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How America's Fragmented Approach to Public Safety Wastes Money and Spectrum

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Abstract

Emergency responders such as firefighters, police, and paramedics depend on reliable and ubiquitous wireless communications. Failures in these communications systems can cost lives. Particularly since 9/11, there has been great concern about the possibility of failures due to lack of interoperability, and failures due to a shortage of public safety spectrum. This paper shows how both of these and other serious problems are a logical consequence of America's fragmented approach to public safety, in which thousands of local agencies make independent decisions without a coherent strategy to unify or guide them. Because of this fragmented approach, public safety agencies build more infrastructure than they should, spend more tax-payer money than they should, and consume more scarce spectrum than they should, all for a system that is unnecessarily prone to interoperability failures. This paper also considers the most widely cited estimates of public safety's spectrum needs, which predict a serious shortage unless considerably more spectrum becomes available to public safety by 2010. We show that estimates for the amount of spectrum needed in 2010 would be vastly lower if the US adopted an effective national strategy that included coordinated planning and modern technology. On the other hand, if the US retains today's fragmented approach, regions where coordination among local public safety agencies is particularly weak may need more spectrum than popular estimates would indicate, leading to an even greater shortage. We conclude that the federal government should start playing a large role in setting the direction of public safety communications, rather than leaving this to many independent local governments.

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1 Introduction

The communications systems used by emergency responders such as firefighters, police, paramedics, and the national guard are critical to public safety. Lives are lost when these systems fail. This was tragically demonstrated on a large scale after the 9/11attacks [1] and after Hurricane Katrina, and it is regularly demonstrated on a smaller scale throughout the United States. Studies of the firefighting and rescue efforts on 9/11 [1] have called attention to concerns regarding communications systems for emergency responders: especially interoperability failures, and potential spectrum shortages. However, to understand these and other serious concerns (including security, and dependability, which is certainly important after a Hurricane), we must consider the bigger picture and the underlying policies that have produced today's communications systems. The US has never developed a coherent architecture for public safety communications infrastructure, nor even a meaningful national strategy that would lead to close coordination of the more than fifty thousand US public safety agencies towards a commonly accepted set of objectives. By US tradition, every police department, fire department, and emergency medical service can make its own purchase decisions, and in most cases, this policy applies to communications systems. It is obvious that without effective coordination mechanisms, any communications infrastructure designed by many thousands of independent decision-makers is prone to producing a tangle of systems that do not interoperate. Although it is less obvious, this paper will argue that this fragmented policy on the design and operation of public safety communications also produces a communications infrastructure that costs more and consumes more spectrum than it should.

This paper will also examine estimates of spectrum requirements for public safety, while considering the impact of this same fragmented policy on communications infrastructure. According to the most widely cited estimates [2], public safety needed an additional 95.3 MHz of spectrum by 2010. This 95.3 MHz could partially be met by the 24 MHz allocated from the 700 MHz analog TV band, if and only if the digital TV transition proceeds at the requisite pace. Some would also include the recent allocation at 4940-90 MHz [3], although a MHz of spectrum at this high frequency is less useful for the intended applications than a MHz under 2 GHz would be, so there is disagreement about its value. These estimates were based on a straight-forward extrapolation of the technologies and policies that have long been used for public safety communications systems, without serious consideration of the impact of fragmentation on spectrum efficiency. This paper will argue that adoption of different technologies, managed through an effective national strategy, would require far less spectrum. Conversely, we argue that these estimates did not fully take into account the inefficiencies resulting from today's fragmented policy. As a result, it is possible that some systems could require even more spectrum than was predicted unless coordination is improved.

Section 2 shows how this fragmented approach to public safety communications infrastructure has led to the deployment of more infrastructure than is needed. Section 3 shows how an excess of infrastructure from non-cooperating local agencies leads to unnecessarily high spectrum use as well as unnecessarily high cost. In Section 4, we discuss the current estimates of how much spectrum is needed for public safety in the US, focusing on how this fragmented policy may make these estimates inaccurate. Conclusions are presented in Section 5.

2 The Architectural Impact of Political Fragmentation

One might expect that the number of antenna structures deployed by public safety in a given region would depend primarily and that region's total area. This proved not to be the case in a recent comparison of public safety infrastructure in 33 US counties [4].[2] Figure 1 is a scatter plot of the number of antenna structures in a given county[3] versus the area of that county. There is no clear pattern, which shows that area alone is a poor predictor of the number of antennas deployed for public safety. To identify better predictors and make inferences about causes, other factors were incorporated into a more complex analytic model. These factors included technically relevant parameters, as well as a measure of political fragmentation.

