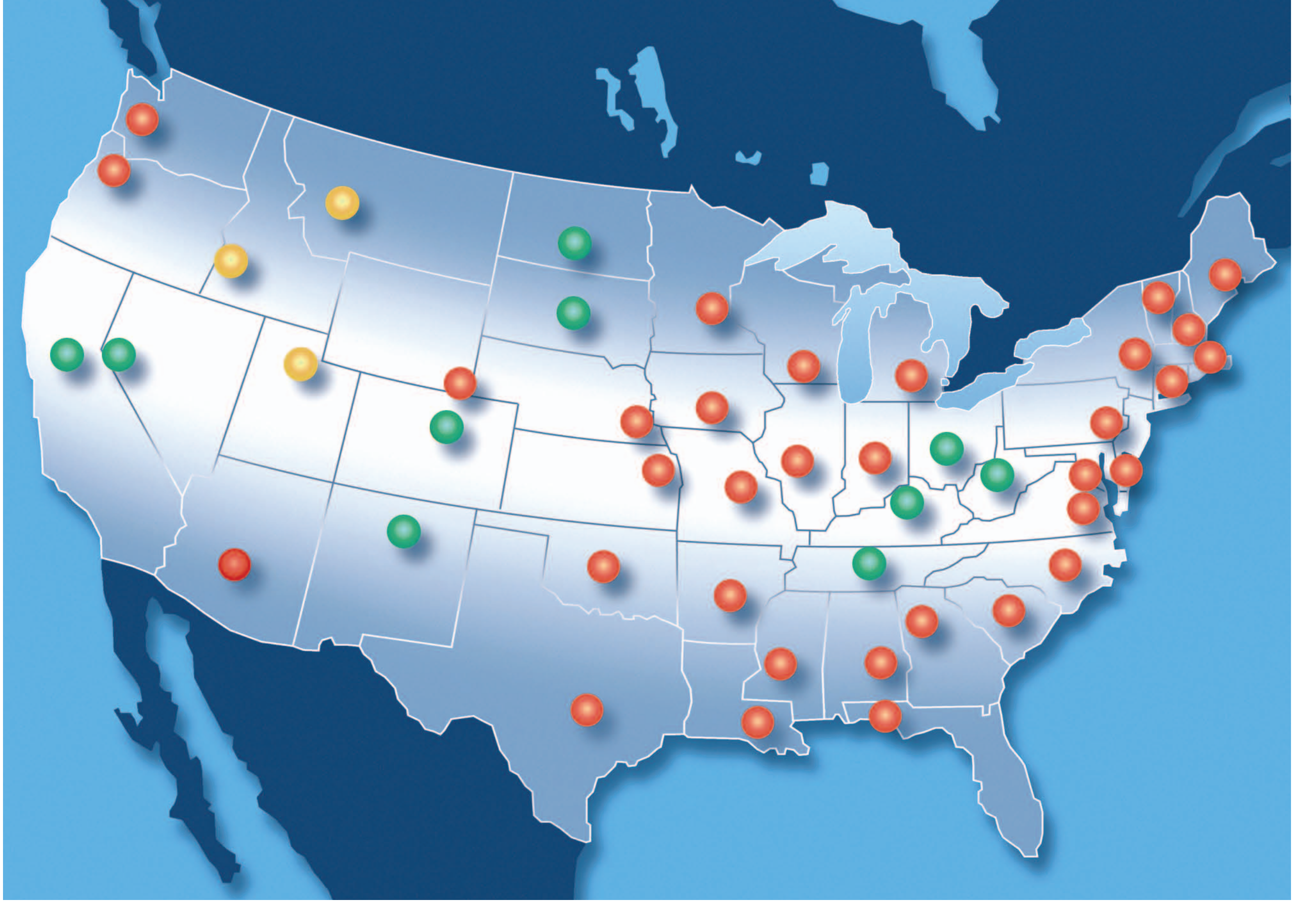

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NATIONWIDE SAFETY

Nationwide Modeling for Broadband Network Services

Richard Rouil,
Antonio Izquierdo,
Michael Souryal,
Camillo Gentile,
David Griffith,
and Nada Golmie

As governments plan nationwide, interoperable broadband networks for their public safety services, the challenge arises of determining how and where to invest limited resources to meet demanding requirements. The United States is in the early stages of planning a nationwide 700-MHz long-term evolution (LTE) network for use by public safety officials at the local, state, and federal levels. This article presents a framework for the modeling and planning of a public safety broadband network on a nationwide scale. This framework addresses the challenges of modeling and planning for a country that is diverse in terms of terrain, user density, and public safety needs. It does so while managing computational complexity so that alternate scenarios (e.g., target areas, user requirements, and site assumptions) can be readily assessed in a timely fashion. The approach utilizes a clustering algorithm to classify areas by their terrain characteristics and user population, an iterative process for sampling and analyzing areas within each cluster, and extrapolation of the results to generate nationwide statistics such as site count, coverage percentage, and network load. Examples are given that illustrate the implications of stringent coverage reliability requirements as well as the impact of high traffic density resulting from an incident response.

