Operator Spectrum Requirements for Mobile Broadband

February 26, 2011
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Executive Summary

This report analyzes operator spectrum requirements to meet the exploding mobile-broadband market opportunity, looking closely at the crucial role of the 700 MHz band for Canadian operators to address growing data demand. Data revenues are expected to exceed 25% of total operator revenues in 2010, representing more than $3 billion of revenue. This market is being driven by a combination of factors including powerful new devices such as smartphones and tablets, new mobile applications, and fast networks. Users are engaging in ever more bandwidth-intensive applications, particularly ones that have video content. Other drivers in this market include users who are making a mobile connection their only connection in what is called fixed-mobile substitution, more network-enabled devices, increasing computing speeds, gaming, higher screen resolution, using phones as Wi-Fi hotspots, embedded modems, and flexible pricing plans.

The amount of capacity in wireless networks depends on a variety of factors, but, in general, mobile-broadband networks have significantly lower capacity than fixed-broadband networks. Capacity can be calculated by assessing the spectral efficiency of different wireless technologies, a value that is represented in bits-per-second-per-Hertz of spectrum (bps/Hz). While new technologies such as LTE are spectrally more efficient than prior technologies, all wireless technologies are reaching the Shannon bound, a law that dictates the maximum spectral efficiency that a technology can achieve relative to noise. In other words, capacity constraints will only be partially addressed with new technology.

By knowing the radio-channel size and the spectral efficiency of the wireless technology, one can estimate the aggregate capacity of a cell site. The capacity values are relatively low. Even in 20 MHz of spectrum, LTE only has a downlink aggregate capacity of 15 Mbps in a cell sector, a capacity that eight users can consume with a 2 Mbps video stream each. This same cell sector could have close to 1,000 subscribers in an urban environment such as Toronto.

By examining market trends with respect to the adoption of different device types, the amount of data likely to be consumed by each device, the number of subscribers in each coverage area, and by estimating network capacity, Rysavy Research has developed a spectrum demand model that forecasts the amount of spectrum that an operator such as Rogers Communications will need to address its growing subscriber base and growing data demand. This spectrum-demand model predicts that Rogers will experience a spectrum shortfall this decade. An alternative spectrum-scaling model considers the amount of spectrum Rogers has already deployed, and scales this based on increasing demand, improving spectral efficiency, and cell site densification. This alternate scaling model confirms that Rogers, despite its current spectral holdings, will experience a spectrum shortfall this decade. Gaining additional capacity through 700 MHz spectrum will be critical.

1 Source: Rogers Communications’ market analysis.
The consequences of insufficient spectrum are dire. As networks become more congested, applications perform unreliably and unpredictably. Ultimately, users will stop using the service since they cannot depend on it.

Beyond capacity, the 700 MHz band will also be crucial for providing ubiquitous coverage. The 700 MHz band is the only low-band spectrum that Rogers can use to implement LTE on a widespread basis in the near term. Finally, the 700 MHz band is becoming the default North American LTE band. To facilitate roaming and to harness economies of scale, Canadian operators such as Rogers need access to this band for LTE. The result will be the widest availability and array of LTE technology, devices, and features, and it will be the focus of ongoing development and support for years to come.


Introduction

This report is an analysis of operator spectrum requirements to meet the exploding mobile-broadband market opportunity. In particular, it examines the role of the 700 MHz Band in this market and the importance of this band to Canadian operators.

This report has been sponsored by Rogers Communications. The analysis, however, pertains equally to all operators and the mobile-broadband market in general. This report responds to some of the questions raised in the Industry Canada 700 MHz Spectrum Consultation process as described in the plan “Consultation on a Policy and Technical Framework for the 700 MHz Band and Aspects Related to Commercial Mobile Spectrum,” November 30, 2010.

Operators are pursuing all avenues for expanding capacity including the deployment of additional cell sites, offloading onto alternate networks such as Wi-Fi and femtocells, using spectrally more efficient technologies such as 3GPP Long Term Evolution (LTE), and phasing out less efficient technologies through incentives to subscribers to upgrade their handsets. Ultimately, however, the industry critically needs more spectrum. Forthcoming spectrum auctions in Canada for the 700 MHz band and the 2.6 GHz band represent important steps in making more spectrum available.

As this report shows, it is vital that all Canadian operators be given access to the 700 MHz auction. Whatever current spectrum any operator may already hold, the nature of the mobile-broadband market is that it will inevitably exhaust whatever capacity is offered. In addition, the 700 MHz band is important, because its propagation characteristics enable a cost-effective deployment approach for widespread coverage including rural areas. Finally, the 700 MHz band is likely to be the most common initial band for LTE coverage in North America, and is thus important for near-term implementation, roaming, and for low-cost devices due to economies of scale.

This report covers the mobile-broadband market, application demands and their consumption of available capacity, spectrum and capacity, spectrum utilization, spectrum need, the effects of insufficient spectrum, coverage requirements, and 700 MHz as the North American LTE band. Appendix A provides an overview of modern wireless technologies, architecture, advanced radio methods, and details on specific technology families. Appendix B analyzes Roger Communications’ specific spectrum requirements.

Mobile Broadband Market

The mobile-broadband industry is continuing to grow at a rapid rate and already represents a tremendous source of revenue. In Canada, data revenue as a percentage of network revenue was 14.8% in 2008 and 19.7% in 2009. 2 At the end of Q4, 2010, Rogers reported that wireless data revenue was

2 Source: Rogers Communications’ market analysis.
31% of wireless network revenue.\(^3\) At that level, data revenue for the industry will exceed $3 billion. Meanwhile, in the U.S., mobile-data service revenues were expected to exceed $50 billion in 2010.\(^4\) A number of factors are acting in concert to drive the industry including faster networks enabled by new technologies, powerful new devices such as smartphones and tablets, and hundreds of thousands of new mobile applications. The mobile-broadband industry is really the convergence of computing, communications, and Internet technology, representing the vanguard of each of these. Consumers and businesses alike are finding a myriad of uses for mobile connectivity, resulting in new lifestyles and productive new ways of working.

One of the biggest drivers of mobile broadband is the rapid adoption of smartphones. With their powerful browsers, multimedia capabilities, and huge numbers of applications, these can consume large amounts of data. Penetration levels of smartphones are increasing quickly. Nielsen recently reported that 45% of new acquirers selected a smartphone.\(^5\)

Another driver for mobile broadband is the number of applications available for fixed broadband. Since modern mobile-data services do provide a “true” broadband experience, users naturally expect to do with their mobile connections what they can do with their fixed connections. This means engaging in any number of bandwidth-consuming applications such as downloading large files, streaming audio, and watching videos. There is a significant disparity, however, between what can be done with fixed connections and what can be done with mobile connections. This stems from fiber having much higher capacity than radio. Capacity constraints are a fundamental characteristic of wireless networks, and must be augmented through every means possible. Failing to do so will result in simply too great a disparity between fixed-broadband capabilities and mobile-broadband capabilities. The effect of this will be to either stall the market on an industry level, or an inability to compete at the operator level.

In addition, an increasing number of people are beginning to use their mobile connection as their only connection, both for voice and data. In Canada in 2008, 8 percent of households reported having cell phones only, though this percentage was much higher, 34 percent, for households consisting only of adults between the ages of 18 and 34.\(^6\) More recent data, once it becomes available, will very likely mirror trends in other countries, showing a rapidly increasing rate of fixed-mobile substitution. For

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example, Nielsen reported 17.1% of U.S. households had substituted a wireless phone for their landline phone in 2008.\textsuperscript{7} For broadband, Ovum predicts that by 2015 on a global basis, 1 billion people will use mobile technology as their primary form of Internet access, representing 13% of the global population and 28% of total broadband users.\textsuperscript{8} The user perspective is easy to understand: why pay for both fixed and mobile connections when the mobile offers all the needed capability? This is a significant development, because first, it moves a significant amount of traffic from fixed networks onto mobile networks. Second, it defeats capacity-augmenting strategies such as Wi-Fi offload and femtocells that depend on a local fixed-broadband connection. This means that the macro network itself must have sufficient capacity to address a wide range of usage scenarios.