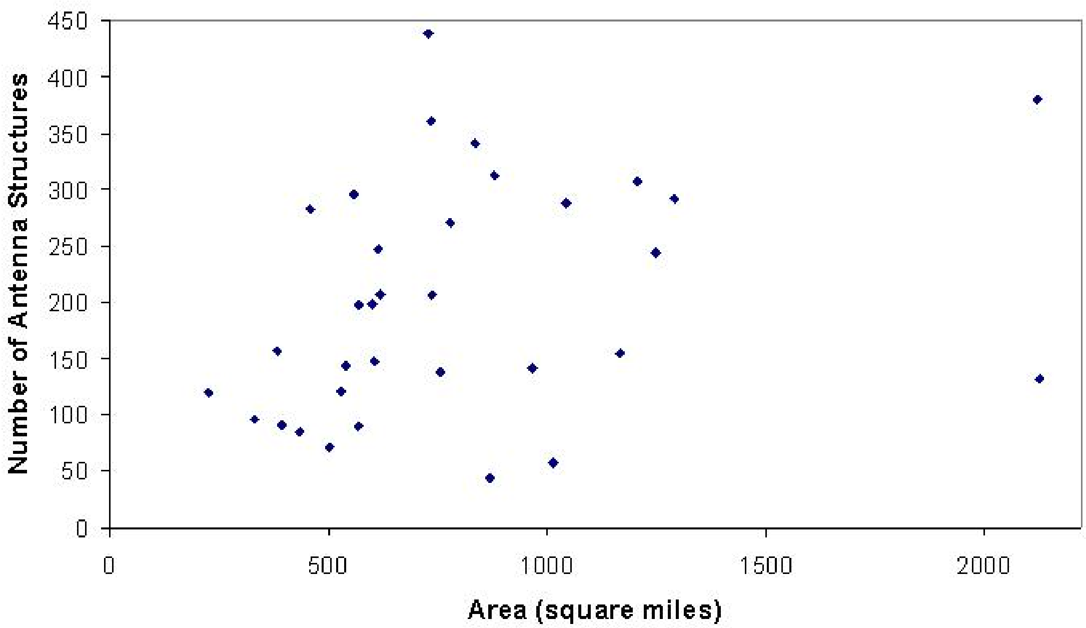

Figure 1: Number of antenna structures in county versus area of county

[2] Counties were selected that include a reasonably large urban area. Otherwise, they are diverse. See the Appendix (Section 8) for the list.

[3] The number of public safety antenna structures was calculated using data from the Federal Communications Commission database on Land Mobile Private, Public Safety Pool, Conventional licensees [5].

From a technical perspective, there are two factors other than area that could influence the amount of infrastructure required: population and terrain[4]. Where population is high, there will generally be more emergency responders using the communications system [2]. In some (but not all) architectures, it is possible to support a greater user density by deploying more antenna structures. Thus, population could affect the number of towers needed. In addition, where the terrain includes many hills and valleys, the area that can receive an adequate signal from a given antenna is smaller, potentially increasing the number of towers needed to cover a given area. Two parameters were used for terrain. The first is terrain roughness, which is the standard deviation of terrain elevation, as specified in the United States Geological Survey's National Map [6]. A flat region would have a small roughness value. A hilly region would have a large roughness value, and a much smaller coverage area per antenna. However, an area with a single mountain peak could also have a large roughness value, but antennas placed on top of the mountain peak could have large coverage areas. To differentiate these cases, the Boolean variable *MOUNTAIN* was defined to be 1 if there is an absolute maximum elevation or a tight group of elevation maxima that are significantly above any other local terrain maxima. Otherwise, it is 0. Where *MOUNTAIN* is 1, the adverse effects of terrain roughness on coverage area should be smaller.

One final variable was included to account for political fragmentation: the number of municipalities in the county. Counties with more municipalities tend to have more public safety agencies and therefore more independent decision-makers, so decisions regarding infrastructure tend to be more fragmented. (There are exceptions where there is strong cooperation between municipalities, or where the State or County has preempted local agencies.) Of course, the laws of physics do not change at municipal borders, so from a technical perspective, the number of municipalities should have no impact whatsoever on the number of antennas needed or desired.

As shown in Figure 2, the strongest correlation with the number of public safety antenna structures is the number of municipalities, despite its technical irrelevance. The correlation of antennas with the number of municipalities is .70, whereas the correlation with area is just .31.

	Municipalities	Population	Terrain Roughness	Area (Sq miles)	Mountain
Antenna Structures	0.70	0.55	0.16	0.31	-0.08
Municipalities	1	0.37	-0.09	0.04	-0.23
Population		1	0.10	0.31	0.04
Terrain Roughness			1	0.52	0.87
Area (sq miles)				1	0.51

Figure 2: Correlations

[4] This assumes that the various wireless systems are offering comparable services, which is reasonable since voice services are the primary application at present.

To further isolate the impact of fragmentation, a first-order regression analysis was used to predict the number of antennas with all of the independent variables above. Then, the analysis was repeated with only technically relevant parameters (i.e. all of these same variables except the number of municipalities). The resulting equations are shown below as Equations 1 and 2, respectively.

Number of antenna structures = [Equation 1]

47.2 + 0.000050 POPULATION + 0.0477 AREA + 0.517 ROUGHNESS - 134 MOUNTAIN + 2.27 MUNICIPALITIES

Number of antenna structures = [Equation 2]

63.2 + 0.000087 POPULATION + 0.0523 AREA + 0.681 ROUGHNESS - 203 MOUNTAIN

It is clear from Equation 1 that the number of municipalities in a county has a big impact. Increasing the number of municipalities by 10 has as much impact as increasing county area by 476 square miles or by increasing population by 454 thousand people. Figure 3 shows a scatter plot of the number of antenna structures in a county versus the number predicted using Equation 1, which takes into account the number of municipalities. Most data falls fairly close to the value produced by Equation 1, which is represented by the line in Figure 3.

