Assessing Spectrum Requirements for Smart Grid Networks

Doug Gray, WiMAX Forum
July 7, 2014

Introduction

Wireless technology offers the best alternative for the deployment of a Smart Grid (SG) network. It is the most cost-effective, quick to deploy, and it is compatible with existing utility infrastructure and right-of-ways. Although wireless has the potential to meet all of the requirements for a secure Smart Grid network, the lack of suitable spectrum specifically allocated for utilities has been, and continues to be, an obstacle for SG deployments. Obviously utilities have the ability to use unlicensed spectrum in a variety of bands and they have access to existing public networks. Although these options can indeed play a role in some SG network segments or selected geographic regions they are not suitable for a complete end-to-end network solution. Unlicensed spectrum is prone to congestion and interference and capacity may not be available when crucially needed by utilities. With the infiltration of smart phones and growing demand for new wireless applications, public networks are barely able to keep up with the current demand from existing customers and therefore, unlikely to have excess capacity to offer utilities for SG. In times when utilities especially need adequate data communications, whether for disaster recovery or periods of peak electric demand, public networks or unlicensed spectrum are options that cannot be guaranteed to be available. The potential benefits of a US nationwide Smart Grid network are significant but, unfortunately, without utility access to suitable spectrum, these benefits may never be fully realized.

Other papers and presentations in the past few years have also addressed SG spectrum issues. Armes, provided an analysis for the 1800-1830 MHz band in a 2010 paper describing its use in point-to-point SG backhaul applications [Ref 1]. Later that year Armes and Bender, did a SG applicability analysis for a UTC paper that included the 700 MHz and 14.5 GHz bands along with the 1800 MHz band [Ref 2]. In 2011, Rodine and Drucker in an EPRI presentation, made some compelling arguments for the need for dedicated SG spectrum and provided a throughput analysis for a point-to-multipoint field area network (FAN) comparing deployments at 700 MHz and 1800 MHz [Ref 3].

The goal of this paper is to provide a quantitative basis for the amount of spectrum required and to show the trade-offs between different frequencies that may be considered for a SG network taking into account the detailed work that has been done since the above-mentioned papers with respect to path loss models, SG capacity, and SG latency requirements. Three frequencies are used for the analysis; 700 MHz, 2000 MHz, and 3700 MHz. The number of base stations (BS) that must be deployed to meet the SG coverage and throughput requirements is closely related to the network complexity and cost and will, therefore, be used as the key metric for evaluating the trade-offs between the frequency bands. The complete SG network comprises a number of sub-networks or segments [Ref 4]. For the purposes of this analysis, the networks considered will be a Field Area Network (FAN) and a Wide Area Network (WAN) as illustrated in Figure 1.