There are a variety of statistics available about the growth of the mobile-broadband market. Cisco in its latest report on mobile-broadband growth projects an annual compound growth rate of 92% for mobile broadband for the next five years as shown in Figure 1.\textsuperscript{9} Cisco, in this same report, indicates that global mobile data traffic grew by a factor of 2.6 in 2010, nearly tripling for the third successive year. For 2011, Cisco’s estimate is for 131% growth in traffic.

Chetan Sharma projects traffic levels even higher than this.\textsuperscript{10} Consistent with these projections, T-Mobile USA recently reported that data traffic had doubled on their network in the last six months. T-Mobile also indicated that users of one of their latest 4G Android devices were consuming 1.2 gigabytes (GB) per month.\textsuperscript{11}


Rysavy Research has developed a spectrum model that projects the following growth of data consumption for different device categories. This model is explained in detail below in the section “Spectrum Need,” but two projections are shown in Figures 2 and 3. Figure 2 shows smartphone data consumption over time.

Figure 2: Monthly Smartphone Data Consumption per Subscriber over Time
Figure 3 shows consumption of other device types such as notebooks, netbooks, tablets, and other mobile platforms. These devices consume more data than smartphones, because the higher screen resolution enables higher-bandwidth video and larger images, and because users are more likely to engage in longer sessions with applications. For example, a smartphone user might watch a short news or sports video while waiting in line, whereas a tablet user might watch an entire movie.

![Figure 3: Potential Monthly Data Consumption per Subscriber for Other Devices over Time](image)

Clearwire indicated in 2010 that subscribers were consuming 7 GB per month.\(^\text{12}\) TeliaSonera in Finland, the first LTE operator, reported LTE data-card subscribers using 14 to 15 GB per month, three times their 3G data-card users.\(^\text{13}\) This monthly amount is consistent with average fixed-broadband consumption of 14.9 GB per month as reported by Cisco.\(^\text{14}\) These amounts are in fact higher than the amounts shown in Figure 3 above. This is because the figure averages smaller form-factor devices such as tablets that

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currently do not consume as much data as a notebook computer. It is important to note that as speeds increase, users can and will consume more data. Caps that made sense for 3G may suddenly be inappropriate for 4G. PC Magazine, in reference to a review of Verizon's LTE service states, “Because downloading large files and streaming full-screen video is effortless on the fast network, you'll be sure to run into Verizon's 5GB (for $50 per month) and 10 GB (for $80 per month) data caps quickly.”

To better understand how data is generated, we need to examine the data consumption of actual applications.

**Application Demands**

The mobility-enhanced world depends on a constant flow of bits between people and the Internet. As mobile devices become more powerful, as device resolution increases, as users employ more applications, and as more applications include dynamic content such as video, this flow of bits is increasing at a dramatic rate. The demand that an application imposes on a network depends on the application. Web browsing of relatively static content and e-mail present a relatively light load. In contrast, streaming applications where content is continuously refreshed at a high rate present a much higher load.

Table 1 shows the typical throughput requirements of various streaming applications, the amount of data each application consumes per hour measured in megabytes, and how many gigabytes each application would consume in a 30-day month based on hourly consumption amounts of .5 hours, 1 hour, 2 hours, and 4 hours.

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The table shows how quickly data amounts can add up on a monthly basis. For example, an hour of Internet radio a day consumes 1.7 GB over a month. Thirty minutes a day of YouTube or Skype consumes 6.8 GB per month. With typical data plans being in the 2 GB or 5 GB per month range, it only takes a small amount of streaming content to consume these plans.

Readers may be tempted to conclude that video is entertainment related, and hence not that important, or something that can be deferred to a home environment. Increasingly, however, video is becoming an integral component of other applications such as social networking, telemedicine, education, field service, and business collaboration. There is no question that video is becoming a significant factor for mobile-broadband networks, as it is for fixed-broadband networks. Bytemobile, for example, expects video to account for more than 60% of all mobile traffic in 2011.\(^1^{16}\)

There are multiple factors that are fueling growth in data usage including:

• **Faster networks.** The faster that data can be exchanged, the more likely it is that applications will take advantage of the speeds, especially since faster speeds can mean less waiting time for users. In addition, developers are likely to develop new types of applications that take advantage of the enhanced performance. The integration of video into social networking applications serves as an example.

• **More network-enabled devices.** New device categories such as tablets and netbooks are expanding overall data consumption. The emerging machine-to-machine market will also contribute to greater usage.

• **Increasing computing speeds.** The faster the platform can compute, the more data an application can process in real time, encouraging application developers to develop new types of bandwidth consuming applications. Real-time video-based augmented reality where the system superimposes data on the image being viewed is an example.

• **Gaming.** Increasingly, gamers will play interactive games over mobile connections.

• **Higher screen resolution.** Greater screen resolution corresponds to higher resolution video options for users. See further discussion below about this.

• **Tethering and phones as hotspots.** While phone users may not consume on average as much data as laptop users, phones can increasingly be used as modems (tethering) or as hotspots where they provide service to multiple connected devices via Wi-Fi. These connected devices can be laptop computers that consume far more data than a phone.

• **Embedded modems.** An increasing number of laptops and tablets come with embedded 3G/4G modems, facilitating the process for users to obtain mobile broadband service.

• **Flexible pricing plans.** In the past, users had to make long-term commitments to mobile-broadband service plans. Now they can opt for short-term plans, sometimes on a month-by-month basis. There are increasingly pre-paid plans available that encourage data usage as well.

Taking just one of these factors, screen resolution, Table 2 shows how increasing resolution results in higher video encoding rates. Assuming typical advanced video encoding and full-screen video, going from the iPhone 3 to iPhone 4 quadruples the video rate. The third and fourth rows present typical TV rates for comparison.
Table 2: Typical Video Rate Based on Type of Device

<table>
<thead>
<tr>
<th>Device</th>
<th>Vertical</th>
<th>Horizontal</th>
<th>Megapixels</th>
<th>Typical Video Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPhone 3</td>
<td>320</td>
<td>480</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>iPhone 4</td>
<td>640</td>
<td>960</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>720p high resolution</td>
<td>720</td>
<td>1280</td>
<td>0.9</td>
<td>2.4</td>
</tr>
<tr>
<td>HD TV, laptop HD</td>
<td>1080</td>
<td>1920</td>
<td>2.1</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Given the typical capacities of today’s wireless networks, the question is how much do applications like this impact the network? The answer is considerably. Figure 4 below takes the network capacities discussed in the next section on “Spectrum, Technology, and Capacity,” and shows what throughput rates are available to how many simultaneous users for different network configurations.

Figure 4: Available Throughput per User Based on Network Loading

Throughput Based on Loading

With multiple users simultaneously accessing streams in the 1 to 2 Mbps range, it only takes a relatively small number of users to reach sector capacity. For example, eight users each with 2 Mbps will consume the capacity of a 10+10 MHz LTE carrier. To put this into perspective, in an urban area there may be 3,000 subscribers per cell site, translating to 1000 subscribers per sector. Eight users represent a tiny percentage of the subscribers.
Clearly then, the bandwidth requirements of many applications have a significant impact on today’s wireless networks. To examine what capacity is actually available relative to spectrum, and how many users can be supported, we need to look at the capabilities of different technologies in more detail.