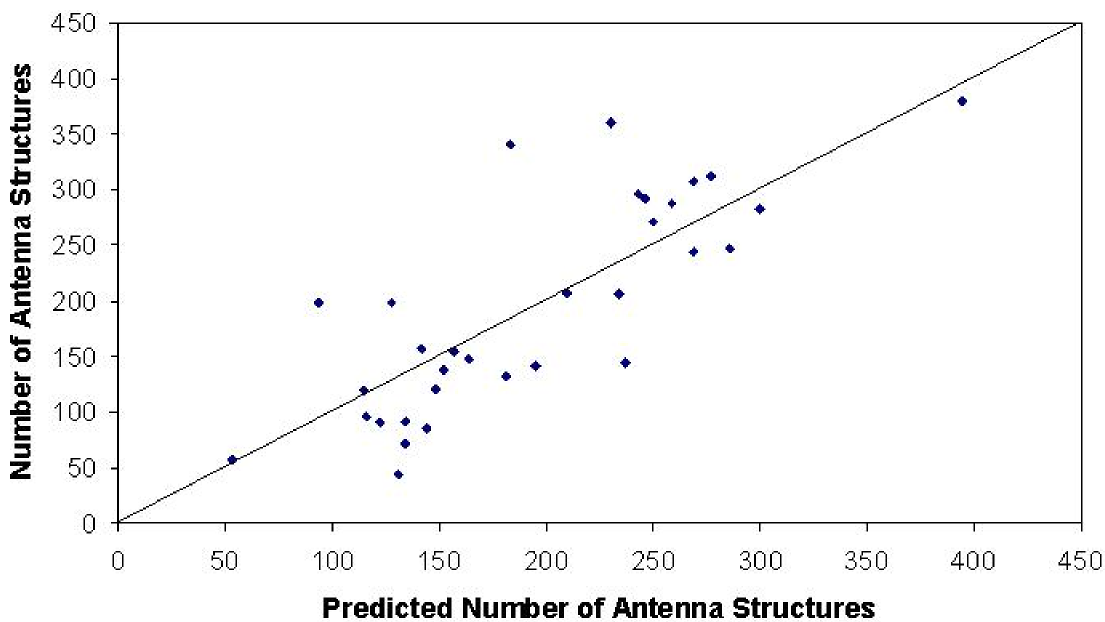

Figure 3: Number of antenna structures in county versus number predicted by Equation 1. Independent variables in this equation include the number of municipalities.

A good measure of how well the results of regression analysis account for the variation observed in actual data is the adjusted R^2 value (also known as the adjusted coefficient of determination). In general, R^2 values range from 0 to 1, where 1 means that 100% of the observed variation is accounted for. The adjusted R^2 was .41 when area, population, terrain roughness, and mountain were considered. The adjusted R^2 increased dramatically from .41 to .61 when the number of municipalities was added as an independent variable. Thus, even when one takes into account any correlation between the number of municipalities and technically relevant factors such as a county's area and population, the number of antennas in a county still depends heavily on the number of municipalities.

3 How Local Systems Can Waste Spectrum and Money

The reason that counties with more municipalities tend to have more antennas is that many municipal agencies operate communications systems specifically designed to cover the area where their emergency responders might someday operate (and perhaps additional area as well), with little or no regard for the communications systems used by their neighbors. Without national or regional planning, local agencies are far less likely to consider sharing their transmission towers or equipment, which leads to unnecessary duplication. They also have great difficulty placing transmitters in the locations that minimize spectrum requirements, or that save money by minimizing the number of towers, because those optimal locations may be far from their base(s) of operations, and sometimes entirely out of their jurisdictions.

To see how this results in inefficiencies, consider Figure 4, which shows two public safety agencies serving neighboring municipalities labeled city A and city B. (We will optimistically assume that there is only one system per city, although in some cities, firefighters and police have entirely separate systems.) Each city has its own broadcast tower(s), and its own license to a block of spectrum with sufficient capacity for its own needs. In these public safety systems, responders cannot "roam," i.e. cannot communicate with towers outside their own city, the way mobile users of commercial cellular systems can. For each city, coverage must extend beyond the municipality itself, so a police car can chase a suspect beyond the city limits without losing communications with its dispatcher, and so a fire truck can assist with a large fire in a neighboring town.