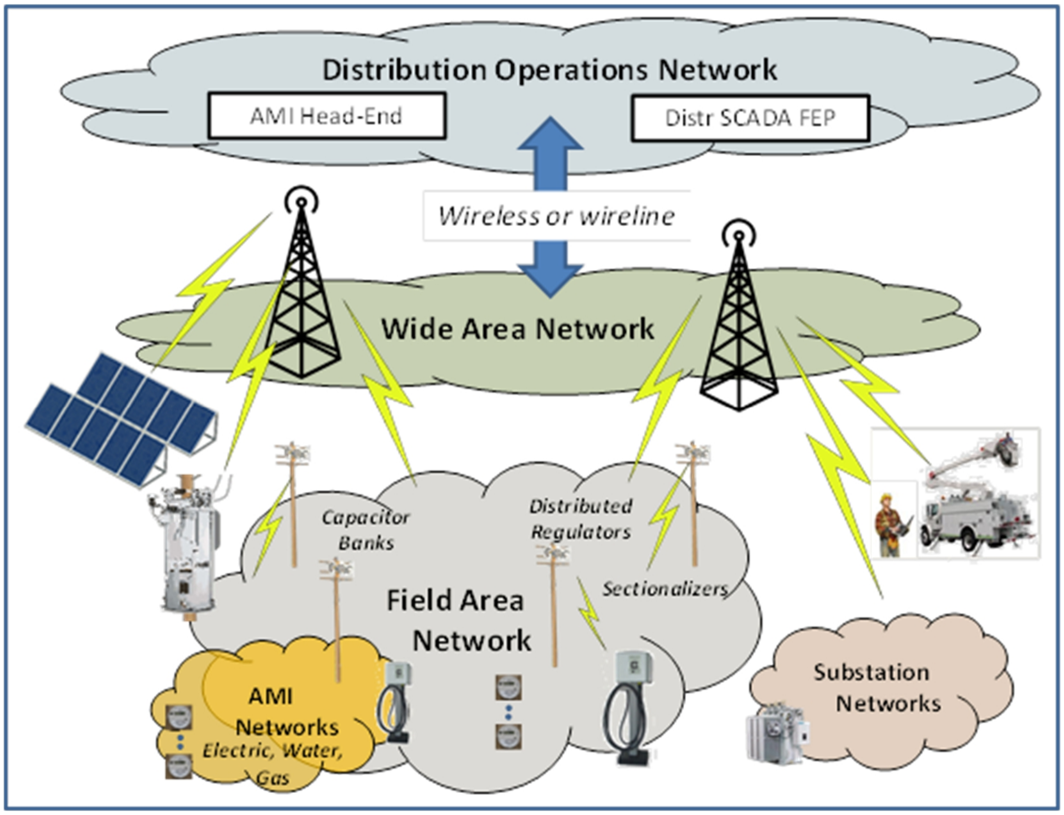

Figure 1: Wireless network architecture

Approach

The work done by the UCAIug - OpenSG- SG-Network Force [Ref 4] and SGIP-PAP02 [Ref 5] provides the basis for the calculations and deployment trade-offs that will be provided in this paper. Geographic and demographic differences play a key role in data requirements and propagation conditions for a wireless network. In the United States the density of residential housing units, by county, range from more than 34,000 HU per sq-mi to less than 1 HU per sq-mi. In dense urban areas wireless coverage is predominantly non line-of-sight (non-LoS); dependent on diffraction around buildings, reflection from buildings, and penetration through building walls. Rural areas can range from square miles of wide open terrain with very favorable propagation conditions to mountainous and heavily forested areas where non-LoS conditions prevail. A wireless Smart Grid network must be able to deal with all of these scenarios to reach all utility customers. To differentiate the deployment challenges relative to demographic differences, it is convenient to partition the demographic regions as summarized in the following table [Ref 5].

Table 1: Demographic area definitions

Demographic Region	Housing Unit Density (HU/ mi^2)	% of US Population	% of US Land Area	Typical Characteristics
Dense Urban	≥ 4,000	11.0	0.05	Large number of high rise multi-tenant buildings large number of businesses
Urban	1,000 to 3,999	34.7	0.6	Densely packed 4-6 story buildings, residential and industrial
Suburban	100 to 999	30.7	3.2	Mix of 1 and 2-family homes, low rise apartment buildings, shopping centers, more trees, parks, etc.
Rural	10 to 99	17.0	22.7	HUs are further apart, low rise buildings, may be flat with few trees to hilly with more trees and terrain obstacles
Low Density Rural	< 10	4.2	72.3	More extreme range of terrain characteristics, HU densities vary from clusters to individual HUs miles apart

Regardless of the demographic area under consideration utilities want to provide ubiquitous coverage to reach all of their residential, commercial, and industrial customers. To minimize costs, they want to maximize the use of existing infrastructure and right-of-ways. Utilities also have to contend with the existing locations for customer end-points which may not always be in a propagation-friendly location. Urban center electric, gas, and water meter banks are often located in the basements of multi-story buildings. Using utility infrastructure may offer considerable cost saving but the structures may not always be in locations optimum for a base station location and existing urban and suburban utility poles will often limit the heights of base stations antennas to 10 meters or less.

The Field Area Network (FAN) provides connectivity to the advanced metering infrastructure (AMI) and many other utility neighborhood area end-points such as capacitor banks, distributed regulators, PHEV chargers, etc. The Wide Area Network (WAN) serves as a backhaul for the FAN, as well as providing connectivity to substation networks, the mobile work force, and other utility end-points not covered by the FAN but within the wireless coverage area of the WAN.