Digital Object Identifier 10.1109/MVT.2013.2252293
Date of publication: 29 April 2013

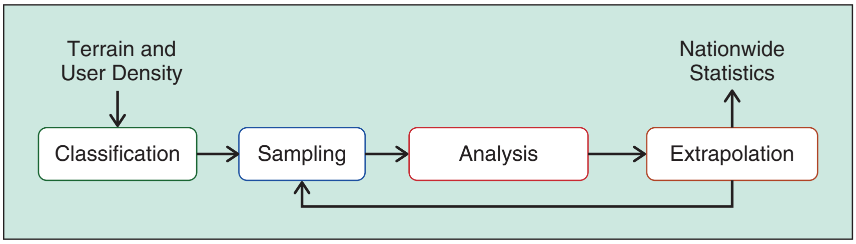

FIGURE 1 The modeling process.

Recent legislation in the United States provides 10 MHz of additional spectrum and the means to build a nationwide public safety broadband network based on LTE technology [1]. This measure is intended to address the bandwidth shortage and the widespread interoperability issues that have plagued public safety communications for decades.

As with most large-scale network deployments, there are many issues to address in the planning phase, such as a cost analysis of the resources needed [2], the expected coverage and capacity, the architecture, and the level of quality of service to be supported. To address some of these issues, it is common to use modeling and simulation to test what-if scenarios and provide insights on the network performance and the resources needed.

In developing a model for the nationwide network, a number of challenges specific to public safety are uncovered. While large-scale commercial network deployments follow pilot programs in a few select locations and are then gradually expanded to satisfy usage and projection needs, the deployment of the U.S. nationwide public safety network is expected to follow an aggressive time schedule that may not fully benefit from lessons learned and prior experience. The second challenge is the need to meet more stringent performance requirements on reliability, latency, and error rate while maximizing bandwidth and coverage. The third challenge is to accurately characterize the public safety user population distribution. Unlike commercial network users, public safety users tend to aggregate near borders, airports, and prisons, in addition to quickly converging at the scene of an incident whether in the middle of an urban, suburban, or rural area. The fourth challenge stems from having to plan for a wide range of scenarios, from day-to-day operations, such as traffic stops, to major incidents, such as earthquakes and hurricanes.

Our objective in this article is to describe the approach to modeling a large-scale public safety network like the one planned for nationwide deployment in the United States. We highlight some of the unique challenges encountered in the modeling and our solutions to account for the specific needs and requirements of public safety communications.

Tackling Large-Scale Modeling

Methodology Overview

To manage the scale, complexity, and computational resources required for modeling a nationwide LTE network, the general approach is to analyze a subset of areas that are representative of the whole and then extrapolate the results of the subset to obtain nationwide metrics, such as site count, coverage percentage, and network utilization. Care must be taken in the choice of representative areas and in the extrapolation to minimize uncertainty. The process is iterative and consists of four major components, as depicted in Figure 1.

1) Classification: subdivides the nation into small areas and groups them into a finite number of classes based on terrain and user population characteristics.
2) Sampling: selects a subset of areas from each class for detailed RF analysis.
3) Analysis: performs an RF analysis of a specific area to determine the resources required to meet coverage and reliability targets and measures the achieved coverage and cell loads.
4) Extrapolation: scales the analysis results to the entire nation and iterates with sampling and analysis until performance metrics converge for each class.

The process of classification, sampling, and extrapolation is described in more detail in the remainder of this section, while details of the RF analysis are taken up in the section "Localized Analysis."

Problem Reduction: Classification

The classification process reduces the problem of simulating an entire nationwide network for public safety users to a set of feasible objectives, whose results can be combined to provide a reasonable estimate of the nationwide network. After segmenting the United States into a uniform grid of square areas, we classify the areas based on their terrain and user density characteristics. We choose these two factors because they directly affect the level of infrastructure needed and the performance of a wireless network: terrain and clutter features affect signal propagation, and user density affects network load and intercell interference.

Terrain elevation data with a resolution of 1 arcsec is obtained from NASA's Earth Observing System Clearinghouse [3]. We use the standard deviation of the elevation in the classification process because the variation in elevation (hills and mountains) significantly affects signal propagation.

The distribution of public safety users is not as readily available. Although one could start with the