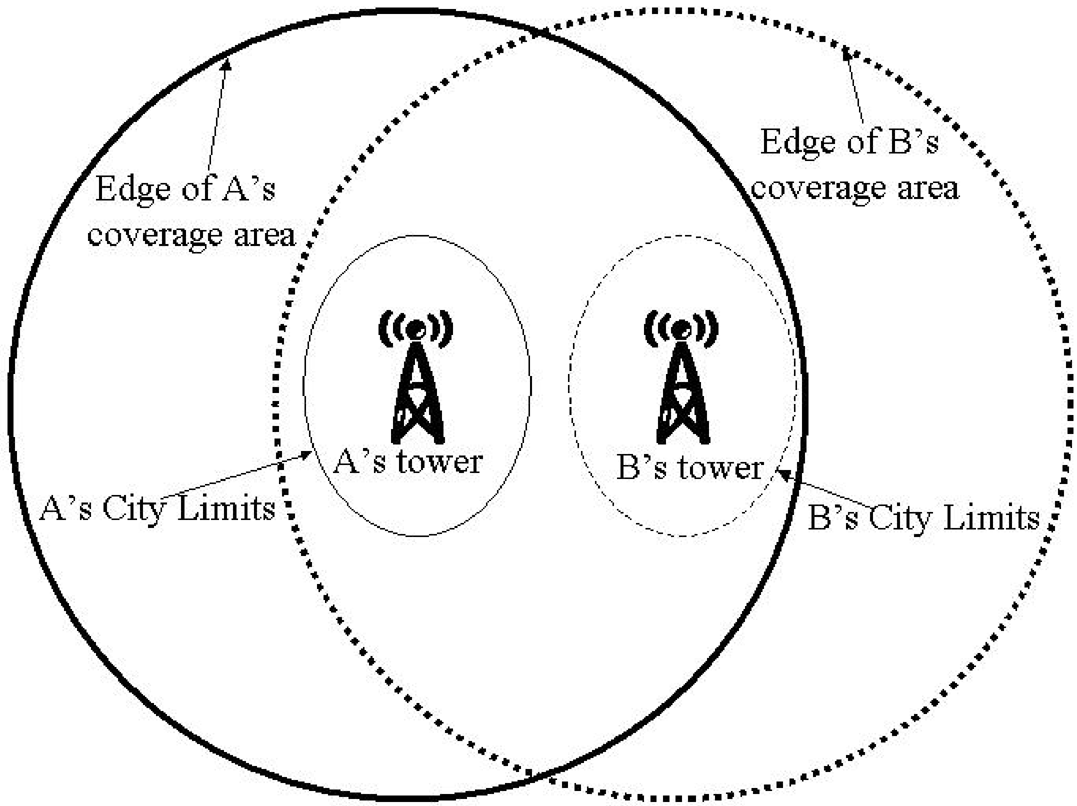

Figure 4: Neighboring Municipalities Running Independent Communications Systems

When responders from different municipalities attempt to respond to the same emergency, such as that large fire, a natural disaster, or a terrorist attack, they will be more effective and safer if they can communicate with each other. Yet, an emergency responder often cannot communicate with equipment owned by the other municipality. This is the core interoperability problem. A common "solution" to this problem is *patching*, as depicted in Figure 5b. Each responder communicates with an antenna structure operated by his own municipality, on a channel dedicated to that municipality through spectrum licensing. These towers are linked to a switch, which connects or "patches" these communications channels together to form a single channel serving a larger area than was otherwise possible.

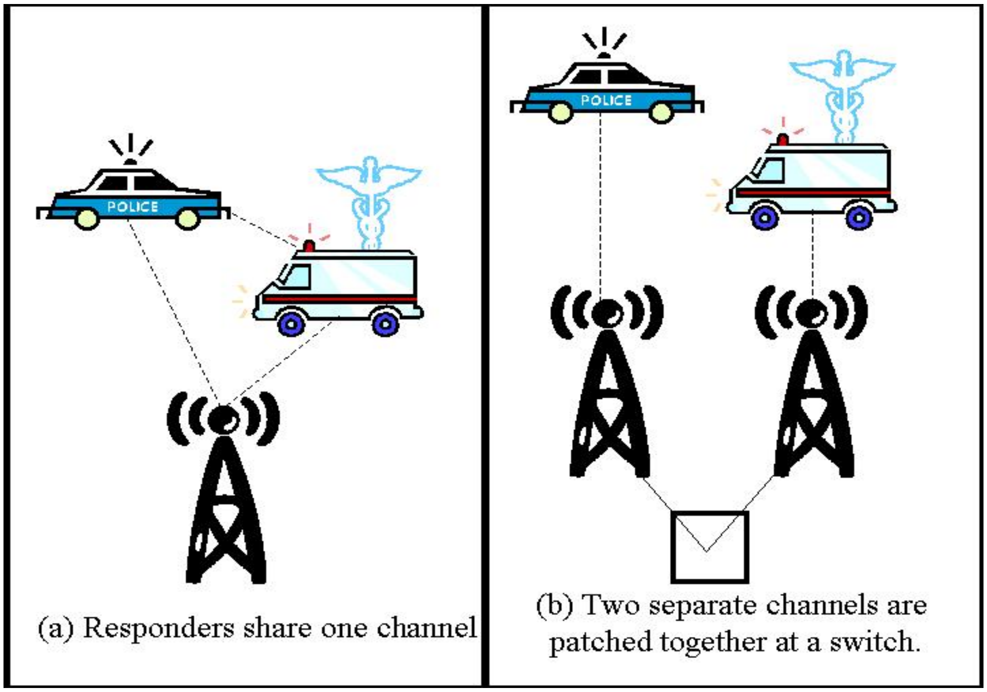

Figure 5: (a) Interoperability by coherent design. (b) Interoperability by patching.