Basis for Capacity Requirements

Table 2 provides a summary of the data density requirements applicable to a field or neighborhood area network. The estimates were derived from the work done by the UCAIug – OpenSG – SG-Network Task Force [Ref 4]. This material subsequently became the basis for the analysis done by SGIP/NIST-PAP02 [Ref 5]. Note that these data estimates are only for data messages. They do not include a provision for video surveillance which is expected to be an important requirement for wide-area situational analysis (WASA), especially with respect to critical infrastructure and for disaster recovery.

The 'Baseload' data is comprised of many small packet payloads and is dominated by uplink (UL) traffic from the SG end-points to the FAN base station. The baseload latency requirements for time-sensitive business application payloads range from ≤ 2 to about 3 seconds. The 'Highload' data is primarily driven by downloads for firmware updates. This downlink (DL) data traffic often comprises large payloads. Although the highload business application payload latency requirements are generally 1 minute or more, the per packet latency requirement will often be in the order of seconds since the large payloads have to be split into smaller packets to conform to packet size limitations for the wireless technology being considered. As will be shown, DL and UL latency requirements play a key role in determining the network capacity requirements.

Table 2: SG Data Density requirements for five demographic regions

	Dense Urban	**Urban**	**Suburban**	**Rural**	**Low Density Rural**
Average HU/mile^2	7,483	1,794	303	26	2.2
Average Comm/Indus/mile^2	1,320	317	54	4.6	0.4
Average Number of End-Points/mile^2	14,212	3,447	1,111	65	4
Average Baseload Requirements					
UL Bytes/mile^2	1,234	449	5,239	10.4	1.4
Average UL Payload (Bytes)	1,020	344	189	274	190
DL Bytes/mile^2	5.2	102	124	3.3	0.7

	Dense Urban	Urban	Suburban	Rural	Low Density Rural
Average DL Payload (Bytes)	90	99	89	99	100
Average Highload Requirements					
UL Bytes/mile^2	16,129	2,314	51,283	66	25.7
Average UL Payload (Bytes)	8,116	1,517	911	1,538	3,178
DL Bytes/mile^2	29,327	5,472	116,023	108	9
Average DL Payload (Bytes)	65,649	4,806	2,538	3,003	1,189

Wireless Technology Assumptions

The assumptions for the wireless technology parameters are consistent with TDD-LTE and WiMAX-Advanced[1] and WiGRID[2] [Ref 7].

- Channel bandwidths (BW) are noted in the various tables that follow
- Time Division Duplex (TDD) is assumed for all channel BWs with a fixed DL to UL ratio of 1. Although WiGRID supports adaptive TDD with either a DL or UL bias, this feature is not considered in the analyses that follow.
- Adaptive modulation from QPSK to 64QAM is assumed for both DL and UL traffic
- In addition to error correction, channel overhead for headers and protocols is assumed to be approximately 30 % and an additional 20 % assumed for higher levels of encryption and higher layer overhead
- Maximum packet size is assumed to be 2000 Bytes

Methodology

The methodology used to determine spectrum requirements and tradeoffs are similar to that described in Ref 5. For the FAN, a hypothetical mid-sized city comprising dense urban, urban,

[1] TDD-LTE and WiMAX Advanced are two wireless technologies recognized by the ITU as 4G
[2] WiGRID is a WiMAX profile developed with features specifically suited for Smart Grid networks

and suburban demographic regions is assumed with end-point and data density requirements as described in Table 2. The pole-mounted base stations in the FAN then become the end-points for the WAN. The capacity requirements for the WAN are increased by 20 % to account for the additional end-points that would also be covered by the WAN.

The goal is to show the number of base stations required to achieve the necessary coverage while meeting the requirements for payload latency and data throughput. The frequencies assumed for the analysis are 700 MHz, 2000 MHz, and 3700 MHz. 700 MHz and 2000 MHz are used simply to illustrate performance in bands below 1000 MHz and bands in the 1500 to 2500 MHz range, respectively. 3700 MHz was selected to show performance at the upper end of the 3650 to 3700 MHz band; a band currently being used for many Smart Grid applications.