**Spectrum, Technology, and Capacity**

Spectrum is fundamental to capacity. Julius Genachowski, the chairman of the U.S. Federal Communications Commission, stated, “... the explosive demand for wireless innovation is testing the limits of a fundamental resource: spectrum. It is the oxygen of the wireless world—fueling every aspect of our mobile-broadband ecosystem.” Recognizing this essential need, the FCC plans to make 300 MHz of new spectrum available over the next five years and 500 MHz over the next ten years. This new spectrum represents an approximate doubling of the 549 MHz of spectrum currently allocated in the United States. The situation in Canada is no different, driven by exactly the same market trends as in the United States. Every operator will need more spectrum. This section examines the capacity that different amounts of spectrum actually provide.

The amount of data that a radio channel can carry depends on the width of the radio channel, the modulation used, and how the data is encoded. Each wireless technology uses radio channels of certain width. For example, CDMA2000 radio channels are each 1.25 million Hz (MHz) wide whereas High Speed Packet Access (HSPA as used by Rogers Communications) radio channels are 5 MHz wide. Long Term Evolution (LTE) radio channels can range from 1.4 MHz in width to 20 MHz. Wider radio channels can offer higher throughput speeds to users, but by themselves do not inherently increase capacity. In other words, two radio channels of 5 MHz each have about the same inherent capacity as one radio channel of 10 MHz.

To derive capacity, we must look at the width of the radio channel and consider the average spectral efficiency of the technology in typical deployments. Spectral efficiency is measured as bits per second per Hz of spectrum. Figure 5 shows the downlink spectral efficiency of different wireless technologies from a project Rysavy Research did for 4G Americas. Vendors and operators use sophisticated mathematical models to calculate the expected spectral efficiencies of different technologies. The

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models assume a network of multiple cell sites with a certain population of users. They calculate the signal levels and interference levels experienced by each user, which lets the models determine the modulation and coding rates for each user’s transmission. Through this process, the models can determine the aggregate data throughput for each cell sector for both the downlink and uplink. This aggregate throughput relative to the amount of spectrum used produces the spectral efficiency. Since the models are complex, and because many assumptions have to be made, spectral efficiency values vary somewhat between groups that calculate them. For the 4G Americas’ project, the spectral-efficiency values used were derived through a consensual analysis involving multiple operators and vendors. As such, they are credible and widely used throughout the industry.

Figure 5 shows a comparison of downlink spectral efficiencies for different technologies.

Figure 5: Comparison of Downlink Spectral Efficiency

Assumptions: 5+5 MHz for UMTS-HSPA/LTE and CDMA2000, and 10 MHz DL/UL=29:18 TDD for WiMAX. Mix of mobile and stationary users.
HSPA in typical new deployments has a downlink (base station to mobile user) spectral efficiency value of about 1.0 bps/Hz. This means a 5 MHz HSPA radio channel has a downlink capacity of 5 million Hz multiplied by 1.0 bps/Hz, which equates to 5.0 million bits per second, or 5.0 Mbps. This is the total capacity in a cell sector for that radio channel, a capacity that must be shared by multiple users. The 5 MHz radio channel actually translates to 10 MHz of spectrum used since there is a separate 5 MHz radio channel for the uplink.

LTE, being a new radio technology, has higher spectral efficiency and can operate in wider radio channels. For example, an LTE radio channel of 10 MHz has a downlink spectral efficiency value of about 1.5 bps/Hz and would thus have a downlink capacity of 15 Mbps. There is also an uplink channel of 10 MHz with a typical spectral efficiency value of .65 bps/Hz, equating to an uplink capacity of 9.75 Mbps. See Figure 6 for uplink spectral efficiency values.

Figure 6: Comparison of Uplink Spectral Efficiency

Figure 7 shows voice spectral efficiency values.

Though newer technologies have higher spectral efficiency than older ones, there are fundamental limits of what can be achieved due to what is known as the Shannon Bound. This bound mathematically specifies the maximum spectral efficiency available from a channel relative to the signal-to-noise ratio (SNR). All modern wireless technologies are effectively operating at the limit of the Shannon bound, as shown in Figure 8.

Since the Shannon bound only applies to a single link, techniques such as MIMO that employ multiple links to propagate signals through the environment can achieve higher efficiency. Each antenna, however, is still subject to the bound. Interference coordination and cancellation methods can also boost efficiency. Going forward, gains in spectral efficiency will only occur at modest rates. For example, LTE has a spectral efficiency of about 1.5 bps/Hz. LTE-Advanced, not expected to be available for deployment for another couple of years, has a spectral efficiency value of 2.2 bps/Hz.

Advances in spectral efficiency will be important, but by themselves do not address the growing need for capacity. Capacity gains will also need more cell sites, offload onto femtocells and Wi-Fi, and more spectrum.

**Spectrum Utilization**

The question then is how much total capacity does an operator actually have for mobile broadband? This depends on how much spectrum they have and how many cell sites they have deployed. More cell sites means that fewer people have to share the radio channel since that radio channel is servicing a

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24 Source: Courtesy Alcatel Lucent.
smaller area. But there are limits to how many cell sites can be practically deployed with most of the easiest-to-deploy locations already in use.

Table 3 shows how cell sector capacity relates to different technology configurations including the number of radio carriers that might be deployed. For example, an HSPA operator that has deployed two HSPA radio carriers in a cell site would consume 20 MHz of spectrum and would have 8 Mbps of aggregate downlink capacity in each sector and 4 Mbps of uplink capacity in each sector. Note that the spectral efficiency values used in the table are somewhat idealized values that assume all available technology enhancements for these technologies have been implemented. Actual values for deployed networks will be lower than these values. See Figure 5 above for details on HSPA and LTE spectral-efficiency values.

**Table 3: Spectrum Used and Sector Capacity for Different Configurations**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Radio Carrier Width (MHz)</th>
<th>Carriers</th>
<th>Total Spectrum Used (MHz)</th>
<th>Downlink Spectral Efficiency</th>
<th>Downlink Sector Capacity (Mbps)</th>
<th>Uplink Spectral Efficiency</th>
<th>Uplink Sector Capacity (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPA+</td>
<td>5</td>
<td>1</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>0.5</td>
<td>3</td>
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<td>60</td>
<td></td>
<td>30</td>
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<tr>
<td>LTE</td>
<td>10</td>
<td>1</td>
<td>20</td>
<td>1.5</td>
<td>15</td>
<td>0.65</td>
<td>7</td>
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<td>4</td>
<td>80</td>
<td></td>
<td>60</td>
<td>26</td>
<td>26</td>
</tr>
</tbody>
</table>

Note: LTE can be deployed in radio channels ranging from 1.4 to 20 MHz. 10 MHz is a typical initial configuration for some operators.

This table shows the total aggregate throughput for a traffic model that largely involves continuous transfer of data. Effective spectral efficiency is much lower for traffic that consists of short messages. Also, loading at full capacity does not result in a good user experience due to low average throughputs per user and higher latency. Capacity, as calculated by spectral efficiency, represents a best case scenario and, in real world applications, networks need to be loaded at levels significantly lower than calculated values.

**Capacity, as calculated by spectral efficiency, represents a best case scenario and, in real world applications, networks need to be loaded at levels significantly lower than calculated values.**

A combination of new sites, new technologies, offload, and additional spectrum will be the primary ways that operators augment capacity. Increasing the number of cell sites is the primary way that cellular
networks have historically augmented capacity. Operators, however, are reaching practical limits of how densely they can deploy cells in the wide area.

It is becoming increasingly difficult for wireless operators to add new roof-top and tower sites, especially in urban and suburban areas, due to local concerns. The average time that it takes to acquire new sites has increased from about 494 days in 2006 to 776 days in 2010. Specific issues include:

- Local residents have increased health concerns.
- Local residents are concerned about the notion that cell sites will decrease their property values. Aesthetics are also a concern.
- Land use authorities (e.g., local governments) often deny applications after they have been pressured by their constituents.
- The availability of potential sites is becoming an issue given that the emergence of new competitors has decreased the amount of available roof-top space and has increased the cumulative radiofrequency field levels on roof-tops, which means that new sites cannot support additional operators.
- Many suitable buildings are owned by multiple owners (i.e., condominiums) and, typically, a majority of these owners must approve the installation of cell sites on their property. It is becoming increasingly difficult to secure a majority approval for the reasons outlined above.
- Network densification sites are required at lower elevations and have a smaller coverage area. In short, they will be located closer to people and residences, and this will make it more difficult to obtain the necessary approvals.

