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700MHz Spectrum Requirements for Canadian Public Safety Interoperable Mobile Broadband Data Communications

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Abstract

In response to a request for technical advice by Public Safety Canada on behalf of national public safety stakeholders, the Centre for Security Science conducted a technical assessment of the 700 MHz spectrum requirements for broadband mobile data communications for public safety and security. The impetus to this assessment relates to the Industry Canada call for consultation SMSE-018-10. The goal was to determine how much spectrum is required to meet the needs of the public safety community for mobile broadband wireless data communications within a 20-year time frame. The data demand for recurring emergency situations was modeled through an interactive process with active participation from Canadian public safety stakeholders. In addition, the capabilities of LTE technology to support the data demands were also modeled. The results show that the amount of bandwidth required to satisfy the needs of public safety is greater than 20MHz in the near-to-mid term, and likely to also exceed 20MHz in the long term, despite advances in technology. This result is based on an analysis that applies relatively conservative estimates for the growth in demand for mobile data communications for public safety and security applications, and relatively aggressive estimates for the rate of technological improvement of spectrum efficiency projected into the future.

Résumé

En réponse à une demande de conseils techniques faite par Sécurité publique Canada au nom des intervenants nationaux de la sécurité publique, le Centre des sciences pour la sécurité a effectué une évaluation technique des besoins de la fréquence de 700 MHz pour la transmission mobile à large bande de données destinée à la sécurité publique. C'est l'appel de consultation SMSE-018-10 d'Industrie Canada qui a motivé l'exécution de cette évaluation. L'objectif consistait à déterminer quelle part du spectre est requise pour répondre aux besoins du milieu de la sécurité publique pour la transmission mobile de données à large bande au cours des 20 prochaines années. La demande en données pour les situations d'urgences récurrentes a été modélisée à l'aide d'un processus interactif auquel les intervenants de la sécurité publique du Canada ont participé activement. Il y a de plus une modélisation des capacités de la technologie LTE pour répondre aux demandes de données. Les résultats démontrent que la part de la bande passante nécessaire pour répondre aux besoins de la sécurité publique est supérieure à 20 MHz à court et à moyen terme, et dépassera aussi probablement 20 MHz à long terme, et ce, malgré les progrès technologiques. Ce résultat repose sur une analyse ayant recours à des évaluations relativement prudentes de la croissance de la demande pour la transmission mobile de données à des fins de sécurité publique, ainsi qu'à des évaluations relativement ambitieuses du degré d'amélioration technologique de l'efficacité spectrale dans le futur.

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Executive summary

700MHz spectrum requirements for Canadian public safety interoperable mobile broadband data communications.

Claudio Lucente, MARTELLO DEFENSE SECURITY CONSULTANTS INC.

DRDC CSS CR 2011-01

In response to a request for technical advice by Public Safety Canada and on behalf of the national public safety community, the Centre for Security Science, with technical oversight by the Communications Research Center, conducted a scientific assessment of the 700 MHz spectrum requirements for broadband mobile data communications. This assessment is provided in support of the Industry Canada call for consultation SMSE-018-10.

The conversion of the broadcast television from analog to digital signals and the resulting re-allocation of the channels has attracted significant interest for the vacated RF spectrum on the part of commercial, private, and public entities. In particular, the Canadian public safety community has a strong interest in a segment of the 700MHz spectrum as described in the Industry Canada call for consultation (SMSE-018-10). Given the excellent propagation properties of this frequency band, it views this as a unique opportunity to lay the foundation for a national mobile broadband communications network that will allow various public safety agencies to better plan, coordinate, and execute their missions, for their day-to-day operations and when responding to crisis events.

New technologies and applications are at hand that can enhance situational awareness and improve coordination between public safety personnel. The mobile broadband wireless network must have suitable bandwidth to provide the data throughput required by the many applications required by today's public safety personnel such as real-time video surveillance, vehicle and blue force tracking devices, ambulance patient video. The bandwidth requirements will evidently vary depending on the operations being conducted be it day-to-day routine calls, crowd control, or major emergency situations. Since the network must be designed to provide connectivity that responders can rely on at all time, the bandwidth requirements must be addressed in the context of how responders intend to use the mobile broadband network during emergencies.

In order to assess the requirement with appropriate context and relevance, stakeholders were consulted across the nation, facilitated through linkages provided by the Canadian Interoperable Technologies Interest Group. Three incident scenarios were selected as case studies for public safety stakeholders to develop the incident-response profiles. The profiles consisted of establishing how many resources and assets would be assigned to each incident and, what applications would they make use of during each incident. The incidents that were chosen as case studies represent major but commonly re-occurring events (such as a sports event). We know that catastrophic events of the scale of a major earthquake or a concerted terrorist attack (9/11) would create demands that would far exceed any available spectrum and so such situations were not considered in the analysis.

The data throughput for each application was derived from empirical studies conducted by public safety agencies, support organizations, and research labs. Thus, the Data Demand Model (DDM) is derived from the incident-response profiles and the applications throughput requirements, in addition to growth assumptions over a 20-year horizon. Particular attention was paid to tactical video as it is expected to prevail in enhancing situational awareness and is often critical, particularly to security operations. It is also the largest consumer of bandwidth. As such, various techniques are considered in the DDM to reduce the preserve bandwidth requirement in the presence of video traffic.

Because of the large push by the commercial sector to deploy Long Term evolution (LTE) networks as the 4th generation of cellular system and since the United States has selected LTE as the technology for public safety mobile broadband, using the same technology in Canada would leverage the economies of scale and enhance interoperability between Canadian and US public safety agencies LTE was therefore selected as the basis to develop the Capacity Model for this report. There are substantial research efforts underway to enhance the capacity of LTE and therefore, the Capacity Model introduces a factor to account for a number of anticipated enhancements in spectral efficiency at various intervals over the 20-year horizon of the model.

Finally, the required bandwidth is revealed by correlating the data demand with the capacity. Several fundamental assumptions are used in the models such as the rate at which research into spectral efficiency is transformed into reality and, the number of users accessing the same applications simultaneously. The effect of varying these assumptions on required bandwidth is examined, as is the effect of uncertainty in predictions, which increases with time particularly as we look into the future 15-20 years.

The result of the modeling, taking into account uncertainty factors, shows that the amount of bandwidth required to satisfy the needs of public safety to conduct their missions during commonly re-occurring major emergency situations with modern tools and applications is greater than 20MHz in the near-to-mid term, and likely to also exceed 20MHz in the long term, despite advances in technology. Clearly even with the full 10 + 10 MHz allocated, the community will need to take measures to efficiently manage broadband data communications carefully during periods of peak demand.

Sommaire

Évaluation technique des besoins de la fréquence de 700 MHz réservée à la sécurité publique pour la transmission mobile à large bande de données

Claudio Lucente, MARTELLO DEFENSE SECURITY CONSULTANTS INC.

DRDC CSS CR 2011-01

En réponse à une demande de conseils techniques faite par Sécurité publique Canada au nom de la collectivité nationale de la sécurité publique, le Centre des sciences pour la sécurité, sous la supervision technique du Centre de recherches sur les communications, a mené une évaluation scientifique des besoins de la fréquence de 700 MHz pour la transmission mobile de données à large bande. Cette évaluation vient en soutien à la demande de consultation SMSE-018-10 d'Industrie Canada.

La transition des signaux analogues aux signaux numériques des services de télédiffusion et la nouvelle répartition des canaux ont suscité un vif intérêt vis-à-vis du spectre des radiofréquences libéré chez les entités commerciales, privées et publiques. Le milieu canadien de la sécurité publique s'intéresse énormément à un segment de la bande de 700 MHz tel qu'il est décrit dans la demande de consultation SMSE-018-10 d'Industrie Canada. Étant donné les excellentes propriétés de propagation de cette bande de fréquence, on considère qu'il s'agit d'une occasion unique de jeter les bases d'un réseau national de transmission mobile à large bande qui permettra aux divers organismes de sécurité publique de mieux planifier, coordonner et exécuter leurs mandats, tant dans le cadre de leurs activités quotidiennes que lors des interventions en situation de crise.

Il existe de nouvelles technologies et applications qui peuvent accroître la connaissance de la situation et améliorer la coordination entre les intervenants de la sécurité publique. Le réseau mobile sans fil à large bande doit avoir une bande passante suffisante pour fournir le débit de données nécessaires aux nombreuses applications exigées de nos jours par les intervenants de la sécurité publique, comme la vidéosurveillance en temps réel, les appareils de suivi des véhicules et des forces bleus et la vidéo de patients transportés par ambulance. Les besoins en bande passante varieront évidemment en fonction des activités, qu'il s'agisse d'appels quotidiens de routine, du contrôle des foules ou de situations d'urgence majeures. Puisque le réseau doit être conçu de manière à offrir une connectivité à laquelle les intervenants peuvent se fier en tout temps, il faut tenir compte des besoins en bande passante en fonction de la manière dont les intervenants ont l'intention d'utiliser le réseau mobile à large bande pendant des situations d'urgence.

En vue d'évaluer les besoins en fonction des bons contextes et de leur pertinence, on a consulté des intervenants partout aux pays, grâce aux liens fournis par le Groupe d'intérêt canadien en technologie de l'interopérabilité. Trois scénarios d'incident ont servi d'études de cas aux intervenants de la sécurité publique pour définir les profils d'intervention des incidents. Les profils visaient à établir la quantité de ressources et de

biens qui seraient affectés à chaque incident et à déterminer quelles applications ils utiliseraient dans chaque cas. Les incidents choisis à titre d'études de cas représentent des événements majeurs récurrents (comme une manifestation sportive). Nous savons que les catastrophes comme un important tremblement de terre ou une attaque terroriste concertée (attaques du 11 septembre) engendreraient des demandes qui iraient bien au-delà de tout spectre disponible. Par conséquent, de telles situations n'ont pas été prises en considération dans l'analyse.

Le débit des données pour chaque application a été obtenu à partir d'études empiriques effectuées par des organismes de sécurité publique, des organismes de soutien et des laboratoires de recherche. Par conséquent, le modèle de demande de données repose sur les profils d'intervention aux incidents et les besoins des applications en débit des données, ainsi que sur les hypothèses de croissance pour les 20 prochaines années. On a porté une attention particulière à la vidéo à des fins tactiques puisque celle-ci devrait s'imposer pour améliorer la connaissance de la situation et s'avère souvent essentielle, notamment aux activités de sécurité. C'est aussi elle qui utilise le plus de bande passante. Le modèle de demande de données a donc pris en considération diverses technologies pour réduire le besoin de bande passante réservée en présence de trafic vidéo.

En raison de l'offensive du secteur commercial visant la mise en place de réseaux LTE en guise de 4^{e} génération de système cellulaire et puisque les États-Unis ont choisi la technologie LTE pour la transmission mobile à large bande de la sécurité publique, l'utilisation de la même technologie au Canada permettrait de faire des économies d'échelle et améliorerait l'interopérabilité entre les organismes de sécurité publique des États-Unis et du Canada. La technologie LTE a donc servi de base à l'élaboration du modèle de capacité du présent rapport. D'importants travaux de recherche sont en cours en vue d'améliorer la capacité de la technologie LTE. Par conséquent, le modèle de capacité introduit un facteur qui tient compte de certaines améliorations prévues de l'efficacité spectrale à divers intervalles au cours des 20 prochaines années du modèle.

Enfin, la bande passante nécessaire est déterminée par la corrélation entre la demande de données et la capacité. Les modèles utilisent plusieurs hypothèses de base, comme la vitesse à laquelle la recherche sur l'efficacité spectrale se transforme en application pratique et le nombre d'utilisateurs accédant simultanément aux mêmes applications. On examine les répercussions d'une variation de ces hypothèses sur la bande passante ainsi que l'incidence de l'incertitude dans les prédictions, qui augmente au fil du temps puisqu'il s'agit d'une évaluation portant sur les 15 à 20 prochaines années.

Les résultats de la modélisation, qui tient compte des facteurs d'incertitude, démontrent que la part de la bande passante nécessaire aux activités du milieu de la sécurité publique ayant recours aux outils et aux applications modernes lors de situations d'urgence majeures et récurrentes est supérieure à 20 MHz à court et à moyen terme, et qu'elle dépassera probablement 20 MHz à long terme, et ce, malgré les progrès technologiques. De toute évidence, même avec une pleine attribution de 10 + 10 MHz, la communauté devra prendre des mesures pour gérer efficacement et prudemment la transmission de données à large bande pendant les périodes de demande de pointe.

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Acknowledgements

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1 Introduction

The demise of analogue broadcast television and the resulting re-allocation of broadcast television channels has attracted significant interest for the vacated RF spectrum on the part of commercial, private, and public entities. In particular, the Canadian public safety community has expressed a strong interest in a segment of the 700MHz spectrum. It views this moment in time as a unique opportunity to lay the foundation for a national mobile broadband communications network that will allow various public safety agencies to better plan, coordinate, and execute their missions, whether it is for their day-to-day operations or when responding to crisis events.

Such a network could enable interoperable broadband communications among Canadian public safety entities and with international agencies during joint operations, such as with the US Department of Homeland Security, provided that technology and spectrum are aligned between Canada and the US. It would enable the goals of Canada's National Strategy for Communications Interoperability[*] .

The demands placed on a mobile broadband data communications network by the public safety community depends strongly on the nature of the missions it executes and the applications it uses during those missions. Situational Awareness (SA) and the ability to coordinate broadly and effectively in improvised circumstances are fundamental capabilities in order to execute a mission in the safest and most expedient manner possible. Whereas, currently, voice communications via Land Mobile Radio (LMR) is the most commonly used method to coordinate and establish SA, it is expected that tactical video, will play an increasingly important role to enhance SA, while LMR will remain the key voice communications tool for the foreseeable future.

Mobile broadband data services will give rise to new applications and innovative uses for data communications by the public safety community. It is envisaged that access to a mobile broadband network will extend to a user-group that is peripheral to first responders and those that occupy supporting roles. As such, the data demands will be driven by the use of new tools, new users, and new applications which, in turn, will foster greater reliance by first responders on the tools and supporting community in the response to incidents.

The goal of this study is to determine how much spectrum is required to meet the needs of the Canadian public safety community for mobile broadband wireless data communications within a 20-year time frame. The results of this study and its conclusions are derived from the correlation of the community's data demands and the capacity of 4th Generation wireless technology to support the applications that first responders intend to use. Fundamental assumptions are validated and inputs are obtained via an interactive process with active participation from public safety stakeholders and federal government researchers. The methods, assumptions, and results are benchmarked against similar studies that have been performed in the USA. [1, 3, 21]

[*] http://www.publicsafety.gc.ca/prg/em/cisapc-scicpa-eng.aspx

1.1 The 700MHz band

The channelization of the Canadian 700MHz band is under study by Industry Canada and so the US 700MHz spectrum allocation is shown here for reference. Figure 1.1 illustrates the US channelization plan for the 700MHz spectrum. Note that Band-14 (circled) spans 10MHz in the down-link (758MHz – 768MHz) and 10MHz in the up-link (788MHz – 798MHz). If the FCC and US Congress allocate the D Block to public safety then that would represent 2x10MHz of spectrum. In this report references to 10MHz LTE pertain to either the up-link or down-link channel bandwidth. When referring to both the up-link and down-link channel bandwidths then it is stated as 10+10MHz or 20MHz.