Propagation models used:

- Erceg-SUI model as modified for validity from 700 MHz to 6000 MHz for BS antenna heights from 10 meters to >30 meters for suburban and rural regions [Ref 5] for terrain Types A, B, and C defined as:
    - Type A: Hilly with moderate to heavy tree density
    - Type B: Hilly with light tree density or flat with medium to heavy tree density
    - Type C: Flat with light tree density
- Modified Erceg-SUI-Terrain Type A used to approximate urban areas with BS antenna heights of 10 meters (Note: Propagation models traditionally used for cellular are only valid for BS antenna heights above surrounding roof-tops)
- ITU-R M.2135-1 Urban Micro-Cell, valid from 2000 MHz to 6000 MHz for a BS antenna height of 10 meters in dense urban environments
- Winner II, COST231-Hata, or Hata-Okumura model, where appropriate, for higher BS antenna heights

A binomial distribution model is used to assess latency. This model is described in Ref 5.

The following table shows the 'hypothetical' mid-size city used for the base station analysis and, for illustrative purposes, includes some US cities that have similar characteristics. The hypothetical city closely resembles the area and population of Omaha and Raleigh, the 43rd and 42nd largest cities in the US respectively. Salt Lake City and Portland with a population density difference of more than 3 to 1, shows how cities with similar land areas vary due to the way the population is distributed between dense urban, urban, and suburban areas.

Table 3: Hypothetical Mid-Sized City for Deployment Analysis

Hypothetical City for Analysis	Land Area (sq-mi)	Population	Population Density (per sq-mi)	Total # of End-Points (FAN)
Dense Urban	10	174,656	17,466	142,118
Urban	40	176,956	4,424	137,869
Suburban	80	60,960	762	88,835
Totals for hypothetical city	**130**	**412,572**	**3,174**	**368,822**
Some comparable US cities				
US City	**Land Area (sq-mi)**	**Population**	**Population Density (per sq-mi)**	
Portland, Oregon	133	603,106	4,520	
Omaha, Nebraska	127	408,958	3,218	
Raleigh, North Carolina	143	423,179	2,963	
Salt Lake City, Utah	109	189,314	1,735	

Results for Field Area Network (FAN) Deployment

Type C terrain is assumed for suburban areas since it represents a worst case scenario for meeting either capacity or latency requirements. Type C terrain results in the greatest coverage area and thus, includes a greater number of end-points as opposed to terrain types A or B. In these cases, as the channel becomes more congested, latency begins to suffer. Hence latency, not capacity, generally becomes the key determinant for base station requirements.

The base station antenna heights are assumed to be at a height of 10 meters for each of the three demographic regions, a height consistent with readily available utility poles in urban and suburban areas. For a worst case link budget, the end-points are assumed to be smart meters and in the 'dense urban' areas, they are assumed to be located in basement locations. The associated penetration loss in the higher frequency bands thus has a profound effect on base station requirements for dense urban deployments. The meter locations in the 'urban' and 'suburban' areas are assumed to be located outdoors just above ground level.

In the table for each of the three frequency bands the channel BW for which the deployment is latency limited is shown for the suburban region followed by the channel BW at which the deployment becomes limited by range. The base station requirements are shown for frequency reuse factors of 1 and 3. With the large number of closely-spaced base stations in these demographic regions a more conservative reuse factor, although requiring more spectrum, is highly desirable for interference management and results in a 10 to 15 % reduction in the number of base stations required. The number of base stations not only has a bearing on equipment costs but must also be a consideration for the visual impact, especially in residential areas.

Since we do not have a valid path loss model at 700 MHz, similar to the M.2135-1 Urban Micro-Cell model, the base station count for dense urban is simply a rough estimate.