Despite these challenges, operators such as Rogers Communications will increase the number of densification cells that are added to their networks in the coming years. They will not, however, be able to add all of the sites needed in order to provide ubiquitous and reliable LTE coverage, as discussed later in this report. Therefore, low-band 700 MHz spectrum will be important to ensure that there will be no holes in coverage.

New technologies such as LTE are spectrally more efficient, but the timeframes for deploying new technologies and reaching high penetration levels among users are extremely long. Consider that GSM was a technology that saw wide deployments begin around 1990, UMTS around 2000, and LTE around 2010. In other words, new cellular technology deployment occurs on 10-year cycles. Not only that, but there is an even longer delay between introduction of a new technology and its peak usage. This delay for many technologies, including new wireless technologies, is 19 years.

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25 Source: Rogers Communications.

26 Source: Qualcomm, PCCA meeting, 2/2/2011.
Other means of augmenting capacity are by offloading onto Wi-Fi networks and femtocells. With Wi-Fi, dual-mode (cellular plus Wi-Fi) devices can be configured to manually or automatically use Wi-Fi for data service. The Wi-Fi connection could be via a hot spot such at an airport or it could be a private connection in a subscriber’s home. With increased availability of Wi-Fi, this approach is relatively straightforward and effective to a degree. The biggest problem is simply that Wi-Fi only covers a small percentage of area compared to wide-area networks. Thus, there is only so much data that an operator can expect to offload. In particular, to offload onto Wi-Fi in a subscriber’s home presupposes that the subscriber has a fixed-broadband connection. The problem, however, is that increasing numbers of subscribers are making mobile broadband their only broadband connection, and hence offloading will not be possible.

Femtocells are another way that operators plan to augment capacity. Femtocells, because they enable very high frequency reuse, can augment overall network capacity, as shown in Figure 9.

Figure 9: Augmented Capacity by Using Femtocells

Macro-cell Coverage

Femtocell Coverage

Aggregate femtocell capacity far exceeds macro-cell capacity for same amount of spectrum
There are a number of considerations that could limit how effective femtocells really are for increasing capacity:

1. There are many complexities associated with femtocells that will take time to resolve, hence delaying their widespread deployment. This includes regulatory items such as femtocells needing to know their exact location so as to determine what frequencies, if any, are allowed to be used. Managing hundreds of thousands, and eventually millions of “base stations” versus thousands will also be difficult for operators. Supporting users who call with technical support questions, especially in trying to connect femtocells to Internet-access equipment out of the operators’ control, will be challenging.

2. Coordinating interference between femtocells and the wide area network will be complex, especially since the operator does not have control over femtocell placement.

3. Because femtocells rely on a fixed-broadband connection to the Internet, they only work if the user has this connection. Subscribers intending their mobile-broadband connection to be their only broadband connection cannot use femtocells.

Nevertheless, over time, offload will play an important role. Figure 10 shows how the throughput per user can dramatically increase through a combination of offload and more spectrum.

Figure 10: Greater Capacity Through More Spectrum and Offload\(^\text{27}\)

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\(^{27}\) Assumption: as much data offloaded as carried on the LTE network.
Increased spectrum translates directly to increased capacity. One way of viewing this is by examining the number of users that can simultaneously obtain certain throughput rates. Figure 11 shows how many users in a cell sector simultaneously obtain a throughput rate of 1 Mbps or 2 Mbps based on the amount of spectrum deployed for LTE, assuming no offload. Note, however, that these numbers are still low relative to the number of subscribers per cell site, which can be as high as 1000.

Figure 11: Capabilities Provided Based on Spectrum Used with LTE

![Graph: Users at Different Throughputs Relative to Spectrum (LTE)]

Rysavy Research 2011

**Spectrum Need**

To assess spectrum requirements, Rysavy Research has developed a spectrum demand model that forecasts the amount of spectrum an operator requires to address mobile broadband requirements. This is a relatively complex model based on a variety of assumptions. Rysavy Research first published the results of this model in February 2010 in a report titled “Mobile Broadband Capacity Constraints and the Need for Optimization.” Rysavy Research also presented this information at the Canadian Spectrum 20/20 Conference in Ottawa on April 21, 2010. Since then, Rysavy Research has been updating the methodology used in this model, and has updated key assumptions to reflect market trends a year later, particularly with respect to mobile broadband consumption.

The model is based on an analysis of the following factors and variables. The exact values used for some of these items are not disclosed since they represent the outcome of a considerable amount of research, and are considered proprietary.
• **Number of subscribers.** This is a fundamental number in determining the demand on the network for both voice and data services.

• **Growth in number of subscribers.** This is the increase year by year in the number of subscribers.

• **Voice spectral efficiency, measured as Erlangs per MHz.** This value enables the calculation of the amount of spectrum required relative to the amount of voice activity in the cell. The value is different depending on whether voice service is being provided via 2G or 3G.

• **Data spectral efficiency, measured in bps/Hz.** Spectral efficiency determines the amount of spectrum required relative to the aggregate data demand for all users in a cell sector.

• **Busy hour for voice.** This is the percentage of the day’s voice traffic carried during the busiest hour of the day. Spectrum requirements are driven by when the cell is the busiest.

• **Busy hour for data.** This is the percentage of the day’s data traffic carried during the busiest hour of the day. As with voice, spectrum requirements are driven by when the cell is the busiest. Unlike voice, however, data demand is spread more uniformly across the day.

• **Maximum network load for voice.** Networks cannot be loaded to a 100% level, so a maximum value needs to be assigned for maximum voice loading.

• **Maximum network load for data.** This is the maximum level of loading for data. This can be significantly lower than 100% if operators want to deliver users a consistently good broadband experience.

• **Spectrum deployment efficiency.** There are inherent inefficiencies in deploying spectrum, such as the need for infill sites, supporting legacy services, and carrying voice and data on separate channels. Thus spectrum is deployed at less than 100% efficiency.

• **Average voice minutes per subscriber per month.** This value is one of many that determine the amount of spectrum needed for voice. Over time, however, spectrum requirements for voice become ever smaller than the spectrum requirements for data.

• **Voice usage growth.** This is the increase year by year in average voice minutes per subscriber.

• **Number of cell sites.** The model uses cell site information to determine how many subscribers are present in each cell site. This is complicated by the fact that subscribers are not uniformly distributed over cell sites and by the fact that users are mobile.

• **Growth in cell sites.** This is the increase year by year in the number of cell sites.

• **Densest cell multiplier.** This is a factor that accommodates the higher density of users found in some cells relative to the average across a coverage area. Operators can also deploy infill sites to address areas of high density.

• **Monthly data consumption for smartphones.** The model assumes that data usage is primarily by a combination of smartphones and larger form-factor devices such as tablets, netbooks, and
notebooks. While feature phones contribute to some data usage, their impact is minimal. Over time, most phones will become smartphones.

- **Annual growth rate for smartphone data.** This is the increase year by year in smartphone data consumption.

- **Penetration level of smartphones.** This is the percentage of the subscriber base using smartphones.

- **Smartphone penetration growth rate.** This is the increase year by year in the penetration level of smartphones.

- **Monthly data consumption for other devices.** The model anticipates higher monthly data usage for these devices, because of larger screens and the tendency for users to be engaged in activities for longer periods of time. On the other hand, penetration levels are lower than smartphones.

- **Annual growth rate for other devices.** This is the increase year by year in consumption of other devices.

- **Other device penetration growth rate.** This is the increase year by year in the penetration level of other devices.