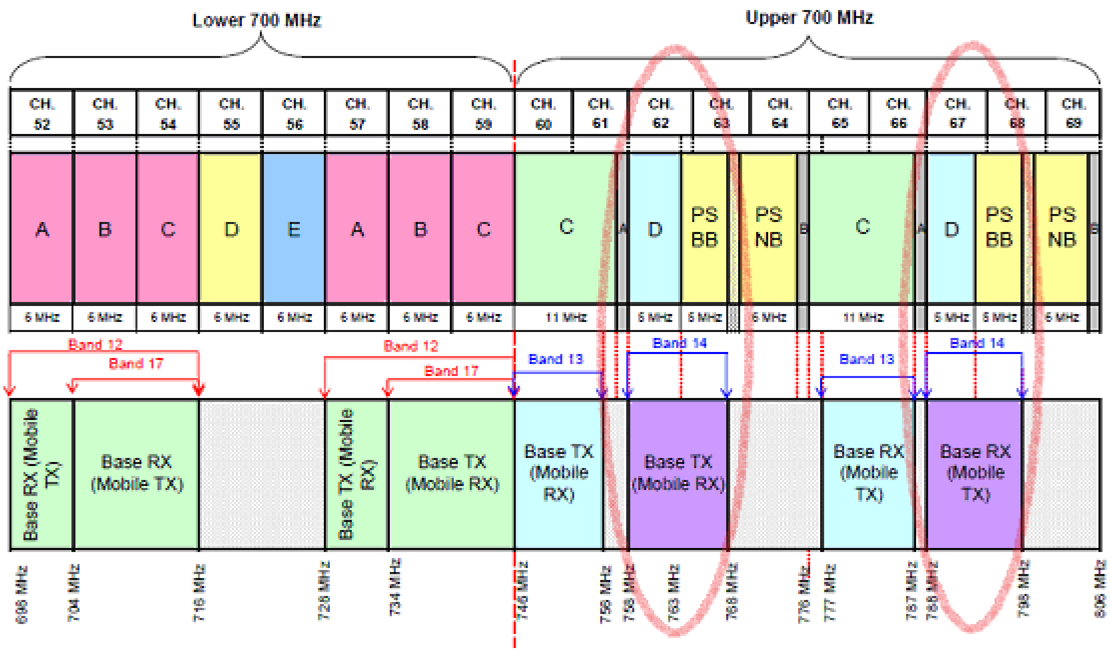

Figure 1.1: US channelization plan for 700MHz spectrum

2 Methodology

The bandwidth required to support public safety operations is based on a number of factors, of which the two most important ones are:

a) <u>Usage in terms of data demand</u>

The data demand, expressed in bits per second, is defined by the sum of the Up-link and Down-link data rates required to sustain the various applications needed to support public safety's data communications needs in day-to-day operations and when responding to emergency situations.

b) <u>Network infrastructure</u>

The amount of bandwidth required to carry the data demand is based on the network infrastructure selected, the communications protocol, and the network architecture.

In this Chapter, the methodology used to define both the data usage and the bandwidth, based on the infrastructure is discussed. The data demand is derived and quantified in §3.

2.1 Usage

The process to establish the data demand is illustrated in Figure 2.1. It involves public safety stakeholders to define how they would use a mobile broadband network and what applications they would make use of. The demand is evaluated for day-to-day operations and for three incident scenario case studies, which represent recurring emergency situations typically encountered by public safety agencies. The case studies are described in §3.1. The Model includes a demand growth factor to account for applications which the stakeholders did not identify or, at the time of the survey, could not predict using in the future.

Once the data demand model was established, another round of feedback was undertaken to validate the assumptions. The Data Demand Model was also reviewed and validated as a sound technical approach with Canadian Government scientists.

Several sources were used to determine the application data rates. These are discussed in more detail in §3.3.1.

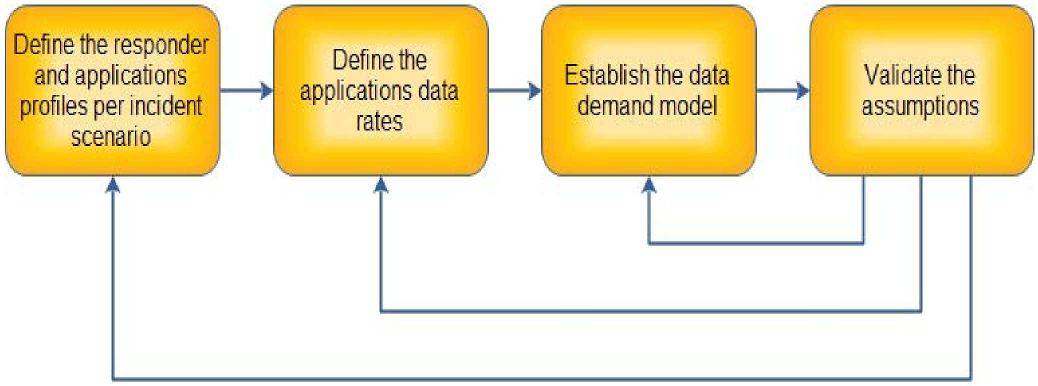

Figure 2.1: Process to develop the Data Demand Model

2.2 Network Infrastructure

The Capacity Model is based on the capabilities of Long Term Evolution (LTE). LTE is the latest generation of mobile broadband technology being deployed by commercial carriers around the world for their 3.9G networks with a migration path to LTE-Advanced (4G). Figure 2.2 illustrates the actual and announced deployments of LTE globally. A large uptake of this technology is expected to drive cost down and provide more incentives for the development of new features and capabilities. In addition, the US Federal Communications Commission (FCC) has recently mandated that public safety broadband networks must use LTE. Canadian public safety can leverage the economies of scale driven by the commercial carriers and be interoperable with US public safety organizations by selecting LTE as the network infrastructure technology for public safety in Canada.

LTE is currently being deployed commercially at Rel.8 and in pilot stages for a small number of public safety agencies in the US. The 3GPP organization is currently defining Rel.9, 10, and 11. Each successive release introduces new capabilities and especially, improved spectral efficiencies. This is discussed in §4.2.

The Capacity Model and related assumptions were also reviewed in detail with Canadian Government scientists having expertise in the wireless communications domain and the approach was judged to be technically valid and appropriate for the purposes of this study.

Figure 2.2: Locations with actual LTE deployments (blue markers) and announced deployments (red markers) *

* www.ltemaps.org

3 Demand for mobile data communications

The need for responders to communicate and access information is felt most acutely during the response to an incident. During these events the mobile broadband network will see the greatest demand for data throughput. Figure 3.1 illustrates that an incident is a localized event and so, unlike day-to-day operations where the data demand is spread over a territory that spans multiple cell sites, an emergency event will drive data demand from within a small geographic area.

Although an incident may arise anywhere on land or on water across the entire Canadian territory, this study focuses on the data demands from public safety agencies in a mid-to-large size urban setting. It is assumed that the deployment of a mobile broadband network will launch in urban centers first before expanding to sub-urban and, eventually rural areas. Urban centers will have the greatest density of users and greatest number of recurring events requiring the intervention of public safety and security forces.

It is important that sufficient capacity be available during an emergency event, as well as suitable congestion management policies to effectively deal with peaks in demand that exceed the instantaneous available capacity. The assertion of congestion management mechanisms must not impede the ability of the responders to execute their mission during the events.

In this section the foundation of the Data Demand Model (DDM) will be described. It considers the demand for data communications during an emergency event overlaid on the data demands of day-to-day operations.

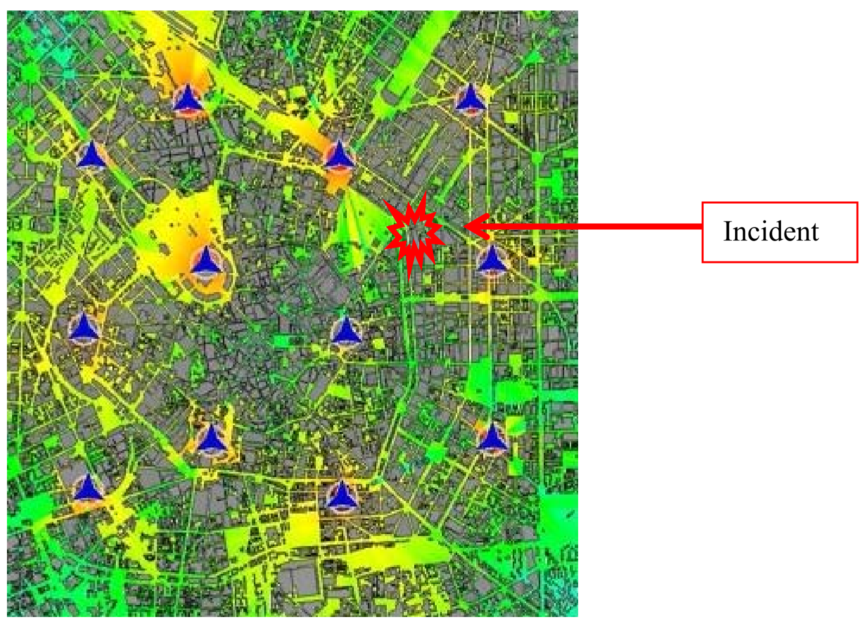

Figure 3.1: Illustration of a localized incident in a multi-cell network deployment.

3.1 Incident scenarios

In consultation with first responder stakeholders and in alignment with similar assessments recently performed in the US, the estimate of the data demands were based on common occurrences and predictable incidents. Three hypothetical, but plausible scenarios have been identified to serve as case studies. These case studies represent events that public safety agencies expect to encounter and for which Standard Operating Procedures (SOP) have been formulated. They are:

- Chemical Plant Explosion and Fire
- A Severe Multi-Vehicle Accident
- Sports Event Riot

A number of representatives of the public safety community from across Canada contributed to defining the nature of the response to each scenario in terms of the number and types of responders and support agencies, and what applications the stakeholders would use during each event. Below are descriptions of the incident scenarios that were used as case studies.

Catastrophic incidents such as a major earthquake or a major terrorist attack are not modelled in this study since the magnitude of the response at that time would overwhelm any mobile data network dimensioned for more routine events such as those which are considered here. Other measures would be required such as diverting or extending capacity from surviving commercial networks.

3.1.1 Chemical Plant Explosion

This case study was adapted from a scenario developed by the Wireless Innovation Forum – Public Safety Special Interest Group[*] and is based on a hypothetical scenario of a chemical plant explosion, with events drawn from a number of sources including the chemical plant explosion scenario developed as part of the US DHS SAFECOM Public Safety Communications Statement of Requirements/TR-8 Broadband Task Group, and analysis of actual events of the fire at a hazardous waste transfer plant in Apex, NC, in October 2006. This scenario is relevant to other types of incidents such as an explosion at a refinery.

<u>Narrative</u>

A large explosion occurs at a 75,000 sq.ft chemical plant in the industrial area of a mid-sized city. The blast shatters windows of buildings in the immediate vicinity. There are a significant number of casualties both from within the chemical plant and outside. Multiple sensors detect and report the incident to the 911PSAP. Within minutes the 911PSAP is also flooded with calls from motorists, pedestrians, and residents. Soon, commercial cellular networks become overloaded.

Air quality sensors around the area detect hazardous substances emanating from the site of the accident. The wind speed and direction reported from environmental monitoring stations indicate that the chemical plume will drift over a residential area with an elementary school, a high school, a library, a hospital, and numerous retail businesses. As it drifts over roads and highways car accidents ensue and some motorists abandon their cars to escape the plume on foot.

Debris expelled by the explosion damages a nearby electrical sub-station, causing a localized power failure.

[*] http://www.wirelessinnovation.org

First responders report that a type of liquid is escaping from the chemical plant and flowing into the on-site retention basins. However, the condition of the basins is unknown.

3.1.2 Severe Multi-Vehicle Accident

This case study is based on serious accidents that are likely to occur for any of a number of reasons, such as poor weather, driver fatigue, mechanical failure, etc… This scenario is also relevant for a train derailment, aircraft emergency landing, and other similar situations.

<u>Narrative</u>

It's early winter and the temperature is rising from many days below freezing to settle just around the freezing mark with precipitation turning to ice pellets. Icy patches form on a highway running through a major urban centre and a foggy mist reduces visibility.

The flow of traffic on the icy highway in front of a semi-trailer comes to a rapid halt and the driver realizes he is unable to stop in time to avoid colliding with the cars in front. He attempts to swerve but his tractor regains traction while the trailer does not. The rig jack-knifes and flips over the median finally, landing onto its side on the opposing lanes. Vehicles immediately following the tractor/trailer are unable to stop and collide with it. Others, while swerving to avoid it cause accidents in their adjacent lanes. A similar scene is playing out on the opposite side and an oil tanker is also involved. It has also ended up on it side. Oil is leaking but no fire has started. The trailer has a hazardous products sign on the rear door.

Drivers are injured and some of them are trapped in their vehicles. Other drivers fearing that a fire will start, abandon their vehicles on both sides of the highway and run along the highway's shoulders.

All traffic stops on both sides of the highway.

3.1.3 Sports Event Riot

This case study is based on a riot that arises from a victory celebration of a local sports team. Although the premise is a sports event, the scenario is also relevant for any large event that attracts crowds and protesters with the potential for violence.

<u>Narrative</u>

It's mid-June and we're in overtime of game 7 of the Stanley Cup finals when the unimaginable happens at Maple Leaf Gardens – the home team scores an incredibly fluky goal. After a seemingly interminable moment, stunned audiences explode with joy. Crowds empty into the streets from the Garden, bars, cafes, and homes from all areas of the city. Soon many streets are clogged with people and the downtown core becomes a grid-locked parking lot.

Emotions rise and without notice the celebration turns ugly. Gangs begin to break store-front windows. Looting ensues. Cars are set alight. Riots break out spontaneously in various parts of the downtown core and the rioters quickly move from one area to another. They twitter to help coordinate their movements.

A number of people are injured by flying debris and others are trampled by surging crowds in tight quarters. Some riot police officers and rioters are also injured.

3.2 Day-to-day operations

In addition to demands for data during incidents, mobile data communications plays a vital role during the day-to-day operations for public safety and security, and other municipal and government agencies. It is conceivable that in urban environments these agencies would share a single mobile broadband data network. Some examples of day-to-day operations are:

- Issuing traffic citations
- Fire-fighting
- Health emergencies
- Patrols
- Incident reporting
- Database querying and records look-up
- Work-site inspections
- Maintenance and waste management services
- Public transit
- Utilities: meter reading, service upgrades or restoration

Incidents, when they arise, do not displace day-to-day operations. Incidents occur while day-to-day operations continue.

Table 3.1 illustrates the profiles for the three incident scenario case studies of §3.1 and for Day-to-Day Operations in terms of the number and types of assets that are assigned to each situation. For the purpose of quantifying the number of devices that generate or consume data, this study defines "assets" as vehicles and assumes that data communications devices are detachable so they can be vehicle-borne or person-borne.

3.3 Applications

In a poll conducted among representatives of the Canadian public safety community (municipal police forces, RCMP, Fire Services, Emergency Medical Services, Provincial Emergency Management, and National Search and Rescue), the participants indicated which applications they were likely to use across a mobile broadband data service. The City of New York, in its analysis of 700MHz spectrum requirements, identified a similar set of applications[3]. The candidate applications are listed in Table 3.2. They are broadly categorized as:

- Video Applications
- Collaborative tools
- Monitoring
- Database access and records upload
- Messaging

The same representatives also identified the main applications they were likely to use during emergencies. The results are shown in Table 3.3.