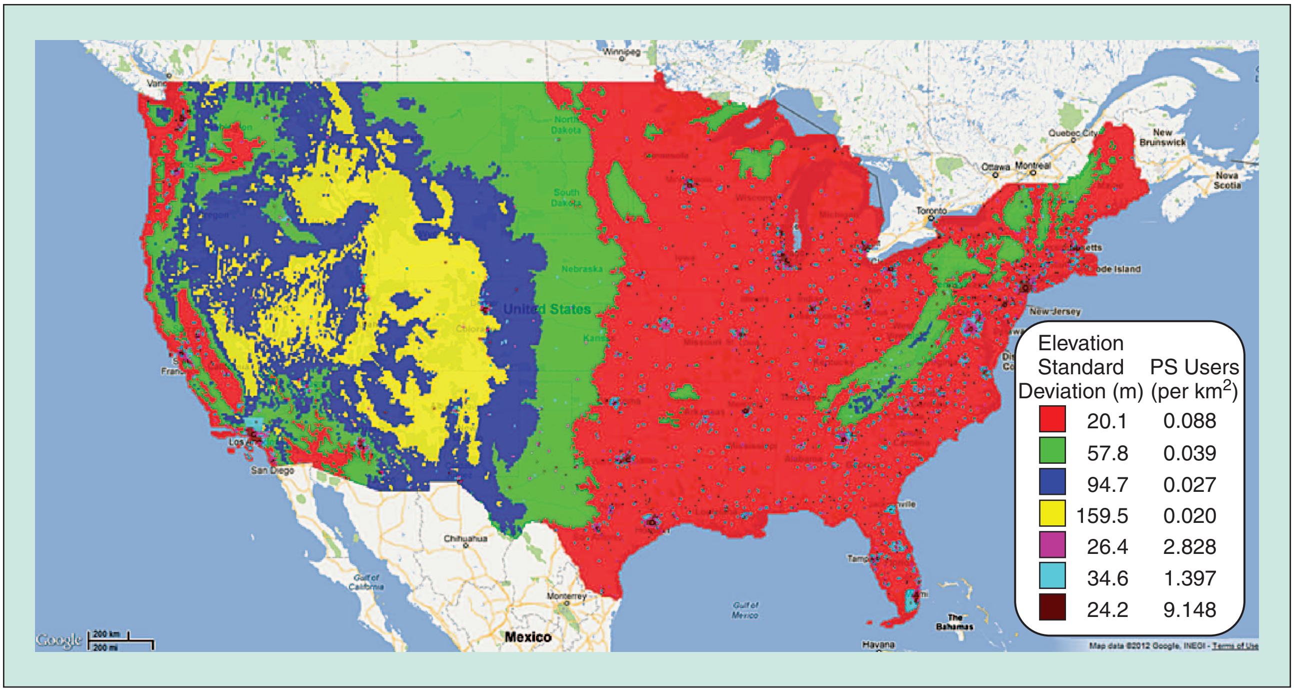

FIGURE 2 Sample classification of the contiguous United States into seven classes based on terrain and public safety user density. (Copyright 2012 Google, INEGI.)

distribution of the general population and apply a fixed ratio to convert it to an estimated distribution of public safety users, this simplified approach does not consider that many of these public safety users perform their work in areas with low or zero population and that there are locations, such as airports, border crossings, and prisons, where the concentration of public safety users significantly differs from that of the general population.

To account for these peculiarities, we gathered information on public safety services in the United States, including federal, state, and local personnel, from multiple sources. When the information gathered did not specify the distribution of the users among the different centers of operation (e.g., the number of border patrol agents per port of entry), we distributed them in proportion to the volume of each center (e.g., the number of travelers entering each port).

The final element is the clustering algorithm, which is responsible for grouping areas into classes that have similar characteristics. To avoid bias, we use an unsupervised classification algorithm for this task, such as K-means [4] or the expectation-maximization algorithm [5].

Figure 2 shows an example classification of the contiguous United States based on terrain and density of public safety employees divided into seven classes. The legend lists for each class the standard deviation of the elevation and the public safety user density averaged over all the areas in the class.

Result Expansion

Once the classification is complete, we randomly sample areas in each class for detailed RF analysis. Each generated class is sampled independently; we obtain the number of samples through an iterative process that uses the results of the analyses in the previous iteration. For each class, an initial set of samples (e.g., five samples) is randomly selected, analyzed, and used to compute performance metrics, including the average number of sites, area coverage, and population coverage. At each subsequent iteration, we select, analyze, and compute average performance metrics for a larger, expanded set of samples within the class. If the performance metrics of the expanded set differ from those of the previous set by less than a predefined threshold (defined by the target confidence margin we intend to obtain), the accumulated samples are deemed to be representative of the class and the sampling stops; otherwise, the algorithm performs another iteration with additional randomly selected samples.

Once the performance metrics generated by the sampled areas in a class have converged, these results are extrapolated to the whole class within certain confidence intervals. Finally, extrapolated results for all the classes are aggregated to obtain nationwide metrics.

Localized Analysis

The approach to modeling a nationwide network described in the preceding section involves a detailed RF analysis of selected representative areas. The results