There are many ways that spectrum and funding for infrastructure are wasted in the scenario shown in Figure 4 (and Figure 5b).

1. Each municipality exclusively licenses spectrum throughout its coverage area, and beyond. Coverage area extends well beyond city limits, even though responders rarely travel beyond city limits to use this spectrum. Without more dynamic techniques (such as dynamic sharing among license-holders, real-time secondary markets [7, 8, 9], dynamic secondary access [8, 10, 11, 12], interruptible service for commercial use [9, 13, 14], etc.), this spectrum is not available for use by responders from other public safety agencies, or anyone else, so this reserved spectrum sits idle.

2. Regardless of the number of emergency responders, there must be enough infrastructure to serve this entire area. Thus, it costs far more to deploy many small systems than it does to deploy a few large ones. For example, studies have shown that the number of antenna towers, base stations, and repeaters used by a public safety agency are largely independent of the number of responders using that agency's wireless system where this number does not exceed 100 [15], and 85% of US public safety agencies support no more than 100 users [15].

3. Spectrum can only be assigned in a discrete number of communications channels. Thus, for example, small agencies with very modest communications needs often get a full channel.

4. Far fewer channels are needed to serve multiple agencies if those channels are shared by all agencies, or equivalently, the same number of channels can support far more mobile users when channels are shared among agencies [16, 17] (if and only if these agencies do not use "greedy" techniques to monopolize spectrum resources at their neighbor's expense [17, 18]). For example, if City A and City B from Figure 5 shared channels, they could support more users per MHz of spectrum. When each agency has its own channel(s), the number of users from each agency must be sufficiently low that one agency's load never exceeds that agency's capacity even in a busy period. In contrast, when channels are shared, it is not a problem when usage on one of those shared channels is too high; some people can simply use another channel. There is only a problem if all channels see heavy usage at the same time, and this does not occur unless load is much higher.

5. Patching is inherently wasteful of spectrum. When communications channels from these two municipalities are patched together, this has the effect of creating one communications channel, but it consumes twice the bandwidth throughout a greater area than a normal channel.

With coordination, all of the inefficiencies described above can be eliminated. Many public safety agencies would share multiple communications channels, as well as the costly infrastructure. Communications equipment from different agencies would interoperate, so patching would be unnecessary. Antenna placement and coverage areas would be optimized for shared use to reduce the cost of equipment, the cost of operations, and spectrum requirements.

Note that the growing concern about interoperability could produce systems that are even more inefficient with respect to both spectrum use and infrastructure cost, if interoperability is achieved without a coherent regional or national strategy and architecture. When patching is the interoperability "solution," improving interoperability means extending coverage even further beyond city limits so responders can communicate with the switch that does the patching even further from home, and increasing the number of patches that can operate simultaneously. This consumes even more spectrum.

An infrastructure consisting of many local systems with patching is also prone to security and dependability problems. There are more towers to protect from accidental failure and deliberate attack, which can be difficult and expensive, but the system is not designed such that one tower can take the place of another after failure. The switch used for patching often constitutes yet another single point of failure.

Another common way to reduce the interoperability problem is force emergency responders to carry multiple types of equipment, so that if one does not work in a given location, they can use another. This is more spectrally efficient, but it is extremely expensive. It is also a problem for the emergency responders who must juggle the equipment, particularly when they are on foot.

An additional source of spectrum inefficiency is in the incentive structures of today's spectrum management policies. Although this problem is not caused by fragmentation, it is exacerbated by fragmentation. Even if spectrum is initially assigned in an efficient way, the assignments may become inefficient over time as needs change. Spectrum is "free" to local agencies, and once given, it is rarely moved from one public safety agency to another. In contrast, public safety funding is limited - sometimes severely limited. Under these conditions, a public safety agency would rather reduce local costs by $10 than save $1000 in costs for a neighboring municipality, or release one million dollars worth of spectrum for other purposes. This can be partially addressed by establishing spectrum fees, although the introduction of spectrum fees creates some formidable challenges for local government agencies [19]. If there were true regional or national planning, local agencies would not compete with each other to hoard spectrum; a central planner could assign and reassign spectrum to meet the post pressing needs.

4 The Perceived Need for More Spectrum

In this section, we examine the most commonly accepted estimates of public safety's spectrum needs. When public safety's spectrum needs are quantified today, the source is usually an extensive report released by the Public Safety Wireless Advisory Committee (PSWAC) in 1996 [2] (or in many cases, a paper that refers to another paper that refers to the PSWAC report). The estimates derived in this report are cited often in the current FCC proceedings on public safety spectrum [20], in recent Congressional hearings (such as [21]), in position papers of advocates for public safety, and in the press. In this report, PSWAC estimated that an additional 95.3 MHz of spectrum beyond their 1995 allocation would be needed to meet public safety's needs in the year 2010. Obviously many of the assumptions in this report could be (and will be) reexamined with the benefit of hindsight, but this particular paper will focus on how these estimates could be affected by coordination among public safety agencies, or lack thereof