Assets	Chemical Plant	Multi-Vehicle Accident	Sports Event Riot	Day-to-Day Operations
Mobile Command Posts				
Fire Services	1	0	0	
EMS	2	0	1	
Police	1	1	1	
Fire chiefs and commanders				
Division	1	0	0	
Platoon	2	1	0	
Department	1	1	0	
District	3	2	0	5
Deputy Chief	1	0	0	
Safety officer	1	1	0	
Fire-fighting vehicles				
pumper trucks	8	3	0	15
ladder trucks	3	1	0	5
Specialized Fire Services Units				
Rehab unit	1	0	0	
Rapid intervention unit	2	1	0	
Rescue unit	2	1	0	
Air mgmt	1	0	0	
Hazmat	4	3	0	
Public safety trained security officers	0	0	4	
Public safety apparatus	0	0	6	
Portable sensors	12	0	12	
Medical/paramedical				
1st Responder Units	12	6	10	20
Bike Medics	0	0	8	8
Ambulances	30	15	15	110
Specialized and supervisory EMS Units				
Emergency Task Force	2	2	6	2
Buses	1	1	1	1
Trucks	1	1	1	1
Supervisors	6	4		12
Public Order units	0	0	6	0
Police patrol units and vans				
Cruisers	15	10	80	420
Vans	2	2	10	33
Inspectors	0	2	8	1
License Plate Readers	0	0	0	30
Utilities, municipal services, govt civil agencies				
Electrical	2	0	0	50
Gas	2	0	0	30
Buses	2	1	5	1000
Public Works	3	1	4	200
Judicial Services	0	0	1	0
Transport ministry	0	1	0	20
Environment ministry	1	1	0	20

Table 3.1: Response profiles for three incident scenarios case studies and Day-to-Day Operations

Video applications		Database access and records upload
Surveillance video		GIS information
Tactical video		still images
Ambulance patient video		Building plans and information
Public Transit video		Hazmat inventory
Video conferencing		medical records
News feeds		NG911 video file
		Weather information
Collaborative tools		internet access
Electronic Command Board		Patient triage
Computer-Aided Dispatch		Traffic advisories
Records Management System		e-Ticketing
		Vehicle Registration
Monitoring		Biometric data
Automated Vehicle Locating		License Plate Reader
Blue Force Tracking		
Vital signs monitoring		Messaging
Automotive telemetry		SMS
Tracking evacuees		MMS
		email

Table 3.2: Broadband data applications

	Surveillance video (ext)	Tactical Video	Patient video	Public Transit Video	Video conference	News feeds	Collaborative tools	Database access	Messaging	Monitoring
Mobile Command Posts	RCV	XMT-RCV		RCV	XMT-RCV	RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Fire Services										
EMS										
Police										
Fire chiefs and commanders	RCV	RCV			XMT-RCV	RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Division										
Platoon										
Department										
District										
Deputy Chief										
Safety officer										
Fire-fighting vehicles	RCV	XMT-RCV				RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
pumper trucks										
ladder trucks										
Specialized Fire Services Units	RCV	RCV				RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Rehab unit										
Rapid intervention unit										
Rescue unit										
Air mgmt										
Hazmat										
Public safety trained security officers										
Public safety apparatus										
Portable sensors										XMT
Medical/paramedical	RCV	RCV				RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
1st Responder Units										
Bike Medics										
Ambulances	RCV	RCV	XMT		XMT-RCV	RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Specialized and supervisory EMS Units	RCV	RCV				RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Emergency Task Force										
Buses										
Trucks										
Supervisors										
Public Order units										
Police patrol units and vans	RCV	XMT-RCV		RCV	XMT-RCV	RCV	XMT-RCV	XMT-RCV	XMT-RCV	XMT
Cruisers										
Vans										
Inspectors										
License Plate Readers										
Utilities, municipal services, govt civil agencies				XMT				XMT-RCV	XMT-RCV	XMT
Electrical										
Gas										
Buses										
Public Works										
Judicial Services										
Transport ministry										
Environment ministry										

Table 3.3: Association of broadband data applications to public safety assets and direction of data flow.

3.3.1 Applications performance requirements

Table 3.4 lists the data rates used in the Data Demand Model. They are separated into UL and DL directions since the LTE spectral efficiencies are different for UL and DL.

	Datarates (kbps)		
Video applications	DL	UL	
Surveillance video HR	1536	0	streamed to Users on demand
Surveillance video LR	64	0	streamed to Users on demand
Tactical video LR	64	64	distribution of tactical video for composite view; constant streaming
Tactical video HR (monitor)	1152	1152	Viewing video imagery on monitors; per selected feed.
Ambulance patient video (LR)	0	64	distribution of patient video for composite view; constant streaming
Ambulance patient video (HR)	0	768	Viewing video imagery on monitors; per selected feed.
Public Transit video (LR)	64	64	distribution of public transit video for composite view; constant streaming
Public Transit video (HR)	384	384	Viewing video imagery on laptops; per selected feed.
Video conferencing	384	384	per User
News feeds	768	0	streamed to Users on demand.
Collaborative tools	50	50	average data rates per user.
Emergency Management System			
Computer-Aided Dispatch			
Records Management System			
Database access and records upload	50	20	average data rates per user.
GIS information			
still images			
Building plans and information			
Hazmat inventory			
medical records			
NG911 video file (pre-recorded)			
Weather information			
internet access			
Patient triage			
Traffic advisories			
e-Ticketing			
Vehicle Registration			
Biometric data			
License Plate Reader	50	256	
Messaging	40	20	average data rates per user.
SMS			
MMS			
email			
Monitoring	30	60	occurs in the background and is assumed to be a constant rate
Automated Vehicle Locating	5	10	
Blue Force Tracking	5	10	
Vital signs monitoring	5	10	
Automotive telemetry	5	10	
Tracking evacuees	5	10	
CBRNE sensors	5	10	

Table 3.4: Applications data rates (kbps).

The following are the different types of video traffic used in the model:

a) Surveillance video HR: scaled from the Incident Video High Resolution (HR) because of the wider angle scene captured by fixed surveillance cameras. Capable of full-motion 30fps.

b) Incident video HR: based on empirical data used in the report by the City of New York to the FCC. [3]

c) Ambulance Patient Video HR: near-field scene capture.

d) Public Transit video HR: mid-level frame rate 15fps, near-field scene capture

e) Video conferencing: near-field scene, mid-level frame rate15fps.

f) News Feeds HR: lower resolution than surveillance or incident video. Full-motion.

g) LR video (Surveillance, Incident, Patient, and Public transit): low-rate transmission of un-viewed video streams. See §3.3.2.1 for further discussion on dual-rate video.

The US National Telecommunications and Information Administration's (NTIA) recommended minimum data rate for tactical video for Standard Definition viewing is 768 kbps for H.264, also known as MPEG-4 Part 10, or AVC (advanced video compression). [4]

3.3.2 Video traffic management

Video applications represent the largest consumer of capacity on a broadband network. As such, management of this application merits particular attention. In this section we will discuss various approaches to make more efficient use of video applications. The techniques described in the following sections will be used in the Data Demand Model to minimize the bandwidth required by the various video applications.

3.3.2.1 Dual Rate Video

As discussed in §3.3.1 the data rate requirement for video depends on the intended use. For example, a high resolution video would be required to view a wide-angle scene on a monitor and be able to distinguish relatively fine details but a much lower resolution video would be needed for simple traffic monitoring,. Figure 3.2, shows a typical picture of a traffic surveillance camera. In order to read license plates from this scene a much higher resolution stream would be required.

However, it is highly unlikely that video captured at high resolution would be needed continuously for its details. Therefore, in order to limit bandwidth, we include in the Data Demand Model a component for dual-rate video, where the lowest data rate is set to 64Kbps and the maximum rate is as given in Table 3.4 for the different types of video. Dual-rate video is a variation of Adaptive Rate Video currently used by Apple, Adobe, and Microsoft, albeit each with their proprietary algorithms[5]. Although video is sampled at the highest rate possible at the source, it is transmitted at low resolution (LoRes) if it's not viewed.

Figure 3.2: Scene captured from a surveillance camera.

Figure 3.3 illustrates one video stream being viewed, thereby sent at high resolution (HiRes), and three video streams displayed as "thumbnails" which are not actively viewed. The latter are carried across the broadband data network at 64Kbps. In this example if a viewer selects from one of the thumbnail scenes, the selected scene would switch to HiRes mode and the previously viewed one would become a thumbnail and revert to LoRes mode.

Figure 3.3: Illustration of one actively viewed video stream and three "thumbnail" streams

In Figure 3.4 sources V1 and V4 are displayed as thumbnails on viewers M1-M4 only. As such their uplink data rates are 64Kbps, whereas V2 and V3 are viewed in expanded mode so they are uplinked at the HiRes data rates.

The DDM applies a video de-rating factor (VDF_{HiRes}) to the average HiRes video data rate, which takes into account the number of sources of video (VS) and the number of authorized viewing instances (VI). VDF_{HiRes} is expressed in Eq.(1):

$$VDF_{HiRes} = 1 - [(VS - 1)/VS]^{VI} \qquad (1)$$

3.3.2.2 Video management policy

Another way to manage video traffic is to limit the number of video sources admitted into the pool of viewable feeds and to limit the number of authorized viewers. This is a policy matter that requires an Operations Support System (OSS) to be able to assign higher priority to some video sources over other sources. For example, in the case study of the Chemical Plant Explosion, video feeds from police cruisers that are re-directing traffic around the affected area may be assigned lower priority than video feeds from fire-fighters.

The OSS would need to permit ad hoc adaptation of the policy to react to evolving circumstances. Following from the previous example, police video feeds may have a higher priority while they are on-route to the incident site and then be assigned a lower priority when the fire-fighters arrive.

The DDM includes a second bandwidth-preserving component by limiting the number of viewable HiRes and LoRes video feeds at any one time. Table 3.5 outlines the video management policy as implemented in the DDM.

Table 3.5: Video Management Policy

	Emergency Operations Centre	Incident Command Vehicles	Authorized First Responders *
Max simultaneous HiRes views	8	2 (each)	1 (each)
Max simultaneous LoRes thumbnails	no limit	10 (each)	3 (each)
Max number of simultaneous video conferencing participants	4	4	4
* not all First Responders would be authorized or equipped to access video feeds. It would be specific to the incident.			

3.3.2.3 Multimedia Broadcast Multicast Service

Multimedia Broadcast Multicast Service (MBMS) over an LTE wireless network allows the same video stream to be viewed simultaneously by multiple subscribers with only minimal overhead penalty. One stream consumes capacity in the down-link direction irrespective of the number of simultaneous viewings. [6]

Figure 3.3 illustrates the function of MBMS through an example of 2 downlink users, M1 and M3, viewing the same scene from V2. Only one feed is streamed in the downlink direction to serve 2 simultaneous viewers.

When there are more viewers than sources of video, MBMS can be treated as a gain which reduces the amount of downlink traffic. MBMS Gain is calculated according to Eq. 2.

$$\text{MBMS Gain} = \frac{[\text{\# of viewers}] \times [1 - \text{MBMS overhead}]}{[\text{\# of video sources}]} \qquad (2)$$

where MBMS overhead is 10%.

If the number of sources exceeds the number of viewers, then MBMS gain is set to 1 and MBMS overhead is 0.

MBMS was released by the 3rd Generation Partnership Project [*] (3GPP) as part of Rel.6 (High Speed Uplink Packet Access – HSUPA) in Dec.2004 and further updated in 2009. LTE Rel.9 includes E-MBMS (Enhanced MBMS), which supports multi-cell reception for improved spectral efficiency at cell-edge.

* www.3gpp.org

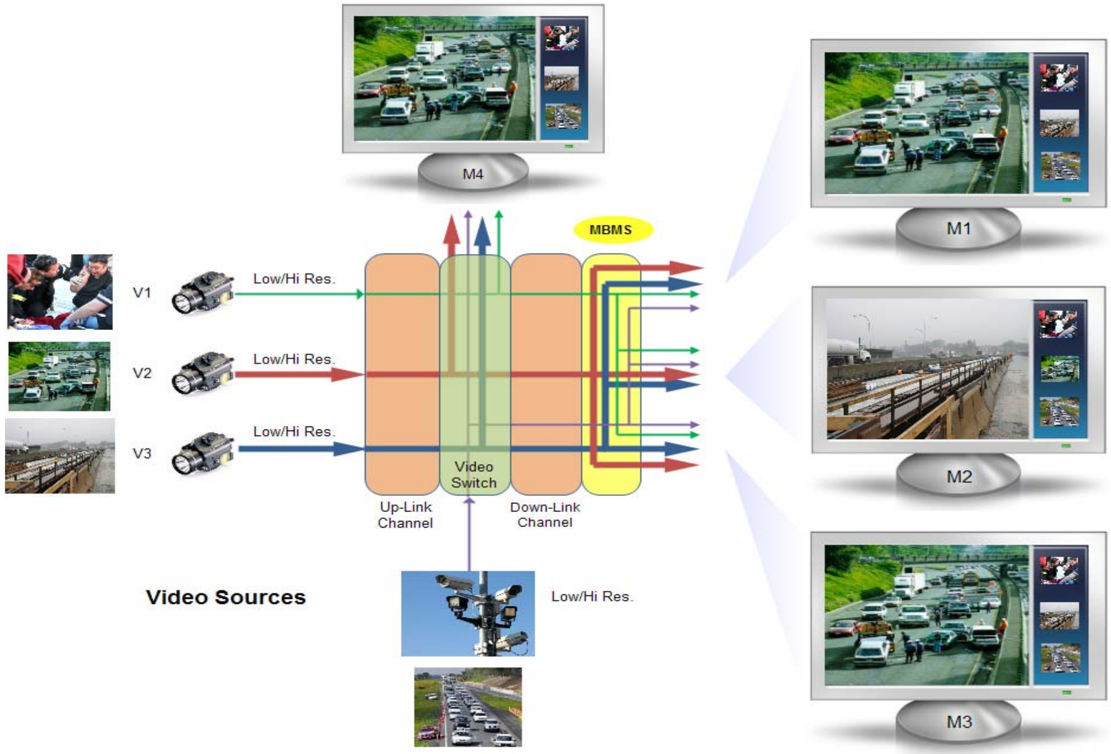

Figure 3.4: Illustration of MBMS function.

3.4 Growth Projections

The global demand for mobile broadband data is experiencing exponential growth in the commercial space fueled primarily by the continued deployment of laptop and netbook computers, and smartphones. Figure 3.5 illustrates the forecasted global demand for mobile broadband data.

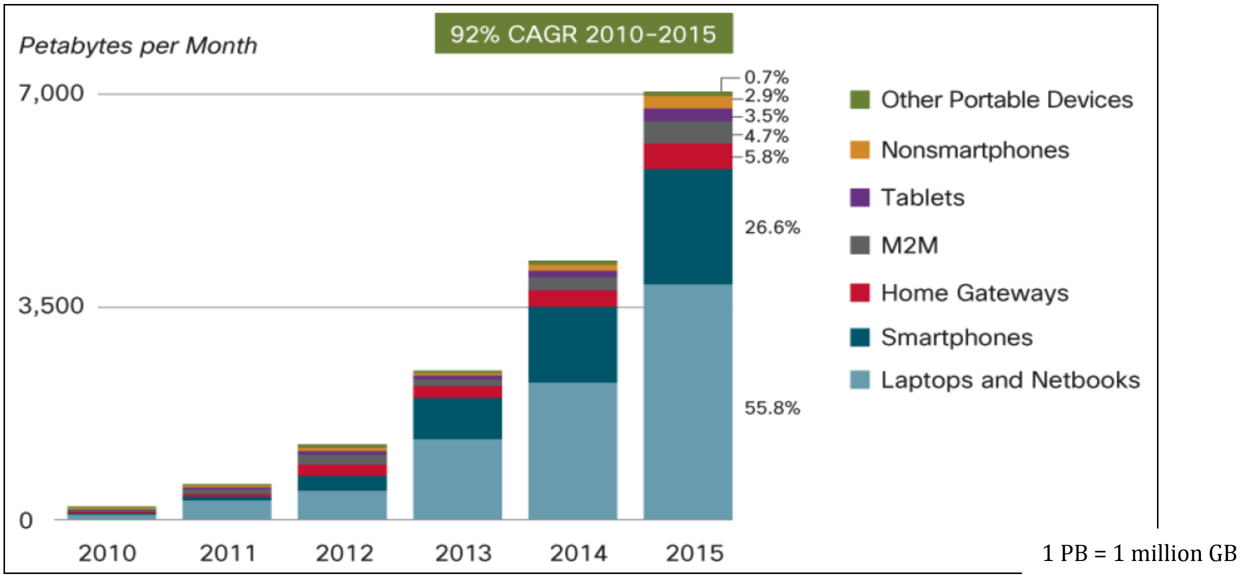

Figure 3.5: Forecasted global demand for mobile broadband data [7].