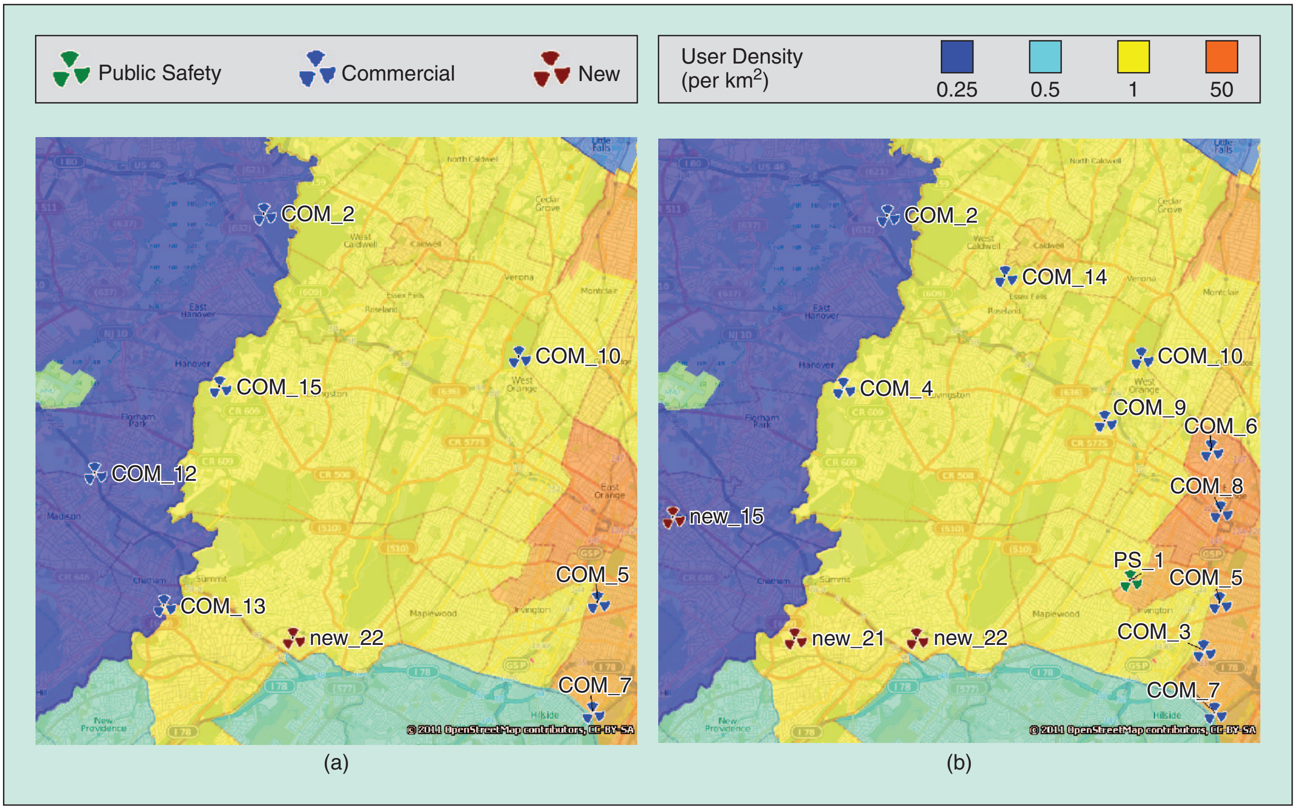

FIGURE 3 Site selections for a 20 km × 20 km area in northern New Jersey (a) with 85% coverage reliability requirement and (b) with 95% coverage reliability requirement. (Copyright OpenStreetMap contributors.)

of this localized analysis include metrics such as the number of sites needed to meet the coverage target, actual achieved coverage (in terms of area covered and population covered), and network utilization. This section describes our approach to localized RF analysis and includes illustrative examples of particular relevance to the public safety community.

Site Selection

A site-selection algorithm selects, from a database of candidate cell sites, the minimum number of sites that meet target coverage levels in the area under analysis. Using the geographic distribution of public safety employees discussed in the previous section, the algorithm first discretizes the public safety user density in the area into demand points using a tiling algorithm [6]. It then selects those sites from the database that are needed to cover the demand points using an iterative greedy algorithm with substitution [7]. A demand point is deemed to be covered by a site if the LTE downlink reference signal received power (RSRP) at the demand point exceeds a threshold. The threshold value is based initially on the target data rate and coverage probability. However, since RSRP is a measure of signal strength only, the coverage metric used in site selection serves as an upper bound. More accurate coverage is determined by a subsequent, more detailed performance analysis that accounts for cell loads and intercell interference on both the uplink and downlink, as described in the section “Performance Analysis.” If the performance analysis shows that coverage targets are not met, site selection is repeated with a higher RSRP coverage threshold, effectively increasing the number of sites. Iterations between performance analysis and new site selection are repeated until either the coverage targets are met or there is only marginal improvement in coverage.

Candidate sites in the database are made up of three categories: 1) existing public safety sites (e.g., land mobile radio towers), 2) existing commercial cellular sites, and 3) candidate new sites. Weights can be assigned to these categories so that, for example, public safety sites are given higher priority than commercial sites in the selection algorithm and new sites are given the lowest priority (since they probably would incur the highest cost to establish). When evaluating a site’s contribution in the selection algorithm, the weight of a site is multiplied by the number of demand points it covers. Thus, the higher the weight, the greater the priority that is given to that site.

Figure 3(a) illustrates an example of executing the site-selection algorithm on a 20 km × 20 km area in northern New Jersey. Overlaid on the map are colors indicating the public safety user density. In this case, the algorithm determined that a total of eight sites (with three sectors/site) are needed to meet a coverage target of 95% of the area and 95% of users with 85% reliability at the cell edge. The selected sites consist of seven existing commercial sites and one new site.

Whereas 85% cell-edge reliability may be acceptable for commercial cellular networks, public safety radio networks are typically designed for higher coverage reliability. Figure 3(b) shows results for the same 20 km × 20 km area, but now with a higher cell-edge coverage reliability requirement of 95%. In this case, the site-selection algorithm determined that a total of 14 sites are needed to achieve the more stringent coverage requirement, among them an existing public safety site, ten existing commercial sites, and three new sites. Such analysis can be used to estimate the cost impact of various coverage reliability levels.

TABLE 1 Traffic model [8, p. 26].