- **Data-offloading.** This model anticipates the amount of traffic carried on the wide-area network and the spectrum required to support this amount of traffic. It does not attempt to quantify the amount of traffic that may in addition be carried on Wi-Fi or femtocell networks.

Based on these variables, the amount of spectrum that Rogers will require to meet escalating data demand depends on a number of factors including market trends such as fixed-mobile substitution and pricing. If a large number of subscribers retain their fixed-broadband connections, then they can offload intensive traffic consumption, such as home movie watching, onto these fixed connections. But if users rely on mobile broadband as their only form of broadband connection, usage rates could be significantly higher, as shown in Figure 12.
Another factor is operator pricing. If operators use tiered pricing, they can control demand. For example, tiers such as $10 GByte as used by Verizon would clearly make 2016 usage levels shown in Figure 12 prohibitively expensive. The fact is, however, that overly restricting pricing will simply stall the market. If users cannot accomplish what they reasonably expect, they will discontinue service.

There is a complex feedback loop from a modeling perspective between pricing and demand that the model simply cannot accurately anticipate. Hence, the projections are more on the basis of demand assuming that pricing is at a level that does not constrain use by most users. The 1% of users who are often responsible for 20% of traffic is not included in the projections.28

**Effects of Insufficient Spectrum**

The consequence of insufficient spectrum is restricted capacity, which combined with burgeoning demand, causes network congestion. For applications, this means sluggish behavior or outright failures. Specific effects include:

- Sluggish behavior (e.g., Web browsing)
- Stalls (e.g., watching instructional video)
- Complete failure (application/system has to be restarted)
- Communications protocols behave erratically (e.g., Transmission Control Protocol)
- Unpredictable application behavior (works at times, not others)

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One way of easily visualizing the impact of multiple people simultaneously accessing a network is to look at Web browsing. Typical Web pages\textsuperscript{29} (e.g., yahoo.com, cnn.com) are over 1 MByte in size. Assuming 1 MByte, Figure 13 depicts the page load time based on the number of users simultaneously accessing Web pages with full-screen devices. Most users would consider a page load time of more than ten seconds to be sluggish performance. According to the figure, this occurs with about 20 users in a 2-HSPA carrier network.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{web_page_load_times.png}
\caption{Web Page Load Times for Typical Web Pages}
\end{figure}

Beyond sluggish performance in congestion situations, there is also the high likelihood that networks will simply have to drop packets. Figure 14 illustrates how this happens. Packets arrive at a base station over a high-speed connection such as fiber, but then the base station forwards the packets using the slower radio connection. If there are too many incoming packets, the inevitable result is that the base station, or infrastructure nodes prior to the base station, will drop or significantly delay packets.

\textsuperscript{29} Web pages formatted for small-screen devices are usually smaller.
Consequences of congestion are not just slower performance, but also application failures. Most communications protocols implement timeouts on their operations including Transmission Control Protocol (TCP) itself, the packet-transport protocol used on the Internet to provide reliable end-to-end delivery. With large delays or dropped packets, communications protocols attempt to deliver data reliably, but at some level of congestion, they can no longer cope properly, and applications will either indicate a failure or, worse yet, hang and require an application or full-system restart. Examples include a user who is in the midst of booking a flight and suddenly loses his or her entire session. Or a student could be taking an exam and lose the session.

The worst problem with congestion for users is that it is erratic. A lightly loaded network will function fine, but as more users get on the network, applications start becoming increasingly unreliable. This makes the service unpleasant to use, and users will simply opt for other broadband options.

**Coverage Requirements**

This report has emphasized the data demand aspects of mobile broadband. These trends show the clear need for Rogers to be able to participate in the 700 MHz spectrum to address capacity requirements. But there is another reason that all Canadian operators, including Rogers, should be able to participate in the 700 MHz auction. That is for coverage. The 700 MHz band is particularly well-suited for providing maximum coverage with the minimum number of cell sites relative to other available bands. This significantly increases the likelihood that an operator will be able to deploy LTE in rural and suburban areas, thus being able to provide coverage that addresses all population areas.

Canada, in particular, provides an extremely demanding coverage challenge, namely huge geography with low population density. Covering this geography with high-band spectrum is simply uneconomic.
given the large number of cell sites required. The 700 MHz band is the only low-band spectrum that Rogers can use to implement LTE on a widespread basis in the near term. The alternative low-band is at 850 MHz, but this will continue to be used to serve 9 million GSM and HSPA customers. Moreover, there is no LTE technology ecosystem for the 850 MHz band.

The 700 MHz band will allow Rogers to implement ubiquitous and reliable LTE coverage in urban and suburban areas including inside buildings, and it will allow Rogers to implement LTE in rural Canada. Without 700 MHz spectrum, rural Canada will not receive LTE coverage, because it will not be economic to serve these areas using only high-band spectrum. There are simply too few Canadians living in these areas to pay for the disproportionately high number of cell sites that would need to be built using only high-band spectrum.

**700 MHz as North American LTE Band**

Beyond capacity and coverage, there is one final reason that Canadian operators including Rogers should all have access to the 700 MHz band. The 700 MHz band is emerging as the North American LTE band. Both AT&T and Verizon in the United States are rolling out LTE in the 700 MHz band. Devices and infrastructure equipment operating in the 700 MHz band will cost less due to higher economies of scale. In addition, it will be easier for device vendors to create devices that operate in both Canada and the United States, facilitating roaming between the two countries.

If Canada wants to keep step with its major trading partner in the implementation of the most advanced mobile-broadband technology and services, then its major commercial mobile operators such as Rogers must have access to 700 MHz spectrum, and the vitally important ecosystem that is developing for it.

Apart from the economic benefits associated with this ecosystem in terms of lower cost, it will also throw off the widest availability and array of LTE technology, devices, and features, and it will be the focus of ongoing development and support for years to come.

**Conclusion**

The mobile-broadband market is a thriving ecosystem of fast networks, powerful mobile computers, and innovative applications. Increasingly, users are enjoying high-bandwidth applications, many of which embed video content. Such applications can include social networking, entertainment, education, telemedicine, and surveillance.

The capacity of wireless networks depends primarily on a combination of the technology used, cell site density, and the amount of available radio spectrum. With cell sites already being deployed in very high densities, and with the most advanced available wireless technologies like LTE being deployed that maximize spectral efficiency, it is essential that Canadian operators have sufficient spectrum to deploy their networks.
Rysavy Research has developed a model that projects the amount of spectrum required to support an operator’s subscriber base, based on cell site density, the spectral efficiency of deployed technologies, and the amount of voice and data consumed by the subscribers. This model projects that all successful mobile operators will experience a spectrum shortfall in the next three to five years. Specifically, it predicts that Rogers Communications will consume its entire available spectrum this decade. Gaining additional capacity through 700 MHz will be critical.

The 700 MHz band will also play a crucial role in two other ways. First, it facilitates the deployment of a nationwide network since it offers excellent propagation characteristics. This will be particularly important for providing widespread coverage outside of urban areas. Second is that it enables roaming and large economies of scale since 700 MHz is becoming the default North American LTE band.
Appendix A – Technology Primer

This appendix is a technology primer that covers the technologies discussed in this report. It includes the following topics: 1G to 4G migration, the principal wireless technology families, wireless network architecture, the key advanced radio methods used in 3G and 4G, EV-DO evolution, HSPA evolution, WiMAX, LTE, heterogeneous networks, and femtocells.

1G to 4G

First-generation cellular refers to analog-cellular systems that were first deployed in the 1980s. The system used in North America was the Advanced Mobile Phone Service (AMPS). Second-generation cellular introduced digital methods in which the radio modulated the carrier waveform to carry ones and zeroes. Vocoder is used to digitize voice. 2G also introduced data services in the form of short-message service (SMS), circuit-switched data, and later packet-switched data. 2G still represents the overwhelming percentage of cellular services in use globally with the primary technology being Global System for Mobile Communications (GSM).