It is unlikely that public safety's demand for mobile broadband data will experience the same exponential growth, in part because the amount of spectrum allocated for public safety is less than what is allocated for commercial users. Nonetheless, there are growth drivers that will affect public safety's demand for mobile data. For example:

- Adoption rate among public safety agencies of devices which allow access to a mobile broadband network. In a given city, region, or territory the rate at which responders will be equipped with the capability to access a broadband network will be strongly affected by budgets allocated for this purpose.
- Introduction of new applications and tools that have not yet been identified in Table 3.2. Innovative new applications and tools that increase safety, improve the way missions are executed, and increase cost effectiveness are highly desirable. It is foreseeable that public safety agencies will adopt new applications and tools over time as they are vetted for stability, as SOPs are created and validated, and as budgets permit. New applications and tools are expected to increase the data throughput requirements.
- Organic growth of the public safety community in line with the growth of the general population.

The DDM has a growth component in the model to account for the contributing elements above as summarized below.

a) Rate at which public safety agencies will equip their staff with capabilities to access a broadband wireless network: **40% of responders equipped at YR-1 followed by 10% per year incremental growth.**

b) Rate of growth of data throughput required by new applications and tools: **5% per year.** It is assumed that the applications of Table 3.2 will be deployed in the 1st three years and that new applications would be introduced starting in Year-4

c) Organic growth rate of public safety personnel and assets: **3% per year**.

3.5 Data Demand Model (DDM)

The demand model uses the following elements:

a) The number and mix of responders that converge onto typical incidents. Table 3.1.

b) Applications that public safety will likely use with a mobile broadband network. Table 3.2.

c) How the applications are used and by whom. Table 3.3.

d) Applications data rates. Table 3.4.

e) Video Management Policy. Table 3.5.

f) Multimedia Broadcast Multicast Services (MBMS) DL gain.

g) Growth projections according to §3.4

3.5.1 Variables

In addition to the above factors, the DDM uses a number of variables. These are listed below in Table 3.6.

The Statistical Gain (SG) is also referred to as over-booking factor and accounts for the fact that not all Users are accessing data at the same time, thus the sum of the Users' data rates is divided by the SG. The City of New York report states that during an incident, first responders make more intense use of the communication tools and, therefore, use SG = 4, compared to SG = 20 during normal operations.

Typically, SG is a static value that network engineers assign to their dimensioning models. The thesis cited as a reference here proposes an approach whereby SG could be specific to the application[8]. So, some applications would have different SG than others. As shown in Table 3.6, the DDM uses different values of SG, which are:

- SG = 4 for streaming video and interactive applications,
- SG = 10 for video conferencing,
- SG = 1 for monitoring applications.

Table 3.6: List of Variables used in the Data Demand Model.

Video management policy	Incident scenarios	Day-to-Day Operations
Number of simultaneous HR feeds that can be viewed at EOC	8	8
Number of simultaneous LR feeds that can be viewed at EOC	balance of feeds	
Number of simultaneous HR feeds that can be viewed at MCV	2	2
Number of simultaneous LR feeds that can be viewed at MCV	10	10
Number of simultaneous HR feeds that can be viewed by selected 1st Responders	1	1
Number of simultaneous LR feeds that can be viewed by selected 1st Responders	3	3
Number of simultaneous video conferencing participants	4	4
Number of Patient Videos that can be viewed simultaneously at med.ctr.	4	40
Number of fixed Surveillance video cameras (not backhauled with LTE)	4	100
Number of live News feeds	1	6
Multicast Broadcast Multimedia Services (MBMS) overhead	10%	10%
Statistical Gain		
streaming video	4	20
video conferencing	10	20
interactive applications	4	20
background polling application	1	1
Growth variables		
Penetration rate for mobile broadband services (per year)	10%	10%
Growth of the user community - assets and people (per year)	0%	3%
Introduction of new and as-yet uknown applications and devices (annually, after year-3)	5%	5%
Area of Operations		
size of the territory (sq.km)		630
radius of a cell (km)		2
number of sectors in a cell		3

EOC means Emergency Operations Centre.
MCV means Mobile Command Vehicle.

3.5.2 Growth Rate

The growth rate of the data demand is assumed to be 5% per year, compounded annually. This is the same value that is used in the City of New York report, which the authors state as being conservative. In §4 the aspect of error in the estimates will be discussed. The actual increase in demand that will be experienced depends on many variables. Some examples:

- Public safety is currently not using some applications due to limited BW availability. When a broadband network is in place, the experience may be higher than what is assumed in this model.

- New tools will appear that will support different types of responses to incidents or day-to-day use. This could increase the data demands of the response profile in the future.

- Lessons-learned from the response to incidents will lead to changes in Standard Operating Procedures, which could have an impact on how tools and applications are used, which ones are used, at what time, and to what degree of intensity.

The model also assumes that a policy is in place to manage the use of incident video and the consumption of video feeds, in general. Video is the application which demands the most bandwidth and, as such, a video management policy would limit the amount of video transmitted on the wireless network.

The Model does not account for improvement in efficiencies for various applications. For example, video coding has migrated from MPEG-2 to MPEG-4, which essentially improved the coding efficiency by 50%. But, a counter-balancing assumption is that software applications become more complex and less efficient in their performance.

3.6 Data Demand profile

Figure 3.6 shows the DL, UL, and aggregate data demand for the 3 incident scenarios added to day-to-day operations, including the effects of compounded growth in demand.

From YR-1 to YR-10, the growth in demand is dominated by the 10-year capital investment plan to equip public safety. Each year 10% of the user group is equipped, culminating in 100% of the users being equipped in YR-10. From YR-11 to YR-20, the growth in demand is driven by the growth factors discussed in §3.4.

The projected growth of data demand for public safety is in sharp contrast with the projected growth for the commercial segment, as seen in Figure 3.5. Whereas the commercial growth follows an exponential trend, the growth for public safety demand follows a quasi-logarithmic trend. The projected growth in commercial demand fuels a vigorous research environment into methods to be able to cope with the expected demand. This will be discussed further in §4.

Another assumption is that the capital investment to equip public safety with the tools and applications that are considered in this study is made incrementally over a 10-year period, with 1/10th of the investment made each year. The responder profiles and applications in Tables 3.1, 3.2, and 3.3 are for a fully equipped responder community, which corresponds to YR-10 in Figure 3.6.

The responder profiles for each incident case study and application data rates have a strong influence on the demand. The incidents that were selected as case studies could have been different, which would have resulted in higher data demands.

For comparison purposes the City of New York published a demand growth profile and is highlighted in Figure 3.7. Note the inflection in the slope, which indicates that the growth in demand slows down after the inflection point, around year-8.

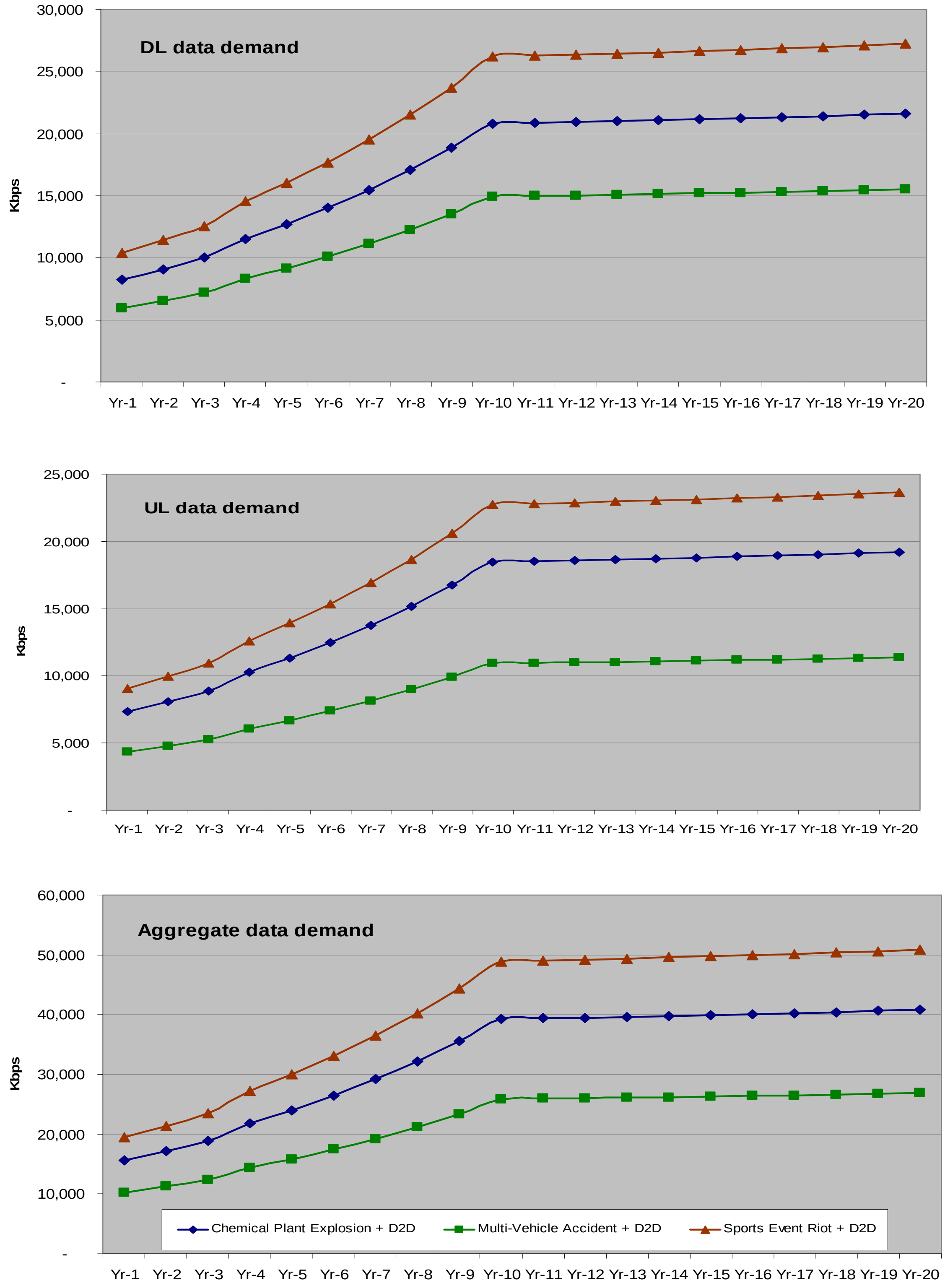

Figure 3.6: Data demand profiles for DL, UL, and Aggregate, including growth effects and day-to-day operations.

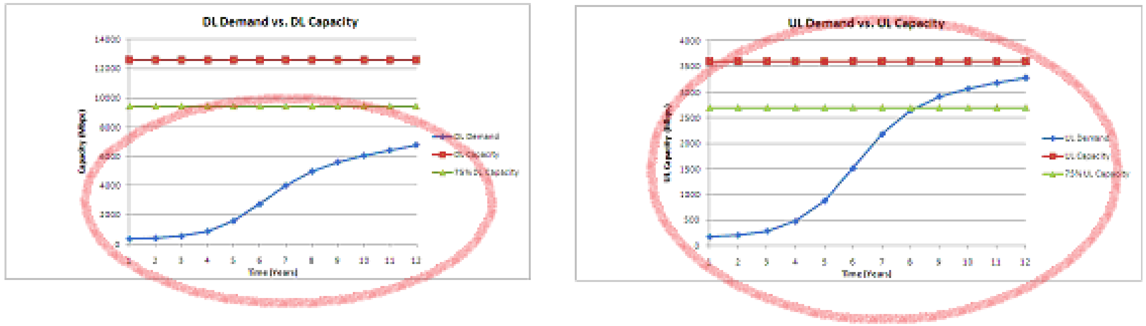

Figure 3.7: Data demand growth profile as reported by the City of New York [3]

4 Capacity model

The Capacity Model establishes how much data can be transported over an LTE system. The model treats Up-Link and Down-Link directions separately since LTE spectral efficiency is asymmetric. The 3GPP has released specifications for Rel.8 and 9, and there is on-going work to define the specifications for Rel.10 and 11. There is also substantial research activity at university and industry levels on ways to improve efficiencies. New features for LTE will one day be implemented and the benefits will be realized, perhaps not to the same extent as predicted, but we can reasonably expect the capacity to increase as the vendor community transforms the research into commercially viable products.

Some technologies, currently under development or the subject of research, were examined for their potential to increase spectral efficiency. Based on these, a hypothetical technology roadmap was established in order to quantify spectral efficiency improvements in the Capacity Model. The various technologies that were examined are described in §4.3.

In §4.4 are the basic assumptions that are considered in the Capacity Model.

4.1 Long Term Evolution (LTE)

Long Term Evolution is the latest standard for mobile wireless access from the same industry group that developed the specifications for GSM and UMTS/HSPA, namely 3GPP. LTE improves upon the performance of previous generations of wireless systems in terms of increased capacity, reduced latency, and support for multimedia applications. Its current release, Rel.8, is referred to as 3.9G. LTE-Advanced (Rel.10) with even superior performance is intended as the first release to cross the threshold into 4G. Some of the key specifications are:

- Peak downlink data rates: 326 Mbps (4x4 MIMO [1]); 173 Mbps (2x2 MIMO) in 20 MHz bandwidth.
- Peak uplink data rates: 86 Mbps with a single transmit antenna in 20 MHz bandwidth.
- Latency: 5ms or less.
- Backwards compatible with: GSM, CDMA-One, UMTS, and CDMA2000
- Able to operate in Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes.
- Able to operate in carrier bandwidths of 1.4MHz, 3MHz, 5MHz, 10MHz, and 20MHz.
- Frequency bands: as shown in Table 4.1 for FDD and Table 4.2 for TDD[*]

[*] TDD approved in Europe, China, India, Japan, Malaysia, Australia.

Table 4.1: LTE frequency bands for FDD

LTE BAND NUMBER	UPLINK (MHZ)	DOWNLINK (MHZ)
1	1920 - 1980	2110 - 2170
2	1850 - 1910	1930 - 1990
3	1710 - 1785	1805 -1880
4	1710 - 1755	2110 - 2155
5	824 - 849	869 - 894
6	830 - 840	875 - 885
7	2500 - 2570	2620 - 2690
8	880 - 915	925 - 960
9	1749.9 - 1784.9	1844.9 - 1879.9
10	1710 - 1770	2110 - 2170
11	1427.9 - 1452.9	1475.9 - 1500.9
12	698 - 716	728 - 746
13	777 - 787	746 - 756
14	788 - 798	758 - 768
17	704 - 716	734 - 746
18	815 - 830	860 - 875
19	830 - 845	875 - 890
20	832 - 862	791 - 821
21	1447.9 - 1462.9	1495.5 - 1510.9
22	3410 - 3500	3510 - 3600

Table 4.2: LTE frequency bands for TDD

LTE BAND NUMBER	ALLOCATION (MHZ)
33	1900 - 1920
34	2010 - 2025
34	2010 - 2025
35	1850 - 1910
36	1930 - 1990
37	1910 - 1930
38	2570 - 2620
39	1880 - 1920
40	2300 - 2400
41	3400 - 3600

4.2 The concept of Spectral efficiency

Spectral Efficiency (SE) is a measure of how much information can be carried in a transmission bandwidth normalized to 1Hz, expressed in bps/Hz. It is the key parameter by which to determine the capacity of a wireless network. SE is a function of the signal to noise ratio (SNR) because a higher SNR allows the signal component to occupy more states and thus carry more information. Figure 4.1(a,b) illustrates a sample constellation of signal states for 16QAM and 64QAM modulation. 64QAM can transport 50% more information than 16QAM, but due to the higher density of signal states, 64QAM requires a higher SNR than 16QAM. This is why User Element (UE) which are closer to the base station can support a higher data rate. Since SNR is lower at greater distances from the transmitter, UEs which are at the cell edge have lower data rates.