Table 4a: Base Stations Required for 700 MHz Field Area Network Deployment

700 MHz FAN	**Required Spectrum for Reuse 3 = 18 MHz**			
Region	**Channel BW MHz**	**Limited by…**	**BS Reuse 1**	**BS Reuse 3**
Suburban Type C Terrain	5.0	Latency	25	25
	6.0	Range	18	16
Urban	6.0	Range	40	36
Dense Urban	6.0	Range	60 (est.)	55 (est.)
Total City	**6.0**		**118**	**107**

Table 4b: Base Stations Required for 2000 MHz Field Area Network Deployment

2000 MHz FAN	**Required Spectrum for Reuse 3 = 10.5 MHz**			
Region	**Channel BW MHz**	**Limited by…**	**BS Reuse 1**	**BS Reuse 3**
Suburban Type C Terrain	3.0	Latency	45	45
	3.5	Range	42	37
Urban	3.5	Range	181	161
Dense Urban	3.5	Range	215	178
Total City	**3.5**		**438**	**376**

Table 4c: Base Stations Required for 3700 MHz Field Area Network Deployment

3700 MHz FAN	**Required Spectrum for Reuse 3 = 7.5 MHz**			
Region	**Channel BW MHz**	**Limited by…**	**BS Reuse 1**	**BS Reuse 3**
Suburban Type C Terrain	2.0	Latency	87	87
	2.5	Range	79	69
Urban	2.5	Range	594	527
Dense Urban	2.5	Range	857	710
Total City	**2.5**		**1530**	**1306**

This analysis, summarized graphically in Figure 2, clearly illustrates the benefit of having a lower frequency alternative available for Smart Grid FAN deployments in regions with higher population density to overcome the propagation challenges arising from height-constrained base station antennas and unfavorable end-point locations.

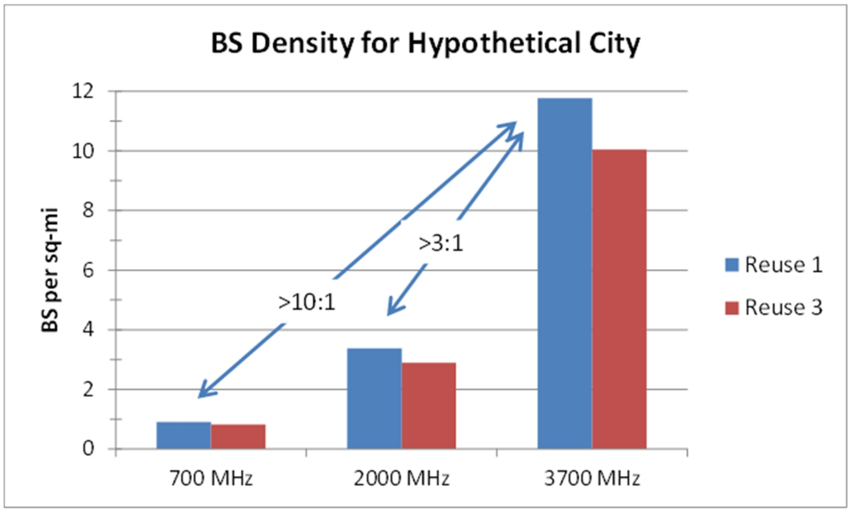

Figure 2: Base station density for Smart Grid FAN deployment in hypothetical mid-sized city

It is important to note that the base station densities are for the hypothetical city with demographic breakdowns as shown in Table 3 and may be a reasonable estimate for Omaha, NE or Raleigh, NC. One can expect a higher base station density for Portland, OR and a somewhat lower base station density for Salt Lake City, UT in accordance with the relative population densities.

Results for Wide Area Network (WAN) Deployment

The following tables summarize the results for a wide area network (WAN) which not only serves as a back-haul network for the FAN but also provides wireless connectivity to substation networks, the utility mobile work force, and other utility infrastructure that lies within the WAN coverage area. The WAN may also include video surveillance for critical infrastructure. The WAN capacity therefore, must be sufficient to accommodate these additional requirements. A 20 % increase is applied to the 'Highload' data density requirements listed in Table 1 to cover these additional use cases.

The primary end-points for the WAN are the outdoor pole-mounted FAN base stations with average antenna heights of 10 meters. Other WAN end-points include strategically positioned fixed outdoor antennas to ensure a much more favorable propagation environment than exists in the FAN. Mobile workforce connectivity is not considered in the following analysis for link-budget purposes. Utility vehicles would be equipped with a lower gain omnidirectional antenna but with the ability to move, would be able to maneuver to a location favorable for communication when required. It is also safe to assume that the mobile workforce would have access to a public network via their mobile phones.