3G was specified by the International Telecommunications Union (ITU) in a project called International Mobile Telephone (IMT) 2000 that required data throughput rates of 144 kbps when mobile (driving speeds), 384 kbps at pedestrian speeds, and 2 Mbps indoors. The leading 3G technologies are Universal Mobile Telecommunications Service (UMTS), which includes a high-speed data service called High Speed Packet Access (HSPA), and Code Division Multiple Access (CDMA) 2000. 3G services are widely deployed in developed nations.

The term 4G originally applied to systems that complied with the ITU’s requirements for technologies called IMT-Advanced. The ITU published these requirements in 2008. In 2010, however, the ITU allowed the term 4G to apply to systems that offered significantly higher performance than 3G. The term is now applied to WiMAX, advanced versions of HSPA called HSPA+, and 3GPP Long Term Evolution (LTE).

Table 4 summarizes the cellular generations.
Table 4: Cellular Generations

<table>
<thead>
<tr>
<th>G</th>
<th>Radio</th>
<th>Requirements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1G</td>
<td>Analog</td>
<td>No official requirements.</td>
<td>Deployed in the 1980s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>New services such as SMS and low-rate data.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Example: GSM</td>
</tr>
<tr>
<td>3G</td>
<td>CDMA (except WiMAX which is OFDMA)</td>
<td>ITU’s IMT-2000 required 144 kbps mobile, 384 kbps pedestrian, 2 Mbps indoors.</td>
<td>Examples: UMTS/HSPA and CDMA2000.</td>
</tr>
<tr>
<td>4G</td>
<td>OFDMA</td>
<td>Originally ITU IMT-Advanced.</td>
<td>Examples: WiMAX, HSPA+, LTE.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Now systems that significantly outperform 3G.</td>
<td>IEEE 802.16m and LTE Advanced being designed to meet IMT-Advanced requirements.</td>
</tr>
</tbody>
</table>

Technology Families

There are three principal wireless-technology families used for wide-area networks, as summarized in Table 5. Global System for Mobile Communications (GSM), a TDMA technology, is the most widely used technology today. Data service for GSM is via a service called Enhanced Data Rates for GSM Evolution (EDGE) that delivers data rates of about 100 kbps.

Universal Mobile Telecommunications System (UMTS) is the 3G successor to GSM and uses CDMA radio methods. High Speed Packet Access (HSPA) is a data service for UMTS, and is enhanced through HSPA+, now being deployed by operators worldwide. HSPA provides user throughput rates of about 1 Mbps and HSPA+, depending on configuration, will increase this by a factor of four to ten.

Long Term Evolution (LTE), based on Orthogonal Frequency Division Multiple Access (OFMDA) is the 4G successor to UMTS. LTE will initially provide throughput rates of about 10 Mbps. Through various enhancements, these rates will increase over time by a factor of ten. Voice over LTE, once available, will be over IP. Operators began deploying LTE in 2010. GSM, UMTS/HSPA, and LTE are likely to co-exist for the remainder of the decade. LTE devices will be multimode, supporting GSM, UMTS, and LTE. LTE Advanced is being designed to meet IMT-Advanced Requirements.

The other main technology family used for cellular networks is CDMA2000. The most broadly deployed version of this is a technology called One Carrier Radio Transmission Technology (1XRTT), a voice and data service. 1XRTT supports data rates of about 100 kbps. CDMA2000 Evolution Data Optimized is a data-only service that provides data rates of about 1 Mbps. EV-DO Advanced will increase data rates further.
WiMAX is an OFDMA technology that today provides data rates of about 5 Mbps. Services emphasize data, with voice handled as VoIP. Mobile WiMAX2, expected to be ready for commercialization in 2011, will meet IMT-Advanced requirements.

**Table 5: Summary of Technology Families**

<table>
<thead>
<tr>
<th>Technology Family</th>
<th>Specifications</th>
<th>Operator Examples</th>
<th>Technology</th>
<th>G</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM/UMTS</td>
<td>3GPP</td>
<td>Rogers</td>
<td>GSM</td>
<td>2</td>
<td>TDMA</td>
<td>Voice and SMS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GPRS</td>
<td>2</td>
<td>TDMA</td>
<td>Initial data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EDGE</td>
<td>2</td>
<td>TDMA</td>
<td>Enhanced data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>UMTS/WCDMA</td>
<td>3</td>
<td>CDMA</td>
<td>Initial voice and data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSPA</td>
<td>3</td>
<td>CDMA</td>
<td>Enhanced data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>HSPA+</td>
<td>4</td>
<td>CDMA</td>
<td>Further enhanced data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LTE, LTE Advanced</td>
<td>4</td>
<td>OFDMA</td>
<td>Data first, voice later</td>
</tr>
<tr>
<td>CDMA2000</td>
<td>3GPP2</td>
<td>Bell, TELUS</td>
<td>1XRTT</td>
<td>3</td>
<td>CDMA</td>
<td>Voice, SMS, initial data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EV-DO</td>
<td>3</td>
<td>CDMA</td>
<td>Enhanced data</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EV-DO Advanced</td>
<td>4</td>
<td>CDMA</td>
<td>Further enhanced data</td>
</tr>
<tr>
<td>WiMAX</td>
<td>IEEE, WiMAX Forum</td>
<td>Bell/Rogers/Inukshuk</td>
<td>Fixed WiMAX</td>
<td></td>
<td>OFDMA</td>
<td>Data emphasis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mobile WiMAX</td>
<td>4</td>
<td>OFDMA</td>
<td>Data emphasis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mobile WiMAX2</td>
<td>4</td>
<td>OFDMA</td>
<td>Data emphasis</td>
</tr>
</tbody>
</table>

The evolution of these technology families, along with their peak data throughput capabilities, is shown below in Figure 15.
This paper provides further details of specific radio technologies, EV-DO, HSPA+, WiMAX, and LTE, below.

**Architecture**

In the GSM/UMTS and CDMA2000 families, voice and data are handled in two different domains. The base station controller separates circuit-switched voice traffic from packet-switched IP data. A mobile switching center (MSC) handles voice communications, while a separate data infrastructure handles IP data communications. For GSM/UMTS networks, the data infrastructure, as shown in Figure 16, consists of a Serving General Packet Radio Service Support Node (SGSN), usually collocated with the MSC, and a Gateway GPRS Support Node (GGSN) that provides a gateway function to external networks such as the Internet. For CDMA2000 networks, the SGSN and GGSN types of functions are handled in an infrastructure element called the Packet Data Serving Node (PDSN). Both GSM/UMTS and CDMA2000 will have to eventually handle voice in the packet domain, and detailed specifications exist for both technology families to do so, but at this time no operators are moving forward with this approach.
For LTE, the architecture changes through the introduction of the Evolved Packet System (EPS), as shown in Figure 17. EPS refers to the combination of the Evolved Packet Core (EPC) and LTE. EPS is designed not only to support LTE, but to provide integration with legacy GSM/UMTS networks, and also to integrate non-3GPP access networks such as WiMAX, EV-DO, and Wi-Fi.
Advanced Radio Methods

Before discussing some of the wireless technologies in a little more detail, it is worth examining some of the advanced radio methods used to make these technologies so efficient. One method is higher-order modulation, in which more bits are encoded in each symbol, as shown in Figure 18. 30 Higher-order modulation increases spectral efficiency, but it requires a higher-quality radio signal that may not be available if the signal is weak or if there is interference.