Spectral Efficiency is also affected by interference. Similarly to noise, interference reduces the space between signal states and leads to a higher probability of incorrectly detecting the instantaneous state of the received signal. In cellular networks interference is a major impairment to spectral efficiency and is the subject of significant research for ways to mitigate its negative effects on SE. However, the effort to improve SE by increasing SNR delivers correspondingly fewer gains relative to the increases in SNR since SE has a logarithmic relation to SNR. Claude Shannon in his seminal paper on the Theory of Communications [1] postulated the mathematical relationship between channel capacity and SNR. His theory is illustrated in the graph of Figure 4.2. SNR is expressed as Eb/No which is the normalized form for SNR.

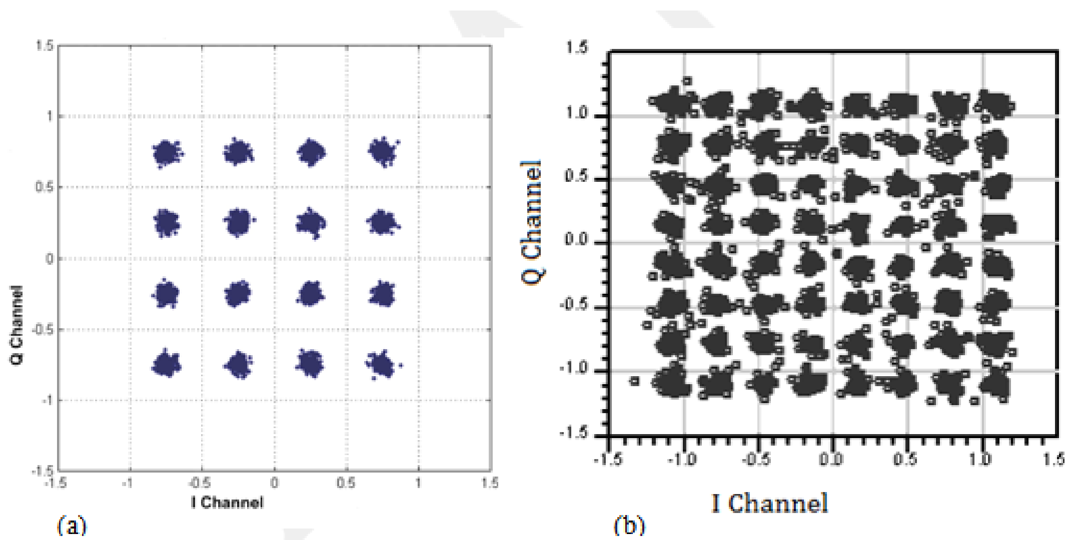

Figure 4.1: Signal state constellation diagrams for (a) 16QAM and (b) 64QAM with noise-induced impairments.

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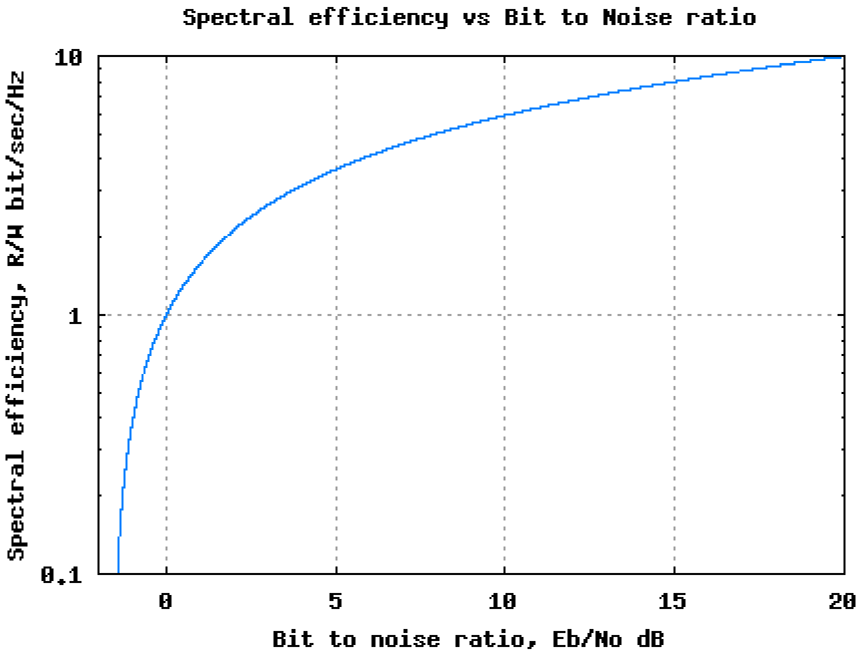


Figure 4.2: Relationship between Spectral Efficiency and Signal-to-Noise Ratio.

4.2.1 Interference effects

Inter-cell interference is one the most important factors limiting the spectral efficiency of a cell. When interference power is combined with Additive White Gaussian Noise (AWGN), the Signal to Interference + Noise Ratio (SINR) ratio is reduced. A User Element (UE) with low SINR means that it must operate at a lower modulation index to keep packet error ratios to an acceptable level for the applications used by the particular UE. A lower modulation index means that the spectral efficiency is reduced for that UE, which in turn reduces the average spectral efficiency for the cell. In essence, higher interference lower SINR lower modulation index lower spectral efficiency.

Figure 4.3 illustrates a typical case where interference triggers the hand-off of the UE from one base station (eNB) to anther eNB. As the UE moves away from its serving eNB, the signal power of the serving source reduces, while the signal power of the adjacent eNB increases. While the UE is still served by the left-hand eNB, the signal from the right-hand eNB appears as interference. Thus the UE experiences a reducing SINR (reducing spectral efficiency) as it moves towards the cell edge. The hand-off process is initiated when the SINR reaches a threshold point.

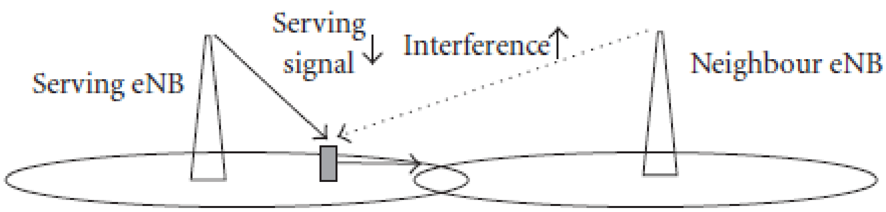
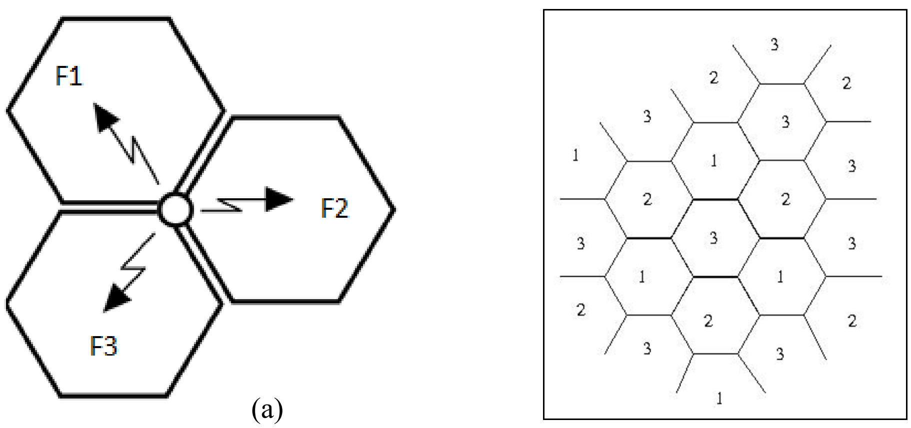


Figure 4.3: Reducing SINR as the UE moves towards the edge of the serving eNB [10].

Interference effects are more significant at cell edges and where cell sectors overlap. A typical cell would be configured into 3 or 6 sectors. Figure 4.4(a) illustrates a 3-sector cell.

One approach cellular network engineers use to mitigate interference is to assign different frequencies to adjacent sectors. In Figure 4.4(b) the Frequency Re-use (FR) factor is 3, but in practice may be as high as 7. The consequence of this approach is to assign 1/3 to 1/7 of the RF spectrum to each sector. Each sector would then have 1/3 to 1/7 of the aggregate throughput.



(a) (b)

Figure 4.4: (a) frequency assignments in a 3-sector cell with FR = 3; (b) network frequency assignments for FR = 3.

Maximizing throughput by various interference mitigation strategies is a rich area of study and will be examined further in this section. The sections that follow review some of the technologies more frequently found in technical literature and oft-cited research.

4.3 Spectral Efficiency Roadmap

Each new generation of wireless technology improves upon the capacity of the previous one. LTE, currently at Rel.8 and Rel.9, will continue to evolve new capabilities into Rel.10, 11, and beyond. Some of the new capabilities will increase spectral efficiency. The Capacity Model assumes a progressively increasing spectral efficiency. Some of the technologies currently under development or in early stages of research are discussed below. Their potential impacts on spectral efficiency are included in the Capacity Model as illustrated in Table 4.3. The SE Roadmap is specific to the Capacity Model. The actual sequence of technology deployment may differ from that shown in the table or the values of SE may also be different.

Table 4.3: Spectral Efficiency Roadmap specific to the Capacity Model.

	T0: YR1-3	T1: YR4-6	T2: YR7-9	T3: YR10-12	T4: YR13-15	T5: YR16-18	T6: YR19-20
bps/ Hz	**LTE Rel.8**	**Fractional Frequency Reuse**	**Adaptive Fractional Frequency Reuse; 4x4 MIMO**	**Multi-User MIMO**	**Cooperative Multi-Point**	**Dirty Paper Coding**	**Femto-cells Relays**
DL	0.686	0.860	1.060	1.329	1.923	2.398	2.849
UL	0.300	0.375	0.457	0.652	1.051	1.485	1.737

4.3.1 Fractional Frequency Reuse

One of the most active areas of research is to increase the throughput of LTE systems by mitigating the effects of inter-cell interference. Inter-cell interference is a dominating factor in limiting the throughput. An important goal is to reduce the FR factor to as near unity as possible. Figure 4.5 illustrates that with FR=1 the network bandwidth is essentially available in each sector. With FR=3, the network BW is divided by 3. Fractional Frequency Reuse (FFR) is made possible by the X2 communications link between LTE base stations. The mechanisms that are applied in a coordinated manner between eNBs are known collectively as Inter-Cell Interference Coordination (ICIC). ICIC-enabled FFR can achieve lower values of FR such as 3/2 as illustrated in Figure 4.6.

FR factor affects the total network capacity (TNC) as in equation (3). A lower value of FR increases total network capacity.

$$\text{TNC} = \frac{[\text{\# of cell sites}] \times [\text{\# of sectors/site}] \times [\text{SE}] \times [\text{available BW}]}{\text{FR}} \qquad (3)$$

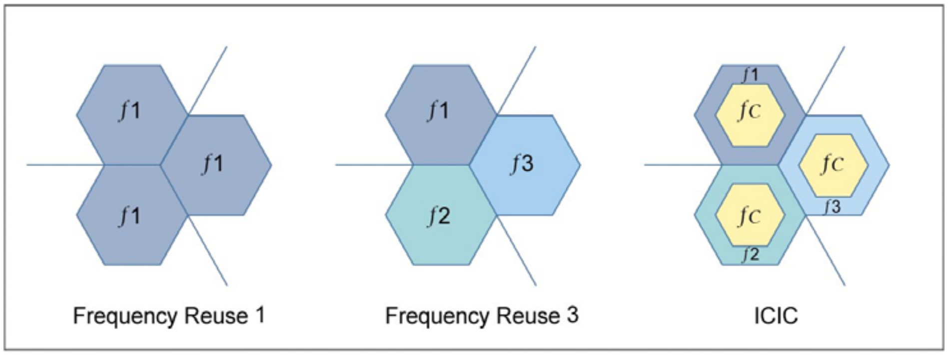


Figure 4.5: Frequency re-use plans FR=1, FR=3, and Fractional Frequency Re-Use (FFR).[11]

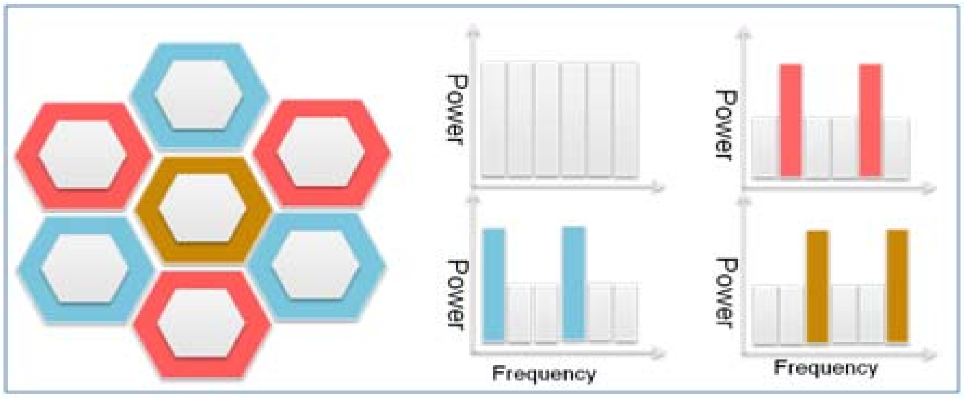


Figure 4.6: Illustration of FR=3/2 using ICIC and associated Power Bandwidth Profiles.

Adaptive Fractional Frequency Reuse (AFFR) is a closed-loop scheme that uses the Channel Quality Indicator feedback from the UE in order to dynamically adapt the scheduling, power level, and channel assignment to the UEs. In addition, AFFR coordinates the actions among all the adjacent eNBs. Simulation results indicate that near unity FR can be obtained. See Table 4.4 for a comparison of simulated LTE sector throughputs for N=1 and AFFR. In the cited article, N ≡ FR. AFFR achieves 99% of the throughput of FR=1.

Table 4.4: comparison of simulated LTE sector throughputs for N=1 and AFFR [12]

	FR =1	AFFR
Sector Throughput (Mbps)	8.01	7.89

4.3.2 Multiple Input Multiple Output (MIMO) techniques

MIMO techniques are used to improve SE. One MIMO scheme, referred to as Spatial Multiplexing (SM), can be used to transmit multiple information streams simultaneously from eNB to the UE. MIMO is also used to cancel interference on streams carrying the same information. LTE Rel.8 is able to dynamically adapt the MIMO scheme in order to maximize throughput using feedback from the UE. This is known as Closed Loop MIMO (CL-MIMO). Figure 4.7 illustrates 2x2, 3x2, and 4x4 MIMO configurations.