Given their assumptions, PSWAC was really estimating the amount of spectrum needed, provided that the entire nation managed its spectrum about as well as Southern California did in 1995, with a few incremental changes over time. It is impossible for anyone to estimate spectrum needs more than a decade into the future without making many assumptions about wireless technology, about the number of emergency responders that must be supported, about the applications favored by these responders, about architecture, and ultimately about the policy environment that shapes all of the above. PSWAC based its quantitative estimates on the needs of areas around New York City and Los Angeles. This is reasonable, if and only if one believes that the spectrum available will be the same throughout the US, and that spectrum demands will be greatest in and around these two large cities. PSWAC's assumptions about coordination in the use and reuse of spectrum in 2010 are based entirely on how spectrum was used in the five-county area around Los Angeles as of 1995, with minor adjustments to account for anticipated changes between 1995 and 2010.

There are two major problems with extrapolating spectrum reuse patterns from Southern California in 1995 to the entire nation in 2010. First, this assumes that the cities with the largest population and area will also have the greatest spectrum needs. As shown in Sections 2 and 3, as long as decisions about public safety are made by uncoordinated local agencies, this is not a safe assumption. Regions with less area and population but greater fragmentation might need even more spectrum than Los Angeles. For those areas, PSWAC estimates could be dangerously inadequate. Further study is required to determine how Los Angeles actually compares with other parts of the country. Second, this extrapolation assumes that the inefficiencies present in Southern California in 1995 may be addressed with incremental changes in technology, but not with fundamental change in technology or in policy. (Clearly, PSWAC could not possibly foresee how the 9/11 terrorist attacks, growing spectrum shortages, and emerging technology might motivate more fundamental change.)

For historical reasons, spectrum reuse in 1995 Southern California (and many other locations in the US) was not efficient. In early mobile communications systems, mobile users all communicated with a single fixed antenna. Any signal transmitted from that antenna was received by all users within that antenna's coverage area. If one wanted to extend the coverage area, one added repeaters to carry the same signal even further. Thus, if a police officer asks a dispatcher whether a speeding car has any outstanding warrants, responders 30 miles away also receive the answer, and they cannot simultaneously use the communications channel for other purposes. The assumptions in the PSWAC report are consistent with this kind of system. PSWAC considered a five-county area in California, whose combined area is roughly 34 thousand square miles. They assumed that spectrum can only be reused between 2.5 and 4 times in this large area. These assumptions were justified by taking reuse patterns in 1995, and allowing small incremental improvements.

A more efficient approach to spectrum reuse [22] was devised at AT&T Bell Laboratories that would later become the basis of commercial cellular telephone systems, wifi-based enterprise networks [23], and more. As shown in Figure 6, with this approach, a region is divided into separate areas or *cells*. A message is transmitted only in the cell or cells that may contain intended recipients. At any given time, different messages can be transmitted in many different cells using the same communications channel, greatly reducing the amount of spectrum needed throughout the region.

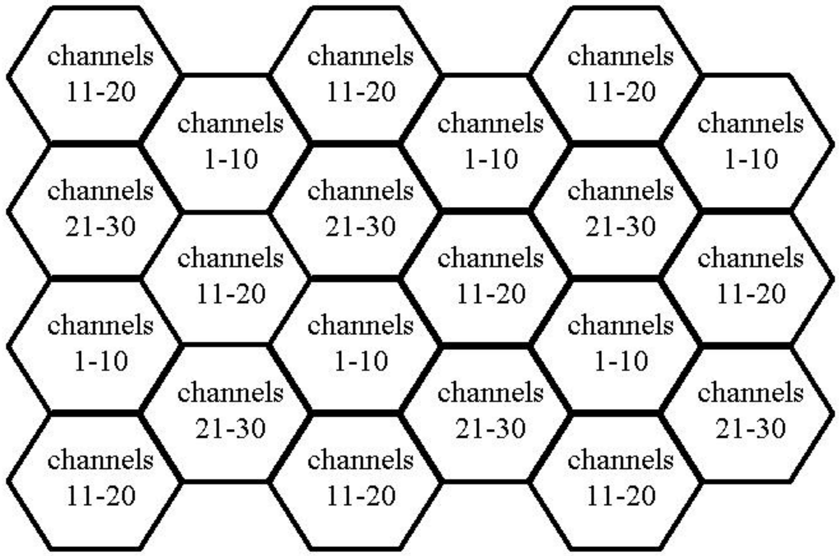

Figure 6: Reusing spectrum with the cellular concept [22]

Let us consider what could be achieved if public safety reused spectrum the way commercial cellular networks and microcellular wifi networks do. We will select the number of antennas based on the public safety needs of Allegheny County (which contains Pittsburgh, PA as well as Carnegie Mellon University). M/A-Com and Motorola have both recently proposed systems that would serve emergency responders throughout Allegheny County with 80 and 40 antenna structures, respectively (in contrast to the 439 currently in the county, as operated by many independent public safety agencies) [4]. These two companies would serve public safety with one antenna per 9.13 or 18.25 square miles, respectively. We will use the more conservative value of one antenna per 18.25 square miles. We further assume a three-cell reuse pattern without sectorization as shown in Figure 6, which compared to today's more efficient commercial cellular systems, is also a conservative assumption. Under these assumptions, if each call went to a single mobile user, or at least mobile users in a single cell, spectrum could be reused 620 times[5] in the five-county area considered by PSWAC. Actually, some calls must go to recipients in multiple cells (e.g. "Calling all cars near First and Main"). For the sake of example, we assume here that 75% of calls go to a single cell, and 25% of calls are broadcast to 40 cells (730 square miles)[6]. Assuming that the non-broadcast calls are spread fairly evenly over all cells, this would increase the load per cell by a factor of

