spectrum in an efficient manner. The system spectral efficiency can be defined as:

$$\eta \approx \frac{R/B}{K} \qquad \text{[bit/s/Hz/site]}, \tag{16.14}$$

in which R is the bit rate, B the bandwidth and K the cluster size.

The fraction R/B can be considered as the link spectral efficiency and is linked to the Shannon formula (Equation (16.1)). So, the link capacity will increase if the SNR is increased. In a spatial re-use system, like in our example, the SNR will be interference limited and Equation (16.10) applies. In this formula the SNR depends on K and the path loss exponent γ. A higher value of both parameters result in a higher SNR and hence a higher link capacity. However, increasing K will also decrease the system spectral efficiency. So, it is up to the system designer to choose these parameters in an optimal way. For example, the GSM system has a system efficiency of 0.17 and for the WiMAX (IEEE 802.16) system this value has increased to 1.2, which makes the system spectral efficiency 7 times higher compared to GSM.

From Equation (16.10) one can derive that it is beneficial for the system spectral efficiency to use a high frequency, as high frequencies have a higher path loss. This is true to get the maximum system spectral efficiency. However, for mobile communication there is also a power constraint, especially for the uplink to the base station. From this perspective, it is beneficial to use frequencies below the 1 GHz. The latter requirement is more important for our application than a higher spectral efficiency.

16.3.7 Anti-jamming

An important requirement of public safety networks is resistance to jamming. Jamming is the intentional use of a strong radio signal, for instance by terrorists, in an attempt to disrupt communication.

The traditional way of coping with jamming is to use some form of spread spectrum. In a spread spectrum signal, the signal energy is spread over a much wider bandwidth than the original signal. Since jammers are usually narrow band signals, they only disturb a relatively small part of the signal. There are two well known spreading techniques: direct-sequence spread spectrum (DSSS) and frequency hopping (FH). In DSSS the signal is multiplied with a pseudo random spreading code, which is also known at the receiver. To make a signal practically unjammable, the signal bandwidth should be at least several tens of megahertz. This means that in our example DSSS would be infeasible due to the limited amount of white space below the one gigahertz. In a frequency hopping system, the transmitter hops after each packet to another frequency. The hopping sequence is known to both the transmitter and receiver. In a cognitive radio, we have an accurate map of available white space, so we could hop from white space to white space. Usually, a jammer does not have this information, which would make jamming difficult.

Cognitive radio provides inherently some robustness against a simple jammer that works on a fixed frequency. Since a cognitive radio will avoid non-empty channels, it will simply move out of the way. On the other hand, a cognitive radio network may be extra vulnerable to a “smart” jammer that follows its target signal. If such smart jammer is used against a cognitive radio network, the network is required to continuously change its frequency. However, each frequency change must be coordinated with other nodes over a control channel, and must be preceded by spectrum sensing. Therefore, the jamming of a single network node will impact the whole network.

However, a truly cognitive radio may even outsmart such smart jammer, because it understands the situation it's in. When a public safety network is clearly under attack, different policies may apply, and the primary user avoidance scheme can be replaced by a jamming avoidance scheme. In such jamming avoidance scheme spread spectrum techniques are very useful.

16.4 Chapter Summary

For the next generation system for public safety communication, there is a huge demand for broadband applications. One reason for this is that pictures and video are very efficient in describing a situation. Another reason is that modern cell phones have broadband internet access, and public safety personnel may start to rely on it. But during a large emergency, cell phones are likely to fail. Therefore, broadband internet access is a requirement for the next generation public safety communication system.

One of the problems is that spectrum in the public safety bands is scarce, and public safety communication has such a high peak-to-average ratio that it is uneconomical to reserve the needed spectrum in the conventional way. Cognitive radio may be a way out of this problem. However, cognitive radio is not allowed to interfere with the primary voice communication in any way.

So before we can add cognitive radio, we first have to acquire a good understanding of how narrow band communication works. In this chapter we therefore reviewed the two foundations of modern public safety communication systems: trunking and cellular frequency reuse. The physical layer of the TETRA standard was reviewed and the implementation in the C2000 system was discussed. Next, we discussed a firework explosion as an example of a public safety situation where traditional communication systems failed. First, there was a shortage of voice channels, because hundreds of calls were made simultaneously in a relatively small area. Secondly, rescue workers could not upload pictures and videos of the situation to the central command post. From this scenario we derived that between 5 and 30 MHz of spectrum must be found by spectrum sensing. From propagation considerations we derived that the preferable spectrum region lies between 400 MHz and 1 GHz. From spectrum surveillance data we see that it is reasonable to expect that such bandwidths can indeed be found in this region of spectrum.

16.5 Problems

1. In Section 16.3.1 we describe the firework disaster in Enschede. In normal day-to-day activities (like house fires) at most 25 public safety workers will

be active in this area. How much capacity, *i.e.*, lines will be required if less than 0.1% of the call is blocked and that the busiest hour there are 0.167 calls per second and the average duration of a call is 30 seconds? To calculate this answer, use the Erlang-B model, which can be downloaded from MATLAB-central.

2. If in the previous question group communications was used with on average 5 rescue workers in one group, what would be the required capacity in this case?

3. Derive the required capacity on the day of the firework disaster. Assume that the busiest hour there are 100 calls per second and the average duration of a call is 20 seconds. How much lines are now required? And what if group communication is used?

4. The TETRA system has four time slots and uses 2 times 25 kHz of spectrum (TDMA + FDD). If we assume that spectrum per MHz has the same costs as the UMTS licenses per MHz (Section 16.1.3). In addition, we assume that cognitive radio technology could provide 80% of the capacity during a large disaster. What are the economical benefits of using this technology?

5. In an analog cellular network one needs an SNR of at least 18 dB for acceptable audio quality of voice communication. What would be the optimal cluster size K?

6. In a digital cellular network you have a total bandwidth S that must be partitioned over clusters of K cells. Which value of K would give the highest theoretical capacity?