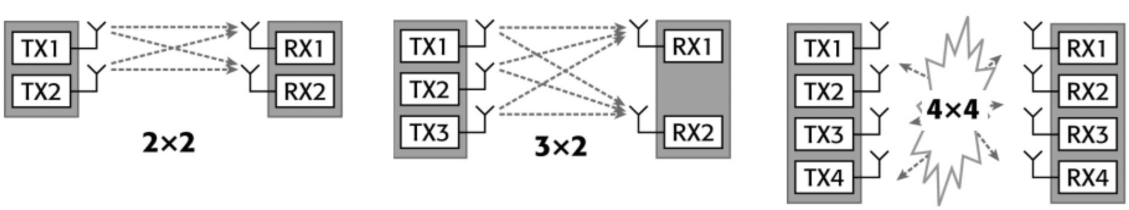


Figure 4.7: Transmitter and receiver arrangements for 2x2, 3x2, and 4x4 MIMO.

Table 4.5 refers to SU-MIMO (Single User MIMO). In this arrangement, the eNB transmits on multiple antennas, whereas the UE transmits on one antenna but receives on multiple antennas. The SE for 2x2 and 4x4-MIMO is given in Table 4.5.

Table 4.5: Average spectral efficiencies for down-link and up-link for 20MHz bandwidth [13] [14]

Down-Link	Spectrum Efficiency		Mean User Throughput		Cell-Edge User Throughput		
	[bps/Hz/cell]	x UTRA	[bps/Hz]	x UTRA	[bps/Hz]	x UTRA	
E-UTRA 2x2 SU-MIMO	1.56	x3,0	0,16	x3,0	0,04	x2,3	Rel.8
E-UTRA 4x4 SU-MIMO	2.41	x4,6	0,24	x4,6	0,08	x4,8	Rel.10

Up-link	Spectrum Efficiency		Mean User Throughput		Cell-Edge User Throughput		
	[bps/Hz/cell]	x UTRA	[bps/Hz/user]	x UTRA	[bps/Hz/user]	x UTRA	
E-UTRA 1x2	0.681	x2.2	0.068	x2.2	0.0044	x2.0	Rel.8
E-UTRA 1x4	1.038	x3.3	0.104	x3.3	0.0094	x4.2	Rel.10

Figure 4.8 compares average spectral efficiencies across different channel bandwidths. The spectral efficiency for 10MHz bandwidth is ≈98% of that for 20MHz bandwidth.

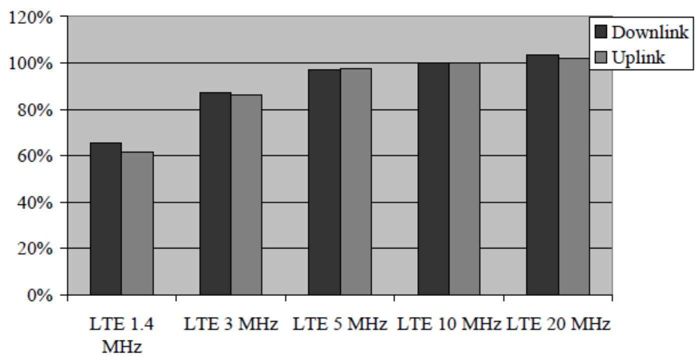


Figure 4.8: Comparison of spectral efficiencies relative to 10MHz channel bandwidth[15].

4.3.3 Multi-User MIMO Uplink

Multi-User MIMO-UL (MU-MIMO-UL) is the equivalent of spatial diversity in the Uplink direction. As in the previous case, interference is estimated from the received signals using Successive Interference Cancellation . Figure 4.9 illustrates a block diagram for the MU-MIMO-UL. Note the feedback from the UE towards the eNB.

This technique can provide ≈ 70% improvement in UL spectral efficiency relative to LTE Rel.8. Refer to Figure 4.10 for a comparison of various techniques being researched by Deutsche Telkom Laboratories to improve SE.

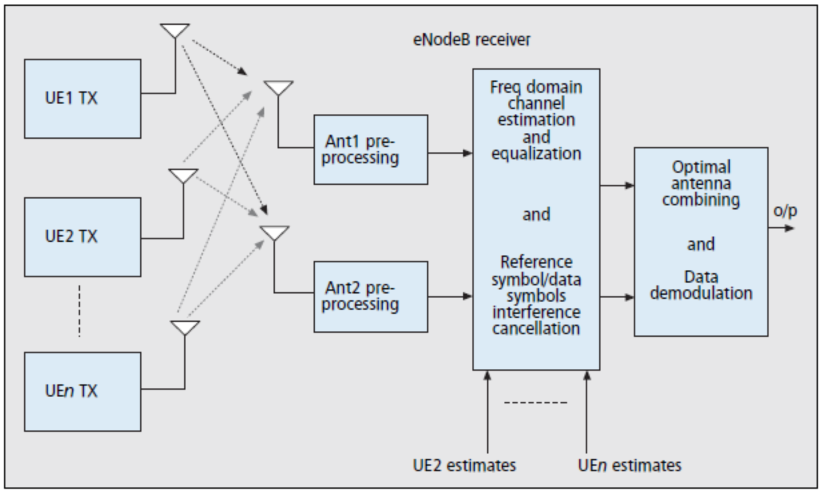


Figure 4.9: MU-MIMO-UL block diagram [12]

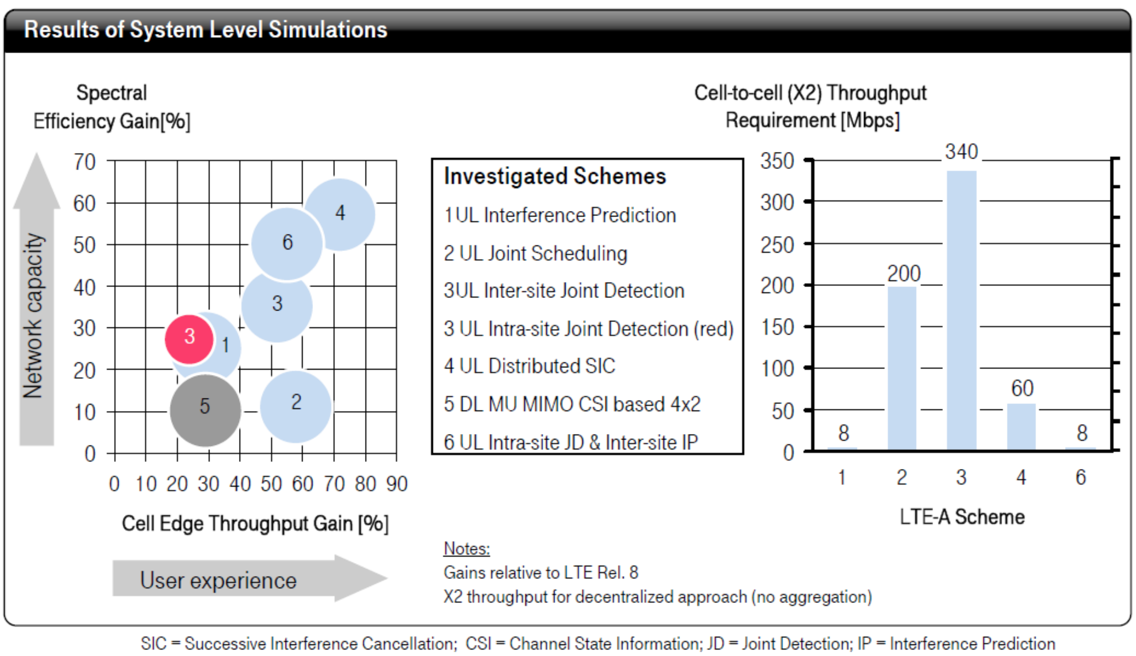


Figure 4.10: Spectral Efficiency Improvements under study. [17]

4.3.4 Multi-User MIMO Downlink, Coordinated Multi-Point

Coordinated Multi-Point (CoMP) with Organized Beam-forming improves the SE at the cell-edge. The average cell throughput is also increased. In organized beam-forming eNBs exchange scheduling and beam-forming information so that multi-site scheduling can be performed. This reduces inter-cell interference. Figure 4.11 illustrates the principle of CoMP. Simulation shows that SE in the DL can be improved by up to 1 bps/Hz using this technique..

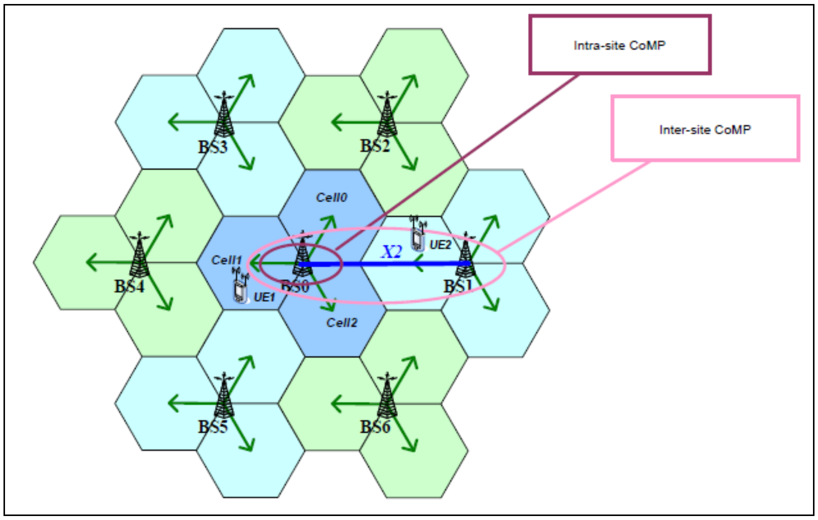


Figure 4.11: Coordinated Multi-Point conceptual diagram [18].

4.3.5 Dirty Paper Coding

Dirty Paper Coding (DPC) is a technique whereby the data is pre-coded at the transmitter using interference information fed back from the UE on the side channel referred to as Channel State Information (CSI). In essence, the transmitter adapts to the interference. Information theorists have presented mathematical arguments that DPC with CSI feedback can approach the performance of Gaussian Noise channels, thereby almost completely cancelling the interference. [19]

Other researchers arrived at numerical results which indicate that DPC can improve the SE of 2x2 MIMO systems by up to 0.8 bps/Hz, and improve the SE of 4x4 MIMO systems by up to 1.35 bps/Hz. [20]

4.3.6 Femto-cells and decode/forward Relays

Femto-cells and relays are used to increase the capacity in a specific location such as malls and conference centres. Femto-cells off-load traffic from the macro node. Relays are used to fill in gaps in coverage from the macro node. See Figure 4.12 for an illustration of the use of Femto cells and Relays.

Both approaches increase capacity although it can be difficult to quantify in general terms since the actual gain is implementation-specific. The Capacity Model assumes a 10% increase in UL and DL SE through the use of Femto-cells and Relays.

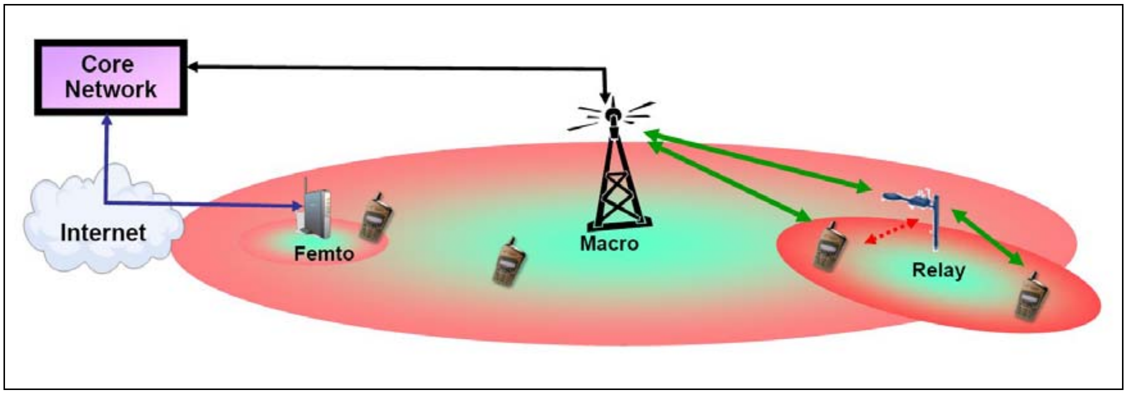


Figure 4.12: Femto cells and Relays used to augment the capacity of a Macro cell.

4.4 Input data and assumptions

The following input data and assumptions and have been used in the Capacity Model.

1. Spectral efficiencies stated in Table 4.5 represent the average of reported results from a number of LTE system and sub-system vendors. They are:
    - Alacatel-Lucent
    - Huawei
    - InterDigital
    - Motorola
    - NEC
    - Nortel
    - Nokia-Siemens
    - Samsung
    - Qualcomm
    - Texas Instruments

2. The introduction of new technology into a network will likely encounter implementation issues and the Capacity Model assumes that there will be a gap between anticipated SE improvements vs. realized improvements. However, the Model also assumes that the gap will reduce in time as the technology matures and implantations issues are worked out. Therefore, the Model applies a de-rating factor to the SE according to the profile: 33%, 25%, 10%, 5%. This means the SE improvement is de-rated by 33% when first introduced, 25% after 3 years, 10% after 6 years, and 5% after 9 years. The un-derated SE values are in Table 4.6. These values are not used in the Capacity Model, but serve as baseline from which de-rating factors were applied.

3. New technology is introduced in the LTE network in 3-year intervals. Even though some technology could be available sooner than it is introduced in the Model, it is assumed that budgets will constrain the ability to procure and update existing facilities. Another assumption is that public safety agencies will be somewhat conservative in upgrading. There will also be some time spent to pilot the upgrades before introducing them into live networks.

4. It is assumed that an incident is a localized event that would be contained geographically within one sector.

5. For FR=3 and FFR, an overlap of 25% is assumed between adjacent sectors. When AFFR is introduced the Model approaches FR=1 and as such no additional capacity is factored into the Model due to overlapping sectors since closed-loop ICIC mechanisms are intended to avoid duplicate scheduling of UEs.

6. SE is a dependent upon the speed of the UE. The Model assumes that the speed of most responders is <3kph at the scene of the incident. LTE SE is higher for lower speeds.

Table 4.6: Un-derated Average Spectral Efficiency (b/s/Hz/sector) not used in the Capacity Model.

	T0	T1	T2	T3	T4	T5	T6
DL	1.529	1.529	2.362	2.362	3.543	3.543	3.897
UL	0.667	0.667	1.017	1.729	1.729	2.729	3.002

5 RF spectrum requirements

This section discusses the results of correlating the data demand with capacity, which is the RF spectrum (bandwidth) required for public safety. It presents the nominal bandwidth and the error introduced by the uncertainty of future predictions. In §5.2 a sensitivity of the bandwidth is analyzed as a function of two key variables. There is also an analysis which presents to what degree public safety would have to back off their requirements in order for 5+5MHz to satisfy the reduced requirements.

Figure 5.1 is an illustration of the growth of data demand (from Figure 3.6) compared to the growth of Spectral Efficiency (from Table 4.3), with YR1 as the reference point. The difference in the growth rates is notable. Given the pressures that commercial carriers face due to the exponential nature of the growth in demand they are experiencing (see Figure 3.5) from commercial users, with no sign of abating, it is expected that they will continue to invest in new technologies to cope with the anticipated growth in data demand. In fact, there is an intense level of research into improving the spectral efficiency of mobile broadband networks 10. The cited article cites a further 64 references.