A reuse factor of 1 is assumed for the WAN since propagation conditions are more favorable and interference easier to manage with fewer and more widely-spaced base stations. The following analysis assumes higher end-point and base station antenna gains in the higher frequency bands.

In the comparison between 3700 MHz and 2000 MHz the higher antenna gains for the same antenna physical size, offsets the increased path loss in the higher frequency band[3].

Table 5a: Base Station Requirements for WAN at 700 MHz with a reuse factor of 1

700 MHz WAN			**BS Required**		**Comments**
Region	**Channel BW MHz**	**Limited by…**	**BS for Coverage**	**Total BS**	
Suburban Type C Terrain	6	Capacity	1	4	Range Limited for Terrain Type A requiring 4 BS
	12	Capacity		3	
	24	Capacity		2	
Urban	6	Latency	1	23	Meets latency requirements for 'Baseload' demand, <2 s, up to 10 s latency for 'Highload' large packet payloads
	12	Latency		11	
	24	Latency		6	
Dense Urban	6	Latency	1	17	
	12	Latency		8	
	24	Latency		4	
City Totals	**6**		**3**	**44**	
	12			**22**	
	24			**12**	

Table 5b: Base Station Requirements for WAN at 2000 MHz with a reuse factor of 1

2000 MHz WAN			**BS Required**		**Comments**
Region	**Channel BW MHz**	**Limited by…**	**BS for Coverage**	**Total BS**	
Suburban Type C Terrain	20	Capacity	2	3	Range limited for Type A or Type B requiring 8 BS and 5 BS, respectively
	25	Capacity		3	
	30	Range		2	
Urban	20	Latency	3	6	Meets latency requirements for 'Baseload' demand, <2 s, up to 8 s latency for 'Highload' large packet payloads
	25	Latency		5	
	30	Latency		4	
Dense Urban	20	Latency	1	5	
	25	Latency		4	
	30	Latency		4	
City Totals	20		**6**	**14**	
	25			**12**	
	30			**10**	

[3] Note that the BS count is always rounded up to the next whole number, so fractional differences do not show up in the tables

Table 5c: Base Station Requirements for WAN at 3700 MHz with a reuse factor of 1

3700 MHz WAN			**BS Required**		**Comments**
Region	**Channel BW MHz**	**Limited by…**	**BS for Coverage**	**Total BS**	
Suburban Type C Terrain	20	Capacity	2	3	Range limited for Type A or Type B requiring 10 and 6 BS, respectively
	25	Capacity		3	
	30	Range		2	
Urban	20	Latency	3	6	Meets latency requirements for 'Baseload' demand, <2 sec, up to 8 s latency for 'Highload' large packet payloads
	25	Latency		5	
	30	Latency		4	
Dense Urban	20	Latency	1	5	
	25	Latency		4	
	30	Latency		4	
City Totals	**20**		**6**	**14**	
	25			**12**	
	30			**10**	

With a comparable amount of spectrum in any of the three frequency bands, there is very little difference between the number of base stations required to meet the capacity and latency requirements for a WAN deployment.

Rural and Low Density Rural FAN or WAN Deployments

Generally higher BS antenna heights can be deployed in 'Rural' and 'Low Density Rural' areas. Antennas can be deployed, where allowed, on existing utility-owned transmission towers, leased space on cellular towers, or other existing structures. For either a FAN or a WAN, deployment in these demographic regions will be range-limited for channel BWs of at least 1 MHz with a reuse factor of 1. The link-budget leading to the results in the Table 6 assumes a 25 meter base station antenna height and outdoor-located smart meter terminals at 1 meter to 2 meters above ground level. It is safe to assume, from a path loss perspective, that other SG end-points in these demographic regions would have either higher antenna gains or more favorable antenna locations.

The BS requirements for a 500 sq-mi area are shown in the far right column with sub-columns to show the differences in BS required for terrain types A, B, and C respctively.