[5] (34,000 square miles) / (18.25 square miles) / 3 = 620

[6] We make these assumptions for all services (voice, video, data), in the absence of hard data. Note that, by PSWAC estimates, video and wideband data require the most spectrum. Thus, estimates regarding the need for broadcast are more important for these applications. Unfortunately, public safety's limited experience with these services to date makes realistic forward-looking estimates more difficult.

$f = 10.75$[7]. If we used PSWAC's equations [2] and all of their assumptions, except that we increase load by a factor of f =10.75 and increase reuse within the Greater Los Angeles area up to 620, we would conclude (using Equation 3 and the data in Figure 7) that public safety will need about 8.3 MHz of spectrum in 2010.[8]

New estimate = [Equation 3]

$$\Sigma_{\text{each service i}} \text{ (PSWAC spectrum estimate i)} * f * \text{(PSWAC reuse assumption i)} / 620 = 8.3 \text{ MHz}$$

Service	PSWAC reuse assumption	PSWAC spectrum estimate
Voice	2.5	32.3 MHz
Narrowband data	2.5	5.3 MHz
Status/Message	2.5	0.2 MHz
Wideband Data	4.0	40.8 MHz
Video	4.0	50.7 MHz

Figure 7: PSWAC [2] estimates of amount of spectrum needed for each service, and number of times each channel can be reused in the Greater Los Angeles area.

8.3 MHz is more than two orders of magnitude less than what PSWAC thought must be added to public safety spectrum. Indeed, 8.3 MHz is less than the 23.4 MHz already allocated to public safety in 1995, even before the reallocation of any analog TV spectrum. Of course, the analysis behind Equation 3 is too simplistic to conclude that 8.3 MHz is really enough spectrum for public safety. Accurate results would require more reliable data on the need for broadcast in public safety systems, in how calls are spread geographically and temporally, and more. Moreover, nothing like this could be achieved without replacing existing systems with a single regional system, which would take time. However, this does demonstrate that PSWAC's results were entirely dependent on their assumptions about spectrum reuse, which in turn are an artifact of policy fragmentation and old technology. Vastly superior results are possible through greater coordination and a different technical approach. In the long run, new policies and new technologies may enable public safety to meet its needs with less spectrum than it has now.

5 Conclusions

A policy that requires each public safety organization to independently make decisions about its communications system without a coherent plan and extensive coordination will produce an infrastructure that is more expensive than necessary, requires more spectrum than necessary, and is more prone to interoperability problems

[7] .75 * (load from this cell) + .25 * (40 cells in broadcast range) * (load from each cell) = 10.75 * (load from each cell)

[8] PSWAC concluded that some of this need can be met through commercial services, thereby reducing the needs of public safety by 10%. However, for this calculation, we did not consider the option of using commercial services.

than necessary. We have shown that US counties with more local governments operate more infrastructure than is technically required. Indeed, the number of antenna structures in a county is correlated much more closely with the number of municipalities than with the county's area, or any other technically relevant parameter. We have further shown how this wastes spectrum as well as increasing costs. The all-too-common contention that the US cannot afford to improve public safety communications systems is ironic, considering how much could be saved by improvements that eliminate such inefficiencies.

These inefficiencies are not new. In an earlier age, the disadvantages of fragmentation may have been outweighed by the advantage of allowing each municipality complete freedom to adjust its strategy to match local needs and resources. However, this is not the case today, for several reasons. First, in the wake of 9/11, emergencies that expose the limitations of public safety communications systems are more likely, and more lives are at stake. Public safety organizations must have the equipment and capacity to simultaneously support a larger number of emergency responders, and to enable seamless communications between responders from many agencies that are responding to the same large-scale emergency. Thus, both spectrum inefficiencies that reduce capacity and interoperability problems now cost more lives. Second, emerging technologies ranging from software-defined radio to inexpensive global positioning systems (GPS) have increased the potential benefits of adopting a new approach by making much greater efficiencies technically possible. These forces have already prompted the reevaluation of policies for commercial spectrum [8, 10, 11, 19]. Third, commercial demand for spectrum has grown, so the societal value of the spectrum currently wasted by public safety is now much greater. This commercial demand for spectrum also provides new opportunities for raising funds to support the transition to a more efficient system. Similarly, growing interest within public safety for new applications [24] such as video and high speed data will place significant new demands on public safety spectrum in the coming years, further increasing the value of spectrum and of spectrum efficiency.