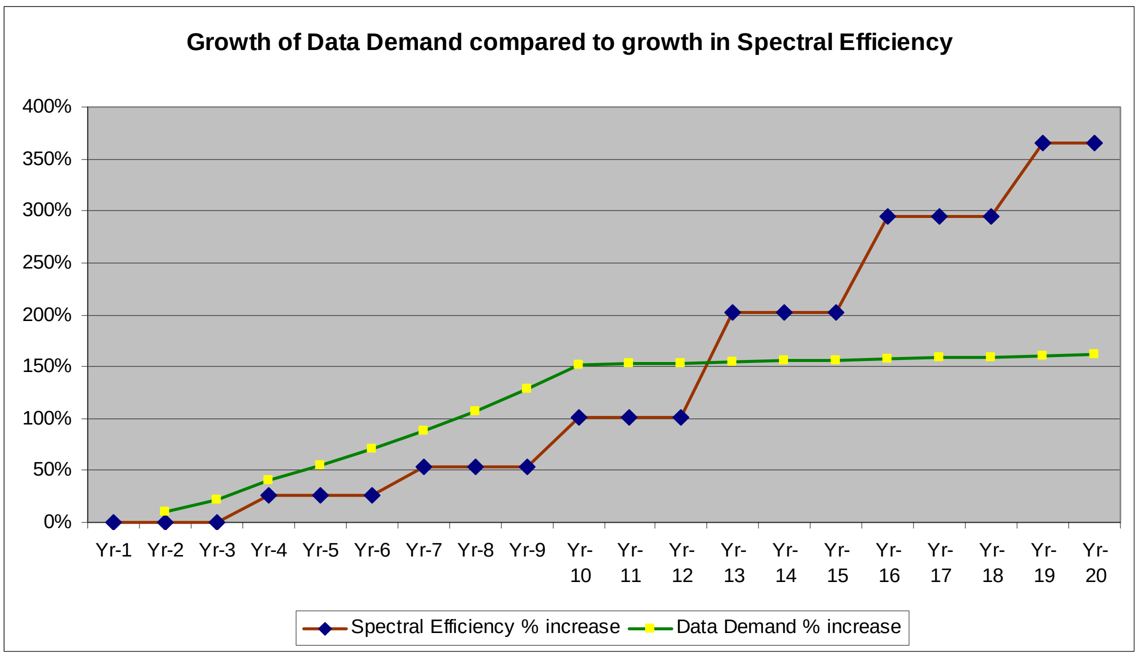


Figure 5.1: growth of data demand compared to the growth of spectral efficiency

It is very difficult to predict what will happen in the future, especially over a 20-year period. Even though it may be easier to predict what the demand could be in the next 1 or 2 years, or what technology would likely be developed in the near-term, there is nonetheless an uncertainty in whatever prediction is made. The degree of uncertainty becomes larger for prediction-horizons that are further out in time.

The Capacity Model has factored an estimating error into the predictions for RF spectrum. Figure 5.2 shows the same growth projections as in Figure 5.1, but also shows the effect of uncertainty using a 10% annually compounded estimating error for demand and the same for SE.

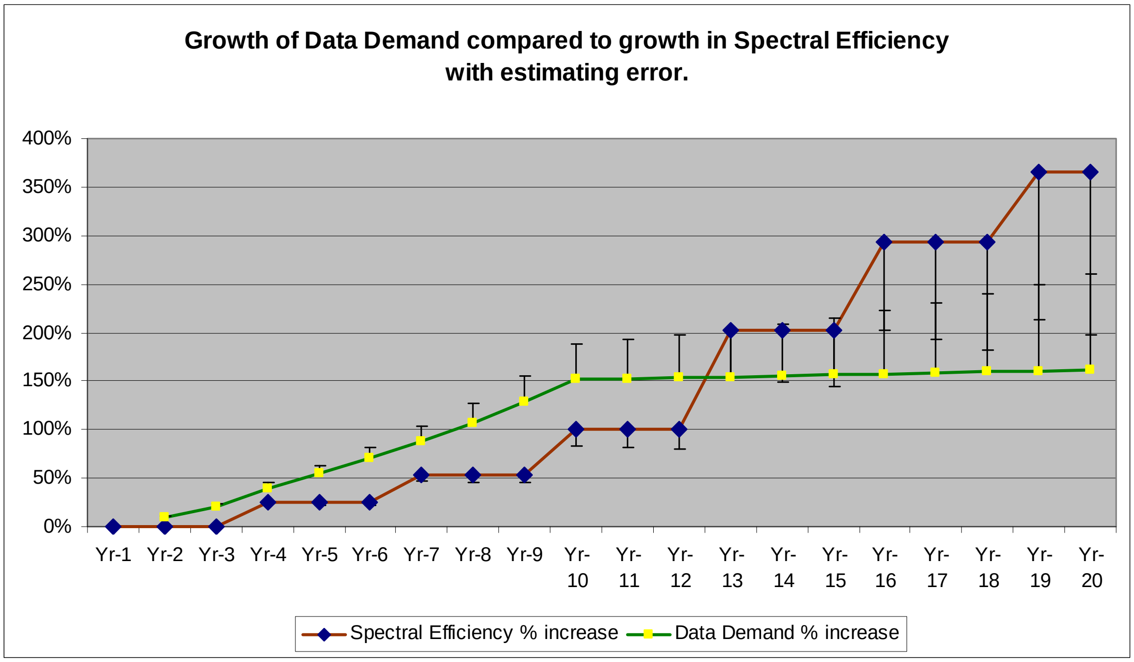


Figure 5.2: Growth of demand and SE with 10% annually compounded estimating error applied to demand and SE.

5.1 RF spectrum requirements – results

This section presents the bandwidth requirements using the inputs below. Alternative scenarios based on sensitivity to SE and SG are examined in §5.2.

(i) Data Demand profiles as shown in Figure 3.6,

(ii) SE values from Table 4.3,

(iii) Estimating error due to uncertainty of predicting future events as shown in Figure 5.2.

Equation (4) is used to calculate the aggregate required bandwidth (BWr):

$$BWr\ (MHz) = \frac{\text{DL Data Demand (kb/sec)}}{\text{DL SE (b/sec/Hz)} \times 1000} + \frac{\text{UL Data Demand (kb/sec)}}{\text{UL SE (b/sec/Hz)} \times 1000} \qquad (4)$$

Figure 5.3(a,b,c) shows the RF spectrum required for an LTE network to provide sufficient throughput to support the data communications needs for the 3 incident case studies, namely Chemical Plant Explosion, Multi-Vehicle Accident, and Sports Event Riot, respectively. The graphs also show the influence of estimating error. In each graph two curves are shown: one curve for the RF Spectrum required to support the aggregate (UL+DL) data demands for the specified incident, and one curve for the aggregate Usable BW based on a 10+10MHz allocation.

Since an incident is a localized event, only one sector's capacity is available, plus the overlap from the adjacent sector. At the outset, the usable capacity within one sector in either UL or DL direction is the Network capacity (based on 10+10MHz) ÷ 3 (FR) x 1.25 (sector overlap) x 75% (frequency re-use efficiency). If 20MHz is allocated, then only 6.25MHz is actually usable in a sector until further improvements in Frequency Reuse are implemented. The Model assumes that, over time, 95% of the Network capacity becomes available within a sector.

The period where RF spectrum requirement increases (YR1-10) is dominated by investments in LTE UE for the User community. Once the user community has been fully outfitted with LTE UE devices, the subsequent period (YR11-20) is dominated by investments in the LTE eNB infrastructure. These investments are characterized as improvements in spectral efficiency. The effect of introducing improvements in SE can be seen in the graphs as step-wise reductions in required bandwidth.

The following conclusion can be drawn from Figure 5.3:

1. Improvements in spectral efficiency outpace the growth in demand and so it is expected that the applications will require progressively less bandwidth when the penetration of LTE devices in the public safety community has saturated and the investments are turned towards accelerating the improvements in the infrastructure. According to Figure 5.3, the saturation point is at YR10.

2. 10+10MHz (UL+DL) is insufficient spectrum in both UL and DL to meet the data communications needs of public safety during commonly recurring incidents, given the anticipated spectral efficiency of LTE for the near-to-mid term.

3. When LTE technology becomes more spectrally efficient, 10+10MHz could be sufficient spectrum to support the data communications requirements for less severe incidents. This may occur beyond YR15 for benign incidents such the multi-vehicle accident.

4. When estimating error is included, 10+10MHz is insufficient spectrum for all cases throughout the 20-year horizon.

5. There is a significant gap between required spectrum and usable spectrum. During the events of the nature considered in this study, public safety will most likely not be able to use all the applications they identified, nor in the manner in which they expect to use them. In order to deal with situations where demand exceeds capacity bandwidth management policies will need to be established, access privileges would need to be asserted, controlled and monitored, and the use of applications will need to be prioritized. The policies and procedures could be re-visited over time as greater efficiencies are introduced into the network.

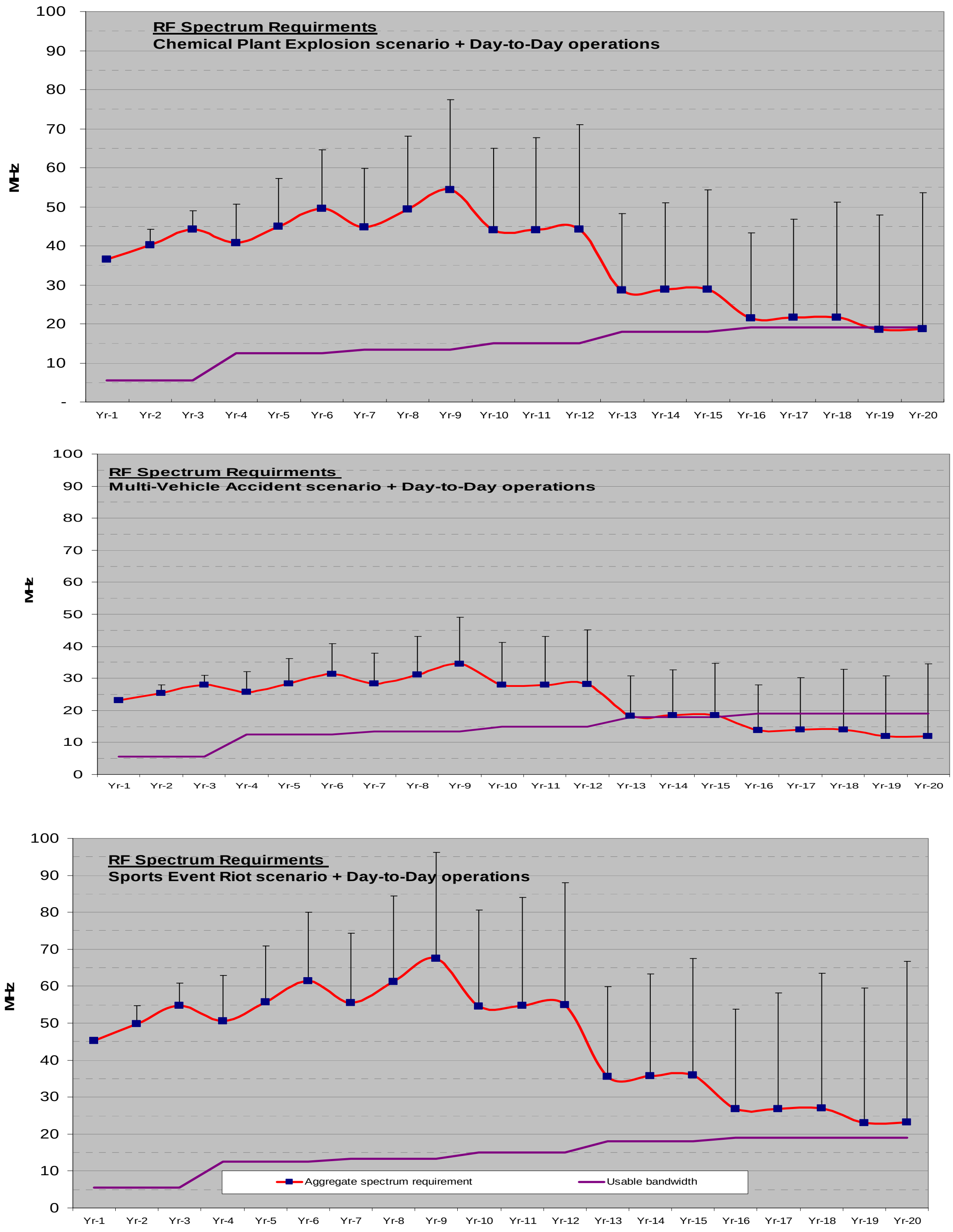


Figure 5.3: Aggregate (UL+DL) RF Spectrum requirements

5.2 Alternative scenarios

The effects of varying some key parameters on RF spectrum requirements will be examined in this section. Two cases examine the effects of aggressive approaches to dimensioning the network. Of course, the results show that less RF spectrum is needed. However, the conclusions of §5.1 remain essentially the same. The only exception would be for less severe incidents, where 10+10MHz would likely be sufficient when technology improves, but 5+5MHz would likely be insufficient.

A third scenario examines how aggressively the parameters need to be adjusted in order to reduce the data demand such that all three incident case studies can be fulfilled with 5+5MHz of RF spectrum.

5.2.1 Accelerated introduction of higher spectral efficiency.

In the Model, de-rated SE values are used to account for slower adoption of new technology in public safety networks due primarily to more restrictive budgets in municipalities or government than in commercial carriers. Public safety will likely have a longer vetting process before adopting new technologies. There would also be less economic/business pressure to upgrade the technology in public safety than in commercial networks.

If the public safety network were to be upgraded at the same pace as a commercial network, this scenario examines the effect of optimistic values of spectral efficiency on required RF spectrum. The un-derated SE values of Table 4.6 are reproduced below. The resulting required RF spectrum is shown in Figure 5.4 (a,b,c).

(copy) Table 4.6: Un-derated Average Spectral Efficiency (b/s/Hz/sector) <u>not</u> used in the Capacity Model

	T0	T1	T2	T3	T4	T5	T6
DL	1.529	1.529	2.362	2.362	3.543	3.543	3.897
UL	0.667	0.667	1.017	1.729	1.729	2.729	3.002

5.2.2 Lower intensity of use of the network.

A key factor in the data demand model is the over-booking factor (OBF). Since first responders will make more intense use of their data communications tools during an incident than during non-emergency situations, the Model uses an OBF ratio of 4:1 for streaming video and interactive applications. Commercial users also make more intense use of the network during emergencies. During these events typical OBF ratios of 20:1 or 50:1 for commercial users no longer apply.

Nevertheless, in this scenario the OBF for streaming video and interactive data is doubled from 4:1, as in the Model, to 8:1. The results for the three incidents case studies are illustrated in Figure 5.5(a,b,c).