		Type of Device	*Percent of PS Users Carrying Device*	*Uplink Data Rate (kb/s)*	*Downlink Data Rate (kb/s)*	*Percent of Time Device Transmits*	*Percent of Time Device Receives*
Normal traffic	Incident traffic	Mobile video camera	25%	256	12	10%	5%
		Data file transfer CAD/GIS	87%	50	300	15%	5%
		VoIP	100%	27	27	5%	15%
		Secure file transfer	12%	93	93	5%	5%
		EMS patient tracking	6%	30	50	10%	5%
		EMS data transfer	6%	20	25	25%	5%
		EMS Internet access	6%	10	90	10%	5%
		Command unit downlink video	—	—	512	—	100%
		Command unit uplink video	—	512	—	100%	—

Performance Analysis

Using the site locations, a detailed performance analysis predicts the coverage and cell loads in the selected area. The analysis consists of Monte Carlo simulations that, for randomly distributed users, calculate the received signal and interference on each LTE link (uplink and downlink) and the time-bandwidth resources (i.e., resource blocks) utilized by each link. The simulations are iterative, yielding at each iteration cell-load estimates that determine intercell interference values for the next iteration. Once the simulations converge, a subsequent network analysis calculates coverage maps showing where the signal-to-interference-plus-noise ratio is sufficient to support the target data rate. The performance analysis is implemented through application programming interface calls to a commercial RF planning tool.

After introducing the traffic model, the remainder of this section analyzes two scenarios, one reflecting normal day-to-day public safety traffic and the other with high traffic density in a small area reflecting an incident-response scenario.

Traffic Model

A prerequisite to conducting an RF analysis is a traffic model that characterizes the voice, data, and video transmissions on the network. A number of traffic models have been proposed in the literature for analysis of public safety scenarios (e.g., [8]–[10]) varying in application mix and data rates and whether they reflect day-to-day operations or an incident response. One example, shown in Table 1, was used to analyze an incident-response scenario based on the 2007 collapse of the Interstate 35 bridge in Minneapolis, Minnesota [8, pp. 25–31]. The traffic model consists of seven applications used by individual first responders that vary in data rate, the percentage of users carrying the device, and the percentage of the time the device actively transmits and receives. In addition to these applications, the model assumes that mobile command centers are on the scene that transmit and receive video traffic at rates up to 512 kb/s per video stream. Since the command unit video streams dominate the traffic load in this model, we use the first responder device traffic (i.e., without the command unit video) to emulate normal day-to-day operations, and the full traffic model (including command unit video) to emulate incident-response traffic.

Analysis with Normal Traffic

We first apply the normal traffic profile, the first seven rows of the traffic model in Table 1, to the public safety user density discussed in the section "Problem Reduction: Classification." The RF analysis is based on the 14-site topology, shown in Figure 3(b), designed for 95% coverage (in terms of both area and users) with 95% cell-edge reliability. According to the user

Table 2 ***LTE settings for RF analysis.***

Duplex scheme	Frequency division duplex
System bandwidth	10 MHz downlink, 10 MHz uplink
Transmit power	43 dBm downlink, 23 dBm uplink
MIMO	2×2 downlink, 1×2 uplink
Downlink antenna	Andrew LNX-6515DS-VTM 0725[1]
Uplink antenna	Uniform, −4 dBi
Channel propagation model	CRC[2]-predict
Slow fading model (standard deviation)	Lognormal (7 dB)

(1) Certain commercial equipment, instruments, or materials are identified in this article in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
(2) Communications Research Centre, Canada.

distribution in this area, there are approximately 400 public safety users in this 20 km × 20 km area under normal conditions. The main LTE settings used in the analysis are summarized in Table 2, and an illustrative uplink budget is given in Table 3.

Table 3 ***LTE settings for RF analysis.***

Transmitter (User Equipment)		
a	Maximum TX power (dBm)	23
b	TX antenna gain (dBi)	−4
c	EIRP = a + b (dBm)	19
Receiver (eNodeB)		
d	Noise figure (dB)	2.5
e	Thermal noise in 720 kHz (4 resource blocks) occupied bw (dBm)	−115.4
f	Target UL SINR (dB)	−0.1
g	Receiver sensitivity = d + e + f (dBm)	−113.0
h	Peak RX antenna gain (dBi)	16.7
i	Cable/connector loss (dB)	2.5
j	Slow fading margin for 95% cell-edge coverage probability (dB)	11.5
k	Interference margin (dB)	3
l	Handoff gain (dB)	2.8
Maximum allowable path loss = c − g + h − i − j − k + l (dB)		134.5