30 A symbol is the adjustment in phase, frequency, or amplitude of a radio-carrier signal.
Thus, the key feature of modern wireless systems is the ability to adapt to changing radio conditions. One of the principal methods is to vary modulation and coding using the highest-order modulation possible and the least amount of coding. Figure 19 provides an example. The data being transmitted is the same for the four scenarios. With the worst quality signal, the system uses a robust, but spectrally less-efficient modulation in combination with a high level of error coding, meaning additional error correction. With a better quality signal, the system uses the same modulation, but with less error coding, hence less communication overhead and better net spectral efficiency. With a yet better signal, the system employs higher-order modulation in combination with a high level of error coding, resulting in yet improved spectral efficiency. Finally, with the best-quality signal, the system uses both higher-order modulation and the least amount of error coding, resulting in the highest-possible spectral efficiency.
Another key feature of modern wireless systems is using intelligent antennas. The two primary methods are beam steering and Multiple Input Multiple Output (MIMO). MIMO has been specified for use with EV-DO, HSPA, WiMAX and LTE. The concept of MIMO, as shown in Figure 20, is to have multiple transmission paths through the environment. On the transmit side, multiple radios transmit different data streams through different antennas. The receive antennas pick up multiple sets of signals from the multiple transmitters, process these and recover the original data transmission. A 2X2 configuration, as shown in the figure, can double spectral efficiency and double peak throughput rates. Similarly, a 4X4 system can quadruple efficiency.
**EV-DO Evolution**

CDMA2000 EV-DO is most widely available today based on Revision A specifications. Table 6 summarizes various enhancements planned for EV-DO. Most CDMA2000 operators have opted for LTE as their 4G platform. Whether or not they deploy more advanced versions of EV-DO will partly depend on how aggressively they deploy LTE.

**Table 6: EV-DO Evolution**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Throughputs</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMA2000 EV-DO Rev 0</td>
<td>400-700 kbps typical 2.4 Mbps peak downlink 1XRTT uplink</td>
<td>One carrier evolution, data optimized</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev A</td>
<td>3.1 Mbps peak downlink 1.8 Mbps peak uplink</td>
<td>Reverse link improvements, VoIP.</td>
</tr>
<tr>
<td>CDMA2000 EV-DO Rev B</td>
<td>Peak theoretical rate of 73.5 Mbps in 20 MHz</td>
<td>3 channels in 5 MHz to 14.7 Mbps typical configuration.</td>
</tr>
<tr>
<td>EV-DO Advanced</td>
<td>32 Mbps in 4 X 1.25 MHz</td>
<td>2X2 MIMO, 64 QAM in DL, 16 QAM in UL</td>
</tr>
</tbody>
</table>
**HSPA Evolution**

High Speed Packet Access (HSPA) is a data service for UMTS networks. HSPA+ or HSPA Evolution refers to various planned enhancements for HSPA employing the following methods: higher-order modulation, MIMO, and multiple carriers. Table 7 summarizes the peak downlink and uplink rates available depending on which features are implemented as per successive 3GPP specification releases.

**Table 7: HSPA Evolution**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Downlink Peak Data Rate (Mbps)</th>
<th>Uplink Peak Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPA as defined in Release 6</td>
<td>14.4</td>
<td>5.76</td>
</tr>
<tr>
<td>Release 7 HSPA+ DL 64 QAM, UL 16 QAM</td>
<td>21.1</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 7 HSPA+ 2X2 MIMO, DL 16 QAM, UL 16 QAM</td>
<td>28.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ 2X2 MIMO DL 64 QAM, UL 16 QAM</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 8 HSPA+ (no MIMO) Dual Carrier (2 X 10 MHz)</td>
<td>42.2</td>
<td>11.5</td>
</tr>
<tr>
<td>Release 9 HSPA+ 2X2 MIMO, Dual Carrier (2 X 10 MHz)</td>
<td>84.0</td>
<td>23.0</td>
</tr>
<tr>
<td>Release 10 HSPA+ 2X2 MIMO, Quad Carrier (2 X 20 MHz)</td>
<td>168.0</td>
<td>23.0</td>
</tr>
</tbody>
</table>

**WiMAX**

WiMAX, like LTE, uses OFDMA. More mature than LTE, WiMAX has been deployed in multiple networks worldwide including in Canada through a joint venture of Bell, Rogers, and Inukshuk. WiMAX networks are IP based and implement voice as VoIP. WiMAX supports both FDD and TDD configurations, but current profiles are for TDD operation only. WiMAX is built on IEEE 802.16 standards that specify the physical and link layers. Network layer functions are specified by the WiMAX Forum, which also promotes the technology, defines profiles, does interoperability testing, and certifies equipment. Figure 21 shows the WiMAX architecture.
**Long Term Evolution (LTE)**

LTE is the technology likely to see the broadest deployment of any new wireless technology over the next decade. LTE employs many of the same features as WiMAX, but being a later technology, it is spectrally more efficient and offers higher throughput rates. The key characteristics of LTE are as follows:

- **IP Based.** All services are handled in the IP domain.
- **OFDMA.** Like WiMAX, the radio link is based on Orthogonal Frequency Division Multiple Access for the downlink. LTE differs from WiMAX, however, in its use of Single Carrier FDMA on the uplink.
- **MIMO.** Initial versions of LTE will use 2X2 MIMO, but higher-order MIMO all the way to 8X8 in LTE-Advanced will further increase throughput rates and spectral efficiency.
- **Frequency Division Duplex (FDD) and Time Division Duplex (TDD).** LTE has been specified to operate in either FDD or TDD modes.
- **Radio Channel Flexibility.** LTE can be deployed in radio channels of varying size including 1.4 MHz, 5 MHz, 10 MHz, and 20 MHz. LTE Advanced allows carrier aggregation for up to 100 MHz of bandwidth. Initial deployments in the United States will use 5+5 MHz and 10+10 MHz FDD.
• **Sophisticated QoS.** LTE defines comprehensive quality-of-service control in conjunction with policy management that can be either static or dynamic.

Table 8 summarizes the peak theoretical rates for LTE.

Table 8: LTE Maximum Throughput Rates

<table>
<thead>
<tr>
<th>LTE Configuration</th>
<th>Downlink (Mbps) Peak Data Rate</th>
<th>Uplink (Mbps) Peak Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using 2X2 MIMO in the Downlink and 16 QAM in the Uplink, 20 MHz</td>
<td>172.8</td>
<td>57.6</td>
</tr>
<tr>
<td>Using 4X4 MIMO in the Downlink and 64 QAM in the Uplink, 20 MHz</td>
<td>326.4</td>
<td>86.4</td>
</tr>
</tbody>
</table>

Figure 23 shows how LTE can dynamically allocate resources to different users in real time. Radio resources are assigned every 1 millisecond. The number of subcarriers assigned to each user over time effectively determines their throughput rate. To mitigate interference, LTE can also selectively use or not use certain subcarriers based on their use in neighboring sectors or cells.

**Figure 22: Example of OFDMA Resource Allocation in LTE**

Minimum resource block consists of 12 subcarriers and 14 symbols over 1.0 msec.

Resources assigned in both time and frequency.
The efficiency of LTE increases with radio channel size as shown in Figure 23. Though deploying 20 MHz radio channels is the most efficient, few carriers have this much spectrum available to deploy LTE. Fortunately, if they deploy LTE in 5 MHz or 10 MHz channels, they achieve 95% or higher efficiency.

**Figure 23: LTE Efficiency Relative to Radio Channel Size**

There are a variety of possible scenarios by which operators will deploy LTE, as shown in Figure 24.

---

31 Source: Rysavy Research white paper for 3G Americas. Channel size refers to single direction.
Release 10 of 3GPP specifications specifies an enhanced version of LTE called LTE-Advanced. LTE-Advanced has been designed to meet the ITU IMT-Advanced requirements, as shown in Table 9.