Table 6: Base Station Coverage for FAN or WAN in Rural or Low Density Rural Areas

Frequency	Terrain Type	Channel BW	Approximate Coverage Area per BS	BS for 500 sq-mi area Terrain Type A	B	C
700 MHz	Type A	>1 MHz	9.1 sq-mi	55		
	Type B		15.6 sq-mi		32	
	Type C		23.8 sq-mi			21
2000 MHz	Type A	>0.5 MHz	5.0 sq-mi	100		
	Type B		8.6 sq-mi		58	
	Type C		12.5 sq-mi			40
3700 MHz	Type A	>0.25 MHz	2.7 sq-mi	183		
	Type B		4.6 sq-mi		110	
	Type C		6.5 sq-mi			77

It would be reasonable to conclude that public networks could easily accommodate the additional Smart Grid data requirements in these lower population density areas but one must also be reminded that these are the areas where public networks are most likely to have 'holes' in their coverage. It is also important to note that these are areas in which critical utility infrastructure may be located; power generation plants, solar and wind farms, etc. If it is deemed necessary to have these facilities under continuous video surveillance, additional dedicated bandwidth would be required.

Summary

FAN for mid-sized city: Even though the end-point densities are high the spectrum requirements are quite modest due to the challenging propagation characteristics resulting from unfavorable meter locations and low BS antenna heights. Frequencies below 1000 MHz are more suitable for dealing with building penetration loss in urban centers and foliage loss in suburban areas. With the higher BS density a reuse factor of 3 is recommended for improved interference management.

Based on the analysis for our hypothetical city the recommended spectrum for a FAN is summarized in the following table.

Table 7: Spectrum recommendations for mid-size city FAN

Frequency	Minimum – Reuse 1	Recommended – Reuse 3
< 1000 MHz	6 MHz	18 MHz
1500 to 2500 MHz	3.5 MHz	10.5 MHz
> 3500 MHz	2.5 MHz	7.5 MHz

WAN for mid-sized city: With more favorable propagation conditions a wider channel BW is necessary to meet the capacity and latency requirements for a WAN. Having access to 25 to 30 MHz in the higher bands is far more cost-effective than having only 6 or 12 MHz of spectrum in bands below 1000 MHz.

Spectrum requirement recommendations for the WAN are summarized in the following table.

Table 8: Spectrum tradeoffs for mid-size city WAN

Frequency	Minimum	Good	Recommended
<1000 MHz	6 MHz May not be economical	12 MHz 50 % reduction in BS requirements	24 MHz Further 50 % reduction in BS requirements
1500 to 2500 MHz	20 MHz No excess capacity for future	25 MHz 15 % reduction in BS requirements	30 MHz Provides opportunity for new SG requirements
>3500 MHz	20 MHz No excess capacity for future	25 MHz 15 % reduction in BS requirements	30 MHz Provides opportunity for new SG requirements

Rural and low density rural areas: Demographics and propagation conditions can vary considerably in these areas but range and coverage to reach all utility customers, not capacity, will generally be the principal consideration for a Smart Grid network. This is another demographic region for which having access to spectrum in a lower, rather than higher, frequency band will have a significant impact on the economics.

Table 9: Spectrum trade-off summary

	Frequency Band			
SG Segment	**< 1000 MHz**		**1500 to 2500 MHz**	**> 3500 MHz**
City-Wide FAN	6 MHz Good	≥ 12 MHz Very Good	≥ 10.5 MHz OK	≥ 7.5 MHz Poor
City-Wide WAN	6 MHz Poor	12 MHz OK	≥ 25 MHz Very Good	≥ 25 MHz Very Good
Rural Area FAN/WAN	≥ 1 MHz Very Good		≥ 0.5 MHz OK	≥ 0.25 MHz Poor

Conclusion

A terrestrial wireless network is not the only solution for a Smart Grid network but it will, in most cases, be the most cost-effective network solution. As this analysis illustrates, spectrum requirements for a wireless SG network differ significantly; it depends on the terrain characteristics and demographics and it depends on the sub-network being deployed. Not having access to spectrum best suited for the specific SG application can profoundly affect the BS requirements and thus; the deployment economics. On the other hand, with the availability of suitable spectrum, the appropriate amount in the right band, a wireless network can cost-effectively meet SG capacity and latency requirements for high density urban areas and meet the coverage requirements to reach utility customers in remote rural areas.

References

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