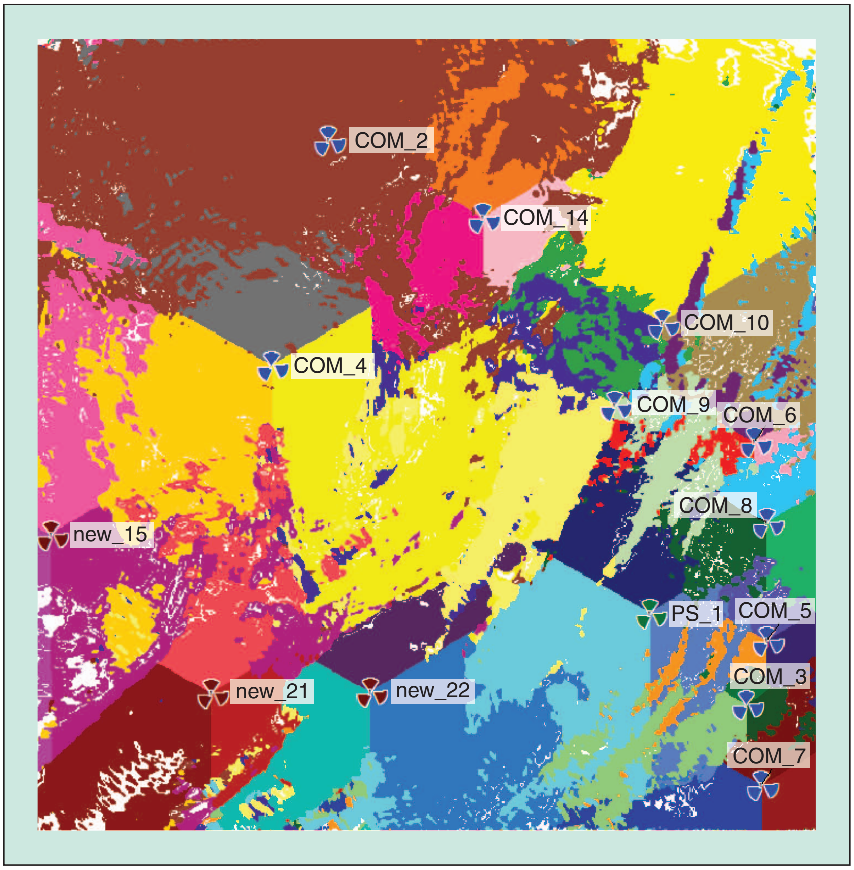

Figure 4 Coverage map of a normal traffic scenario.

The results of the analysis show that 96.8% of the area is covered and 95.3% of the users are served with 95% reliability, meeting the performance targets. Figure 4 shows a coverage map color-coded by serving sector, with areas in white representing coverage holes. Furthermore, the downlink and uplink aggregate throughput of the 42 sectors under the assumed normal traffic conditions are shown in Figure 5. The three most loaded cells are sectors 1 and 3 of COM_8 and sector 1 of COM_10 (sectors are numbered clockwise from the north). These sectors cover the higher user density areas in the northeastern and southeastern parts of the area, as seen in Figure 3(b). Nevertheless, these loads occupy less than 5% of time-bandwidth resources, implying that ample capacity exists to absorb additional traffic.

Analysis with Incident-Response Traffic

To model an incident-response scenario, we designate a 3 km × 3 km area in the center that has ten times the normal density of public safety users (see Figure 6). In addition to the traffic generated by these first responders, we introduce six mobile command centers (MCCs) uniformly distributed in the 9-km^2 incident area. We assume that each MCC receives six command unit video streams on the downlink and transmits two command unit video streams on the uplink, for a total of 36 downlink video streams and 12 uplink video streams in the incident area.

The resulting sector throughput from the analysis is shown in Figure 7. Here, one cell is much more loaded than the rest, with 10.2 Mb/s of traffic on the downlink (83% utilization) and 3.6 Mb/s on the uplink (40% utilization). This cell, sector 2 of COM_4, is directed at the incident area and provides the bulk of the coverage in that area. The second most loaded cell is sector 3 of COM_9, which is also directed toward the incident area but covers a smaller portion of it.

Due to the higher cell loads and corresponding intercell interference in the incident area, only 91.6% of the incident area is covered, less than the target of 95% (with 95% reliability). Furthermore, over the Monte Carlo simulations, on average only five of the six mobile command centers are served. The primary reason that not all MCCs are served is insufficient downlink resources, indicating a capacity-limited system. This is consistent with the fact that the incident area is primarily served by one sector with a downlink utilization of 83%.

Two approaches can be taken to address capacity limitations in incident-response scenarios. In the first approach, the fixed radio access network can be designed with incident-response scenarios in mind. Rather than applying the site-selection algorithm to the normal traffic density, we could apply it to a much higher traffic density, resulting in more sites. For instance, when running the site-selection algorithm on the 20 km × 20 km area with twice the normal traffic density and 50 MCCs distributed over the entire area, 31 sites are needed to meet the 95% coverage requirement. At four times the normal traffic density and 100 MCCs, 57 sites are selected but they provide only 90% coverage. Clearly, this approach can be very costly, as site costs tend to dominate capital expenses. Another approach is to rely on the use of rapidly deployable infrastructure (e.g., cell-on-wheels). In this approach, the fixed site network is designed to handle

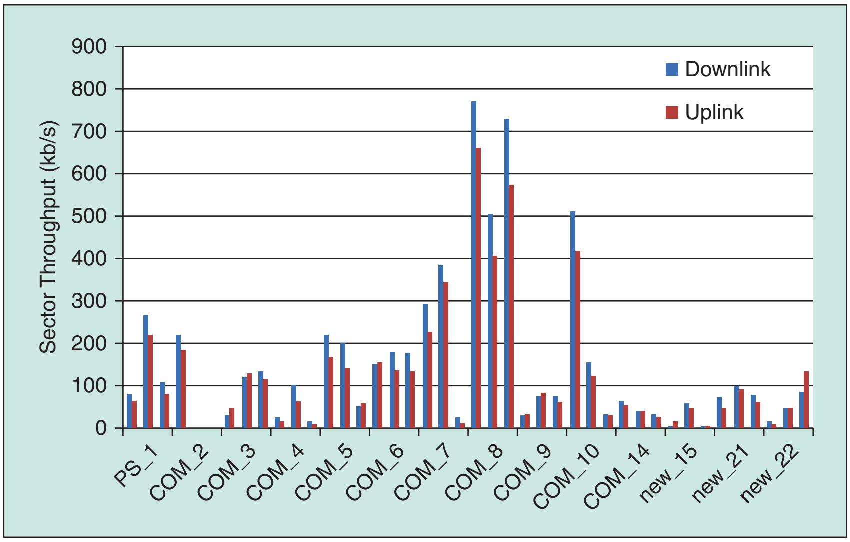

FIGURE 5 Sector throughput with normal traffic.