---

**Table 9: CDMA to LTE**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Today</th>
<th>Medium term</th>
<th>Long term</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3G1X</td>
<td>3G1X</td>
<td>3G1X</td>
</tr>
<tr>
<td></td>
<td>EV-DO RevA</td>
<td>EV-DO RevA/B</td>
<td>LTE</td>
</tr>
<tr>
<td>B</td>
<td>3G1X</td>
<td>3G1X</td>
<td>3G1X</td>
</tr>
<tr>
<td></td>
<td>EV-DO RevA</td>
<td>EV-DO RevA/B</td>
<td>LTE</td>
</tr>
<tr>
<td>C</td>
<td>3G1x</td>
<td>3G1x</td>
<td>3G 1X</td>
</tr>
<tr>
<td></td>
<td>LTE</td>
<td>LTE</td>
<td>LTE</td>
</tr>
</tbody>
</table>

**Table 9: W-CDMA to LTE**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Today</th>
<th>Medium term</th>
<th>Long term</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>GSM</td>
<td>GSM</td>
<td>GSM</td>
</tr>
<tr>
<td></td>
<td>WCDMA</td>
<td>WCDMA</td>
<td>WCDMA</td>
</tr>
<tr>
<td>B</td>
<td>GSM</td>
<td>GSM</td>
<td>GSM</td>
</tr>
<tr>
<td></td>
<td>WCDMA</td>
<td>WCDMA</td>
<td>WCDMA</td>
</tr>
</tbody>
</table>

**Table 9: GSM to LTE**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Today</th>
<th>Medium term</th>
<th>Long term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GSM</td>
<td>GSM</td>
<td>GSM</td>
</tr>
<tr>
<td></td>
<td>LTE</td>
<td>LTE</td>
<td>LTE</td>
</tr>
</tbody>
</table>

**Table 9: WiMAX to LTE**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Today</th>
<th>Medium term</th>
<th>Long term</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WiMAX</td>
<td>WiMAX, 16+</td>
<td>WiMAX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>evol some 16m features</td>
<td>LTE</td>
</tr>
</tbody>
</table>

---

32 Source: Courtesy Alcatel Lucent.
Table 9: LTE-Advanced Capability Relative to IMT-Advanced Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>IMT-Advanced Requirement</th>
<th>LTE-Advanced Projected Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Data Rate Downlink</td>
<td>1 Gbps</td>
<td></td>
</tr>
<tr>
<td>Peak Data Rate Uplink</td>
<td>500 Mbps</td>
<td></td>
</tr>
<tr>
<td>Spectrum Allocation</td>
<td>Up to 40 MHz</td>
<td>Up to 100 MHz</td>
</tr>
<tr>
<td>Latency User Plane</td>
<td>10 msec</td>
<td>10 msec</td>
</tr>
<tr>
<td>Latency Control Plane</td>
<td>100 msec</td>
<td>50 msec</td>
</tr>
<tr>
<td>Peak Spectral Efficiency DL</td>
<td>15 bps/Hz</td>
<td>30 bps/Hz</td>
</tr>
<tr>
<td>Peak Spectral Efficiency UL</td>
<td>6.75 bps/Hz</td>
<td>15 bps/Hz</td>
</tr>
<tr>
<td>Average Spectral Efficiency DL</td>
<td>2.2 bps/Hz</td>
<td>2.6 bps/Hz</td>
</tr>
<tr>
<td>Average Spectral Efficiency UL</td>
<td>1.4 bps/Hz</td>
<td>2.0 bps/Hz</td>
</tr>
<tr>
<td>Cell-Edge Spectral Efficiency DL</td>
<td>0.06 bps/Hz</td>
<td>0.09 bps/Hz</td>
</tr>
<tr>
<td>Cell-Edge Spectral Efficiency UL</td>
<td>0.03 bps/Hz</td>
<td>0.07 bps/Hz</td>
</tr>
</tbody>
</table>

While throughputs and low latency get most of the attention when discussing LTE, it is another capability that will play an important role in LTE networks, namely quality-of-service control. LTE defines nine different Quality Class Indicator (QCI) values that control priority, delay, and packet loss. See Table 10. GBR refers to guaranteed bit rate, and is provided with the first four QCI values.

This framework enables operators to reliably implement services such as VoIP and video. It also allows for policy-based control of services, which are controlled via a network function called the Policy Charging and Rules Function (PCRF). The Evolved Packet System architecture shown in Figure 17 above shows the location of the PCRF. An example of using PCRF is automatically applying the appropriate QoS values when a user engages in an interactive video call. The PCRF also enables operators to develop pricing plans that apply different policies to different types of applications.
Table 10: LTE Quality Class Indicators

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource Type</th>
<th>Priority</th>
<th>Delay Budget</th>
<th>Packet Loss</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100 msec.</td>
<td>$10^{-2}$</td>
<td>Conversational voice</td>
</tr>
<tr>
<td>2</td>
<td>GBR</td>
<td>4</td>
<td>150 msec.</td>
<td>$10^{-3}$</td>
<td>Conversational video (live streaming)</td>
</tr>
<tr>
<td>3</td>
<td>GBR</td>
<td>3</td>
<td>50 msec.</td>
<td>$10^{-3}$</td>
<td>Real-time gaming</td>
</tr>
<tr>
<td>4</td>
<td>GBR</td>
<td>5</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Non-conversational video (buffered streaming)</td>
</tr>
<tr>
<td>5</td>
<td>Non-GBR</td>
<td>1</td>
<td>100 msec.</td>
<td>$10^{-6}$</td>
<td>IMS signaling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Video (buffered streaming), TCP Web, e-mail, ftp, ...</td>
</tr>
<tr>
<td>7</td>
<td>Non-GBR</td>
<td>7</td>
<td>100 msec.</td>
<td>$10^{-3}$</td>
<td>Voice, video (live streaming), interactive gaming</td>
</tr>
<tr>
<td>8</td>
<td>Non-GBR</td>
<td>8</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Premium bearer for video (buffered streaming), TCP Web, e-mail, ftp, ...</td>
</tr>
<tr>
<td>9</td>
<td>Non-GBR</td>
<td>9</td>
<td>300 msec.</td>
<td>$10^{-6}$</td>
<td>Default bearer for video, TCP for non-privileged users</td>
</tr>
</tbody>
</table>

Initial LTE networks will not support voice, but there is a fully standards-based approach for voice defined. There are various ways that voice can be handled in LTE. The approach likely to be adopted by most operators is to begin with a method called Circuit-Switched Fallback (CSFB). This means that if a device is using LTE, and it needs to make a phone call, it switches to 2G or 3G to make the phone call using legacy circuit-switched methods. Over time, operators will install VoIP infrastructure using the IP Multimedia Subsystem (IMS). With this subsystem in place, operators will be able to support voice in the packet domain, as shown in Figure 25. A GSM Association (GSM) industry initiative called Voice over LTE (VoLTE)\(^ {33} \) specifies the details. CSFB will still be required for users who exit the LTE coverage zone. Eventually, once LTE network coverage matches 2G/3G coverage, voice calls will stay on the LTE network.

**Heterogeneous Networks**

An essential capability of next generation networks will be to accommodate and integrate multiple types of networks, as shown in Figure 26. Characteristics will include:

- Different frequency bands.
- Different technologies including Wi-Fi, 2G, 3G, and 4G.
- Multiple cell sizes ranging from 10 meters range (femtocell), through picocells or metrocells, to macro cells of up to 50 kilometers range.
- Ability to use wireless links for backhaul.
- Self-organizing and self-optimizing. Self-optimization includes load balancing between base stations, interference control, and management of capacity and coverage.
Femtocells

An important component of heterogeneous networks will be femtocells. Femtocells use an operator’s licensed frequencies. To a mobile device, a femtocell is indistinguishable from a normal base station. Femtocells not only can improve indoor coverage, but through their high frequency reuse, can augment capacity.

Figure 27 shows the femtocell architecture. The key components are: the femtocell access point that connects to a subscriber’s fixed-broadband connection; a configuration server that contains access point parameters, that manages AP firmware, and that has security information; and the femtocell gateway to the wireless operator network.
Figure 27: Femtocell

Configuration Server:
- Access Point Parameters
- Firmware management
- Security certificates