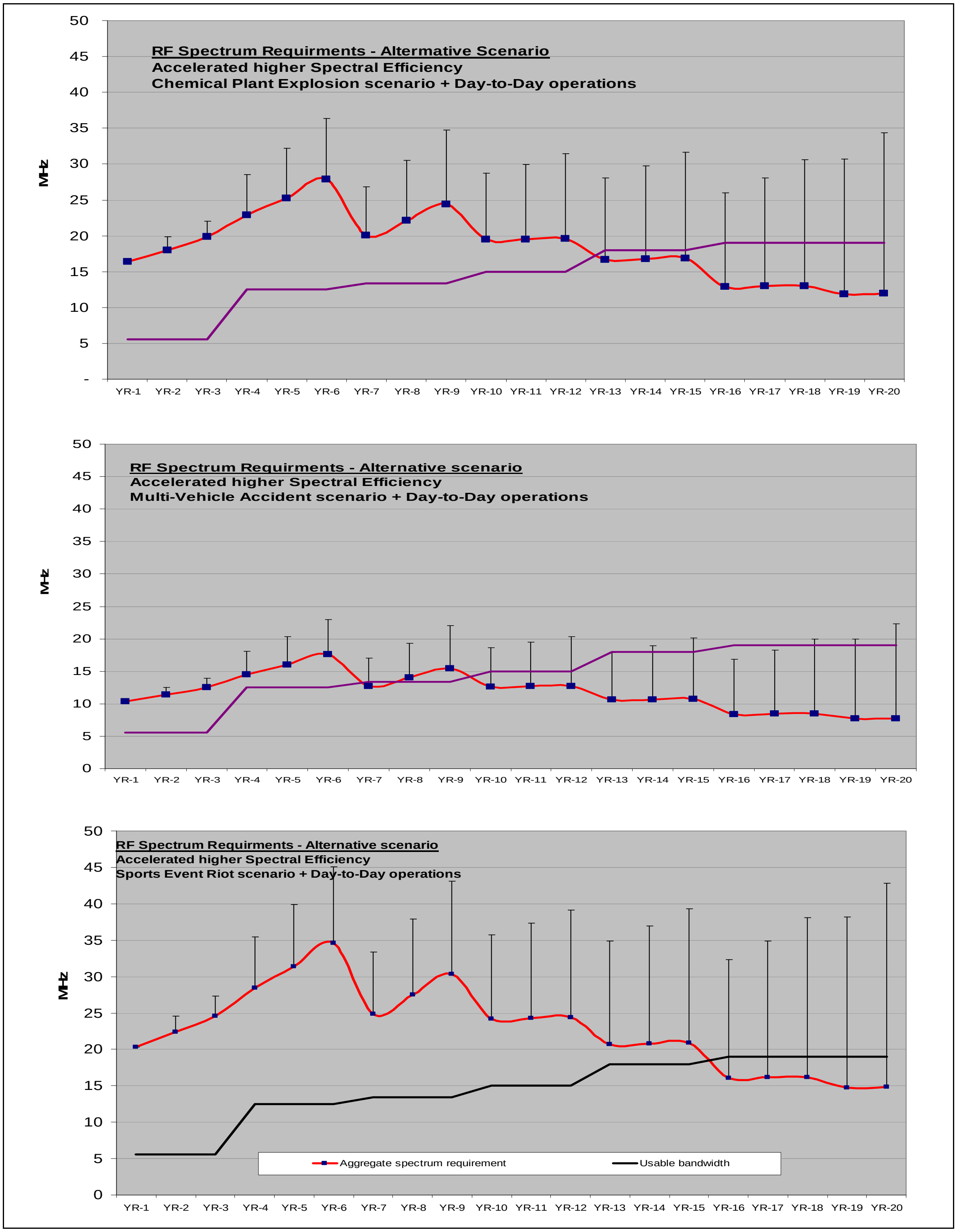


Figure 5.4: Aggregate (UL+DL) RF spectrum requirements considering accelerated improvement in SE.

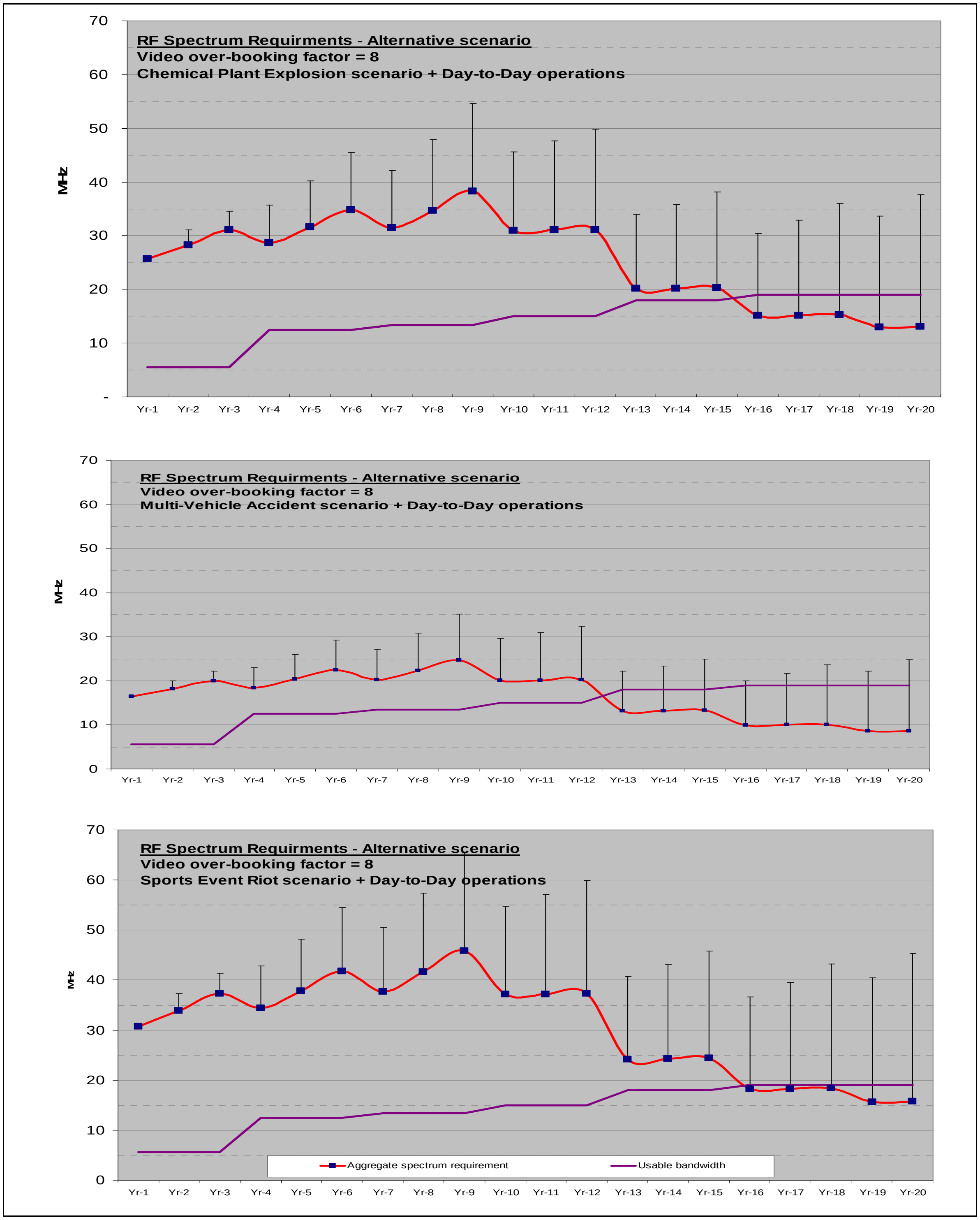


Figure 5.5: Aggregate (UL+DL) RF spectrum requirements considering aggressive OBF.

5.2.3 Level of compromise required to fit into 5+5MHz

Three parameters are simultaneously varied in order to determine how far public safety would have to back off from their requirements in order to fit into 5+5MHz of spectrum. The three parameters are:

- Video data rate
- Over-booking factor
- Spectral efficiency

In Figure 5.6(a,b,c) are graphs of RF Spectrum requirements which can be satisfied with 5+5MHz allocation. In order to fit into this profile, the following adaptations to the Model were made.

a) Video data rates were reduced by 50% compared to the values in the Model.

b) Over-booking factor was set to 20:1

c) Spectral efficiency was set to the un-derated values as in §5.2.1.

This means that in order for the data demands of the three incident case studies to be satisfied with 5+5MHz of the spectrum,

1. Video would not be usable to distinguish people, labels on chemical containers, or other similar level of detail.

2. The use of the network would have to be scaled back so that 1 in 20 users would be able to send or receive data simultaneously versus 1 in 4. One in 20 is the same OBF used by commercial carriers to dimension their networks for consumer-grade service.

3. New technology would need to be evaluated and implemented by public safety at the same pace as commercial carriers.

Item 3 above is based on optimistic expectations for technology roll-out. Items 1 and 2 would restrict the ability of first responders to make beneficial use of the network during emergencies. They would have to make significant compromises compared to how they intend to use a mobile broadband network if only 5+5MHz of spectrum would be available.

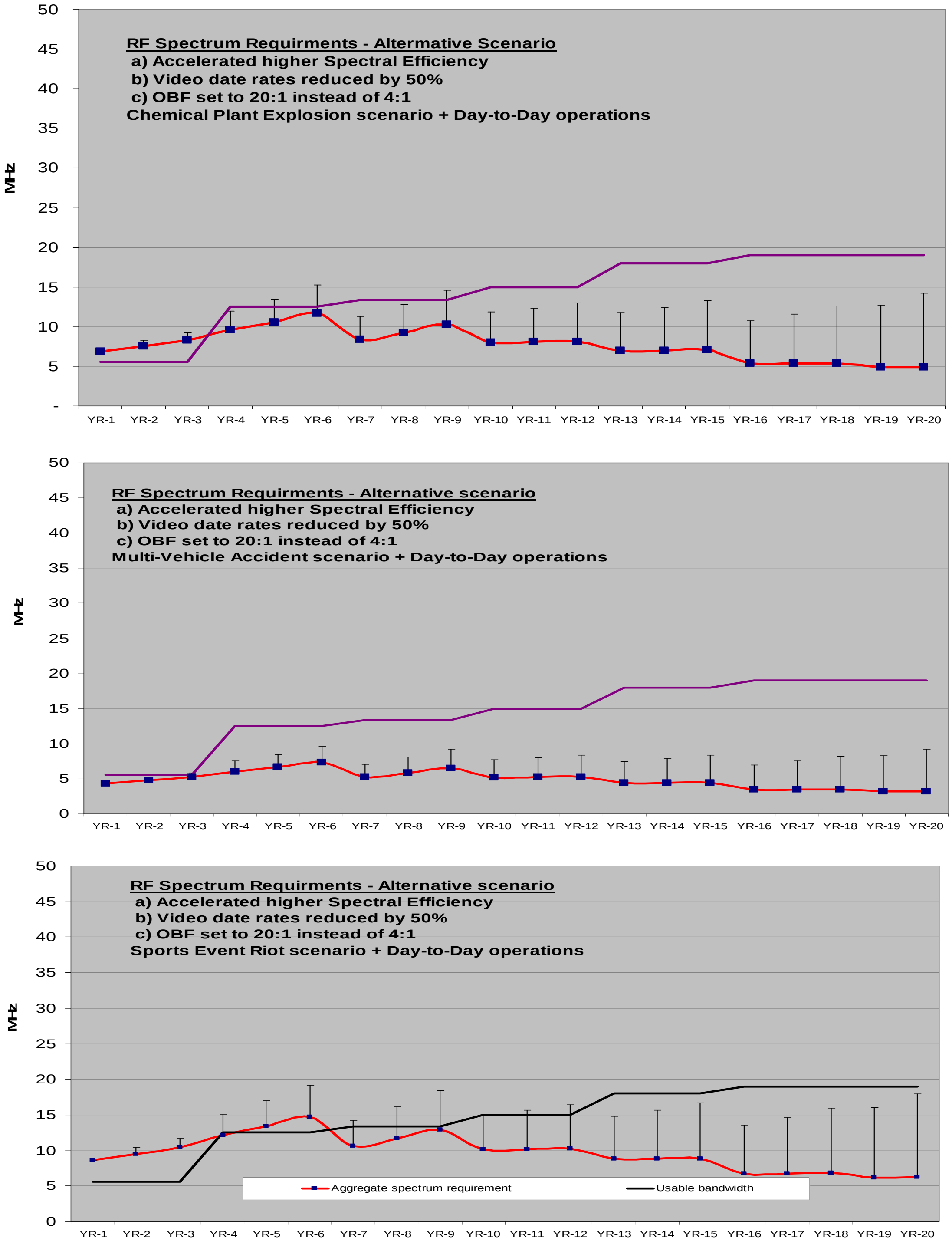


Figure 5.6: Level of compromise needed to fit spectrum requirements into 5+5MHz (UL+DL)

6 Conclusion

The question of how much bandwidth a mobile broadband network requires to meet the needs of public safety is answered by examining how the public safety community would use the technology and what throughput the technology offers.

This study followed a similar approach that others have taken to establish the anticipated usage. That is, to determine the data demand for incident scenarios of emergency events which are recurring in nature. Representatives from Canadian public safety stakeholders provided their views on how they anticipate using a mobile broadband network for three scenarios and how they would use the network in the course of their day-to-day operations.

The throughput requirements for each application that public safety could use were established based on empirical results from other studies and in consultation with the Communications Research Centre of Canada. The data demand profiles were determined from the anticipated usage and the applications data rates.

Correlating the data demand with the spectral efficiency of the mobile broadband network yields the required bandwidth. The analysis is performed for a 20-year horizon. LTE is the technology used in the study.

This study attempts to present a balanced perspective on demand and on capacity. It is unique in examining the effects of anticipated advances in technology to improve spectral efficiency over time and ways to manage high data-rate traffic such as video. The introduction of estimating error into the model is an innovative approach to quantify uncertainty of predicting future demand and capacity.

The key conclusions that are derived from this study are:

a) 10+10MHz is insufficient bandwidth to support the needs of public safety in the 10-15 year horizon.

b) Improvements in spectral efficiency will likely outpace public safety's demand for data and as a consequence, the requirement for bandwidth should begin to attenuate beyond YR10, which is the point when penetration of LTE devices in the public safety community is expected to saturate.

c) Despite the rapid pace of technical innovation, the ability to meet the needs of public safety with 10+10MHz of spectrum in a distant future, ie beyond 15 years, is not evident, but it is likely that 10+10MHz will not be sufficient at that time either..

In anticipation of being granted 20MHz of spectrum, and for the foreseeable future, congestion management will be an essential component of the mobile broadband network. The public safety community should develop policies and procedures, and make use of appropriate bandwidth management technology in order to avoid congestion-related issues during emergency situations.

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In response to a request for technical advice by Public Safety Canada on behalf of national public safety stakeholders, the Centre for Security Science conducted a technical assessment of the 700 MHz spectrum requirements for broadband mobile data communications for public safety and security. The impetus to this assessment relates to the upcoming Industry Canada call for consultation SMSE-018-10. The goal was to determine how much spectrum is required to meet the needs of the public safety community for mobile broadband wireless data communications within a 20-year time frame. The data demand for recurring emergency situations was modeled through an interactive process with active participation from Canadian public safety stakeholders. In addition, the capabilities of LTE technology to support the data demands were also modeled. The results show that the amount of bandwidth required to satisfy the needs of public safety is greater than 20MHz in the near-to-mid term, and likely to also exceed 20MHz in the long term, despite advances in technology. This result is based on an analysis that applies relatively conservative estimates for the growth in demand for mobile data communications for public safety and security applications, and relatively aggressive estimates for the rate of technological improvement of spectrum efficiency projected into the future.

En réponse à une demande de conseils techniques faite par Sécurité publique Canada au nom des intervenants nationaux de la sécurité publique, le Centre des sciences pour la sécurité a effectué une évaluation technique des besoins de la fréquence de 700 MHz pour la transmission mobile à large bande de données destinée à la sécurité publique. C'est l'appel de consultation SMSE-018-10 que lancera bientôt Industrie Canada qui a motivé l'exécution de cette évaluation. L'objectif consistait à déterminer quelle part du spectre est requise pour répondre aux besoins du milieu de la sécurité publique pour la transmission mobile de données à large bande au cours des 20 prochaines années. La demande en données pour les situations d'urgences récurrentes a été modélisée à l'aide d'un processus interactif auquel les intervenants de la sécurité publique du Canada ont participé activement. Il y a de plus une modélisation des capacités de la technologie LTE pour répondre aux demandes de données. Les résultats démontrent que la part de la bande passante nécessaire pour répondre aux besoins de la sécurité publique est supérieure à 20 MHz à court et à moyen terme, et dépassera aussi probablement 20 MHz à long terme, et ce, malgré les progrès technologiques. Ce résultat repose sur une analyse ayant recours à des évaluations relativement prudentes de la croissance de la demande pour la transmission mobile de données à des fins de sécurité publique, ainsi qu'à des évaluations relativement ambitieuses du degré d'amélioration technologique de l'efficacité spectrale dans le futur.

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Emergency, management, planning, communication, Interoperability, 700 MHz, Broadband Communication, LTE, Long Term Evolution, video, public safety network, spectrum, allocation, data, mobile, technical, assessment.