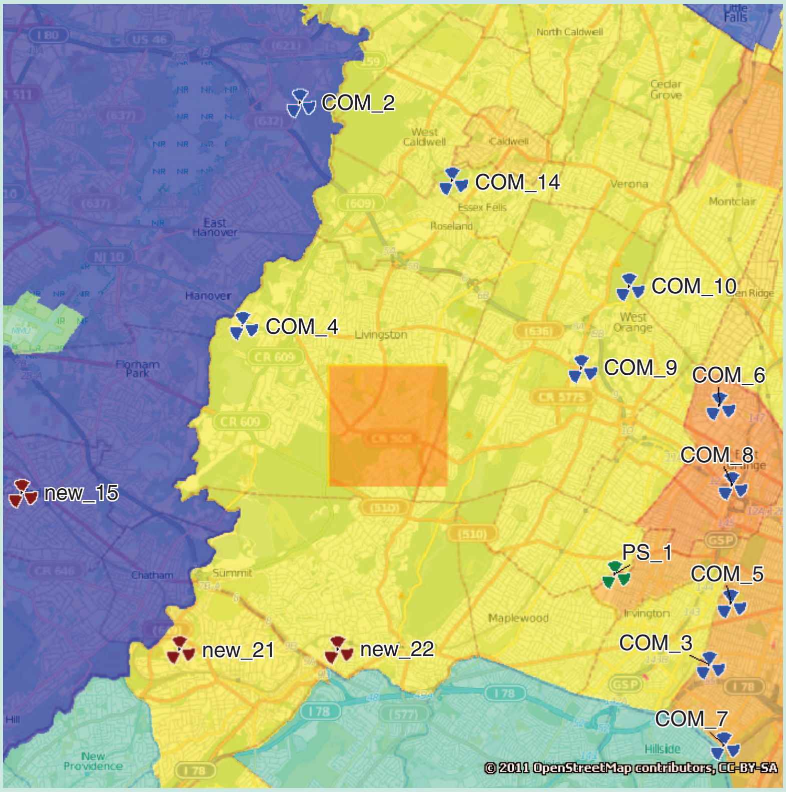

FIGURE 6 Analysis area with 3 km × 3 km high-traffic incident area at the center. (© OpenStreetMap contributors.)

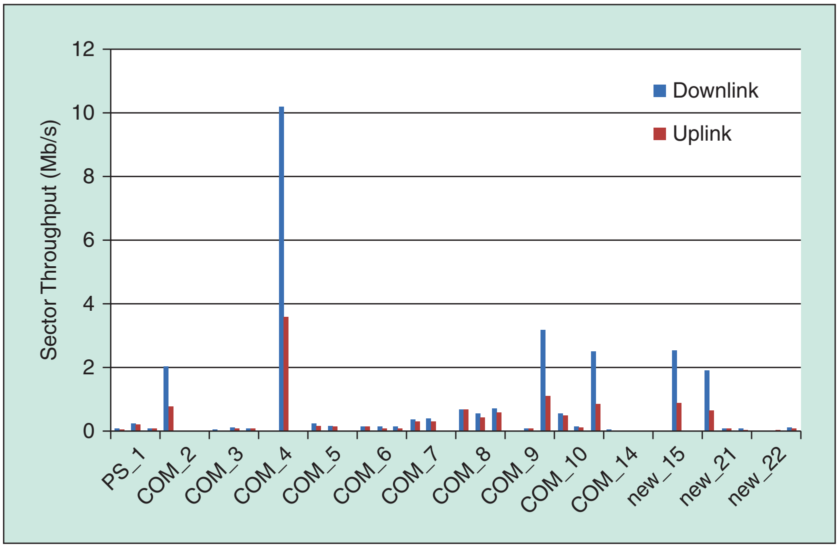

FIGURE 7 Sector throughput with incident area traffic.

normal traffic, and possibly small-scale incidents, and temporary sites with wireless backhaul are used to augment capacity for large-scale incidents.

Limitations and Future Enhancements

Channel propagation models are a critical component of any RF analysis. The results in the section "Localized Analysis" were generated with a path loss model (CRC-Predict) that uses topographic data to calculate the diffraction attenuation due to irregular terrain. To improve accuracy, propagation models can be tuned with signal strength measurements collected from drive tests. Since it is unrealistic to collect measurements from every potential site of a nationwide network, one possible approach is to tune the model for each class with measurements collected in select representative areas of the class.