Some incremental progress has been made in the degree of cooperation among agencies, but there has been no fundamental shift. For example, some useful standards have been defined to address multiagency problems like interoperability (e.g. [25]), and inclusive Regional Planning Committees (RPCs) have been created [26]. RPCs should improve cooperation over past practices, but a truly coherent regional design generally requires designers optimizing over the entire region, rather than just a committee of stakeholder peers negotiating to meet their individual local needs. Moreover, RPCs are to be given "maximum flexibility" [27] to devise their own plans, which runs contrary to the idea of a coherent national plan that is consistent from region to region. Ultimately, this approach of incrementally improving regional cooperation is no substitute for establishing meaningful regional and national plans.

The federal government should develop a national strategy that requires much more coordination among agencies, and a new architecture based on open standards. This strategy could produce a nationwide infrastructure that serves all authorized public safety agencies and is managed by a federal entity. Alternatively, it could produce a concatenation of many locally managed systems that were specifically designed as integral pieces of a much larger infrastructure, as opposed to today's hodgepodge of local systems designed for local needs and then clumsily glued together. (Commercial networks may also have a greater role than they do today [9, 28].) This strategy might be implemented first in spectrum bands newly allocated to public safety, allowing legacy systems in current public safety bands to be replaced or incorporated into this national system over a period of years.

This paper has also argued that the most widely accepted estimates of spectrum needs for public safety [2] cannot be accepted at face value. PSWAC estimated that 95.3 MHz of spectrum must be allocated to public safety by 2010. PSWAC made assumptions that may underestimate spectrum requirements in regions that have the least coordination among public safety organizations. This requires further study. On the other hand, by adopting a new national strategy for public safety communications systems, the total amount of spectrum needed could be drastically reduced to far below their estimate. Thus, it could be possible to avert a serious shortage of public safety spectrum, without taking a great deal of spectrum from other valuable uses. Indeed, after effective policies have been adopted and modern technology has been deployed, public safety's needs may eventually be met with a smaller allocation than they have today.

Today's newfound interest in public safety interoperability may advance the important cause of communications systems for emergency responders, but it will be counterproductive if interoperability is the exclusive focus, which is a possibility. One cannot easily "fix" interoperability as an afterthought to today's infrastructure, anymore than one can easily "fix" fuel efficiency on a racecar that was designed exclusively for maximum speed. Moreover, we have shown that the obvious ways to incrementally improve interoperability could significantly decrease spectrum efficiency and increase costs. They can also undermine dependability and security. Thus, a national strategy must consider many factors, including but not limited to interoperability.

Ultimately, the development of a national strategy is also an opportunity to re-think security requirements, dependability requirements, the role of commercial companies, and the possibility of spectrum-sharing with systems other than public safety [9, 28].

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8 Appendix

Counties considered in the regression analysis described in Section 2.

County	State	Largest City	Population	Area (sq miles)	Munici-palities	Antenna Structures	Mountain	Terrain Roughness
Allegheny	PA	Pittsburgh	1,261,303	730	130	439	0	43
Bernalillo	NM	Albuquerque	581,442	1166	10	155	1	263
Bexar	TX	San Antonio	1,471,644	1247	23	244	0	71
Broward	FL	Miami	1,731,347	1205	32	308	0	10
Cumberland	ME	Portland	270,923	836	27	341	0	41
Cuyahoga	OH	Cleveland	1,363,888	458	59	283	0	55
Dallas	TX	Dallas	2,284,096	880	26	313	0	28
Davidson	TN	Nashville	569,842	502	7	72	0	36
Douglass	NE	Omaha	476,703	331	7	96	0	25
El Paso	CO	Colorado Springs	550,478	2126	14	132	1	207
El Paso	TX	El Paso	705,436	1013	4	57	1	92
Erie	NY	Buffalo	941,293	1044	28	288	0	99
Franklin	OH	Columbus	1,088,944	540	43	144	0	23
Fulton	GA	Atlanta	818,322	529	10	121	0	24
Hampden	MA	Springfield	461,190	618	23	207	0	112
Hartford	CT	Hartford	871,457	735	29	361	0	74
Hennepin	MN	Minneapolis	1,121,035	557	46	296	0	17
Hinds	MS	Jackson	249,087	869	9	44	0	18
Honolulu	HI	Honolulu	902,704	600	1	199	1	202
Jackson	MO	Kansas City	659,723	605	18	148	0	27
Jefferson	KT	Louisville	699,017	385	12	157	0	27
King	WA	Seattle	1,761,411	2120	39	380	1	394
Marion	IN	Indianapolis	863,251	396	7	91	0	17
Mercer	NJ	Trenton	361,981	226	13	120	0	18
Multnoma	OR	Portland	677,813	435	12	85	1	288
Onondaga	NY	Syracuse	460,517	780	35	271	0	122
Polk	IA	Des Moines	388,606	569	8	90	0	20
Sacramento	CA	Sacramento	1,330,711	966	7	141	0	38
Salt Lake	UT	Salt Lake City	924,247	737	15	207	1	397
Santa Clara	CA	San Jose	1,678,421	1291	15	292	1	297
Shelby	TN	Memphis	906,178	755	7	138	0	15
Tulsa	OK	Tulsa	570,313	570	7	198	0	17
Wayne	MI	Detroit	2,028,778	614	44	247	0	15