Other factors affecting path loss predictions include indoor building penetration and ground-level communication. While our initial analysis is based on an outdoor model, building penetration models that depend on the thickness and material properties of walls can be used to provide estimates of indoor coverage. Furthermore, heterogeneous network components (femtocells and picocells) will likely be used to improve indoor coverage as well as supplement coverage or capacity during large-scale emergency events. While traditional macro sites are typically located at building and tower heights, heterogeneous and rapidly deployable components will more likely be at ground level with vehicle-mounted antennas. Similarly, peer-to-peer communications, a highly desired capability in public safety communications, imply RF links at human height. Ground-level communications can behave quite differently than tower deployments due to predominant non-line-of-sight, especially indoors, and high path loss exponents [11]. Also, studies at 2.4 GHz have shown that, when transmitters are placed at pedestrian height, attenuation from a human body can be up to 20 dB as opposed to 3 dB at other heights [12]. This is critical when emergency response workers/victims are aggregated around an incident. To date, there are limited data collected for ground-level propagation in the 700-MHz band.

Also significant is whether site configurations are optimized. Optimization involves a multidimensional search in a nonconvex space for the optimum transmission power, antenna height, azimuth, and tilt of each sector to maximize some metric (e.g., coverage). Because site optimization is computationally intensive, especially when a large number of sites are involved, our initial analysis is based on default site configurations. However, practical optimization algorithms can be incorporated, ideally in conjunction with site selection.

Cellular planning tools, such as the one used to generate the results of the RF analysis, are based on static signal-to-interference-and-noise ratio (SINR) predictions and are useful for predicting coverage and average throughput. In reality, the SINR is highly dynamic both in time and in frequency due to frequency-selective fast fading and intercell interference. Packet-level simulations can be incorporated in our framework to supplement the static RF analysis and provide quality-of-service metrics such as delay and packet loss. Such metrics are especially important when studying incident-response scenarios, during which the network can be susceptible to congestion.

Conclusion

In this article we have presented a framework to address the challenges of modeling and planning the deployment of a nationwide public safety broadband network. We have outlined an approach for decomposing a large network into smaller areas, identifying and analyzing areas with similar characteristics, and extrapolating the data to the national level. This approach takes into account the terrain and user density diversity in addition to public safety needs. Illustrative examples are given to highlight the impact of high traffic density due to an incident response and the implications of imposing more stringent coverage reliability requirements.

Author Information

Richard Rouil earned his Ph.D. in computer science from Telecom Bretagne, Plouzané, France. His research focused on mobility in heterogeneous networks. He is

currently a researcher working at the National Institute of Standards and Technology, Gaithersburg, Maryland. His research interests include modeling and simulation of wireless networks, such as LTE and WiMAX. His current research focuses on the performance evaluation of LTE to support the deployment of networks used by public safety officials.

Antonio Izquierdo received his Ph.D. in computer science from Carlos III University of Madrid, Spain, in 2006 and his computer science degree from Universidad Pontificia de Comillas ICAI-ICADE, Madrid, Spain, in 2003. He is currently a researcher at the U.S. National Institute of Standards and Technology at the Advanced Network Technologies Division, Gaithersburg, Maryland. His research is focused on security and network performance metrics. His most recent work revolves around the study, characterization, and modeling of public safety networks, for which he has taken part in various projects researching, developing, and evaluating the security and performance of multiple wireless networks and security protocols. He has several papers published in international journals and conferences, as well as simulation models developed during his research.

Michael Souryal earned his D.Sc. in electrical engineering from George Washington University, Washington, D.C. He also has an M.S. in information networking from Carnegie Mellon University, Pittsburgh, and a B.S. in electrical engineering from Cornell University, Ithaca, New York. He is currently working with the Advanced Network Technologies Division at the National Institute of Standards and Technology, Gaithersburg, Maryland, conducting research in wireless communication systems. He was awarded an NRC Postdoctoral Fellowship at NIST in 2004. He was formerly with Telcordia Technologies where he focused on new service development for public network providers. He holds an adjunct appointment as professorial lecturer at George Washington University. His research interests are communication theory, dynamic spectrum access, and public safety communications.

Camillo Gentile received his B.S. and M.S. degrees from Drexel University, Philadelphia, and his Ph.D. degree from Pennsylvania State University, University Park, all in electrical engineering. He has been a researcher in the Advanced Network Technologies Division at the National Institute of Standards and Technology, Gaithersburg, Maryland, since 2001. His current interests include RF channel modeling, the smart grid, LTE, and millimeter-wave telecommunications.

David Griffith received his Ph.D. in electrical engineering from the University of Delaware. He worked on satellite communications systems at Stanford Telecommunications and Raytheon and is currently with the Information Technology Laboratory at the National Institute of Standards and Technology, Gaithersburg, Maryland. His research interests include mathematical modeling and simulation of wireless communications networks, including public safety broadband networks and the Smart Grid.

Nada Golmie (nada@nist.gov) received her Ph.D. in computer science from the University of Maryland, College Park. Since 1993, she has been a research engineer in the advanced networking technologies division at the National Institute of Standards and Technology, Gaithersburg, Maryland. She is currently the manager of the Emerging and Mobile Network Technologies Group. Her research in media access control and protocols for wireless networks led to over 100 technical papers presented at professional conferences, published in journals, and contributed to international standards organizations and industry-led consortia. She is the author of *Coexistence in Wireless Networks: Challenges and System-Level Solutions in the Unlicensed Bands* (Cambridge University Press, 2006). She is a member of the NIST Public Safety Communication Research program and is leading the efforts on the simulation modeling and evaluation of LTE in support of public safety communications. She is the editor of the *IEEE Journal on Selected Areas in Communications* smart grid series.

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