The New Home as a Hotspot: Wi-Fi Meet CBRS LTE and Meet Your Long Range Brother LoRa

A Technical Paper prepared for SCTE•ISBE by

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Introduction

We have given customers a valuable resource – the home Wi-Fi hotspot – a well understood 'inside out' service. Is there an opportunity to use the Home for additional inside out services? We now can potentially add to Wi-Fi with CBRS LTE and LoRA services – leveraging the connection to the DOCSIS or Fiber network to provide in home and outside services. With the inclusion of a home cell containing CBRS and LTE, the service provider can build an inside out network targeting the emerging CBRS capable smart phone and NB-IOT devices.

This paper reviews the home architecture required to add CBRS and LoRA home cells to complement existing Wi-Fi hotspots and the software solutions to manage them. The paper further discusses the potential for adding LoRa to the home, as an inside out LoRa edge network, and how to build a comprehensive NB-IoT solution. The RF decisions around the deployment of this cell will also be discussed – 1 per home or 1 per X homes for more efficient initial coverage.

Content

1. Snapshotting the Wireless Home

Home Wi-Fi may be thought of as a cable bandwidth enfranchisement technology which binds wireless cable-native or 'Bring your own' CPE used in the home (and immediately on its periphery) to the wireline cable network for backhaul. Emerging management layers seek to assign available Wi-Fi spectrum to this (potentially dynamically mounted) client palette in a manner which load balances air time and wireless channel usage based on anticipated consumption rates, service priorities, user priorities and monitored spectral availability with the goal of maximizing availability and throughput of these user devices and the services they represent. Home Wi-Fi as yet only unevenly accommodates 2.4 GHz ISM band sharing with non-Wi-Fi, NB-IoT radio traffic (as defined by the Bluetooth/BLE family of devices, Thread 802.15.4, and the various Zigbee flavors) – begging additional remediation gambits like band co-existence (TDM) semaphore schemes and (perhaps, in future) explicit FDM (parsing) of the 2.4 GHz band to assign narrowband data conduits through the Wi-Fi clutter for IoT devices to establish competing inband links (dependent upon their radio/MAC technology and service propositions).

While these areas of investigation are being paced in a demanding, immediate market sense by inflating home Wi-Fi bitrate demands and new IoT vertical businesses with critical latency expectations, additional wireless capability (and service hardening – the addition of battery power to bridge mains loss and a wireless backhaul option for loss of wireline) can be found in out-of-Wi-Fi-bands overlay architectures represented by 3.5 GHz CBRS/LTE and 900 MHz LoRa. With respect to the former, the presence of wideband channels also facilitates the deployment of data or voice services in addition to the payloads associated with IoT – the lone motivation in the case of LoRa.

2. 3.5 GHz CBRS

As regards CBRS, the FCC's creation of this 3.5 GHz spectrum opportunity in 2016 mandates no particular services to be mounted or MAC to be used (though for unlicensed enthusiasts of fine-granularity scheduling and low-latency connectivity either a private LTE network or a new MAC offering called MultiFire were possible; and while not pursued in the literature, one could have conceivably employed 802.11ac in the band at that time as well.) The band's location between the Wi-Fi 2.4 GHz and 5 GHz bands also promises at least a derivative understanding of its propagation characteristics (with respect to known Wi-Fi art) – and this, in regard to both in-home and inside-out strand-mount AP reach.

As a bookmark, CBRS was broadly envisaged by the FCC to be exploited as a private LTE/TDD technology consisting of fifteen 10 MHz wide channels contiguously arrayed from 3.55 GHz to 3.70 GHz whose spectral access was to be dynamically managed by an entity called the Spectrum Allocation System (SAS). SAS arbitrates requests for bandwidth from potential users and refers these to an executive policy which determines if the request comes from an Incumbent, Priority License Access (PAL) license holder or a member of the General Authorized Access tier. Incumbents (largely shipborne radar, though some fixed satellite and wireless ISP accounts are represented) are given pre-emptive priority. That is, even if services are running on a channel to which they request access, such services are forced to idle themselves.

The FCC mitigated the impact of incumbent exclusion zone requirements by relaxing the radar keep-out footprint in acknowledgment of CBRS' reduced radiated power impact, as shown below – the early cut is in yellow and the final boundary is in blue.

Figure 1 - 3.5 GHz CBRS Shipborne Radar Coastal Exclusion Zones

PAL accounts receive the next use preference and in fact are the highest priority users in most inland use scenarios. They are guaranteed access to 70 MHz of the 150 MHz CBRS spectrum. The final tier (GAA) represents the lowest priority unlicensed users who are guaranteed 80 MHz of spectrum. Note that SAS was originally intended to operate on a highly granular geographic basis (census tract cell sized) with leases of only 1-3 year duration (to promote access by interested small entities). This original notion facilitates highly granular and rapid spectral re-use, in direct proxy to small cell operational dynamics. For example, the City of Philadelphia, with 369 sq km, has 19,000 Census tracts with an average of 1/3 sq km of area. However, recent considerations of the FCC seem to suggest a more "large business entityfriendly" posture, with service footprints moving to county-sized plots and lease durations running to 7-10 years. In any event, the following figure exemplifies SAS' priority considerations:

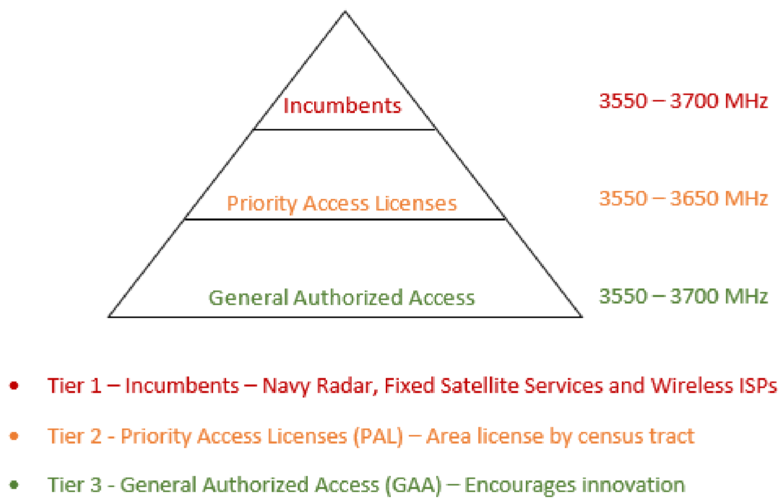


Figure 2 - CBRS Priority Tier Membership Distribution

Fundamentally, the SAS maintains a regionally referenced, curated database of potential users annotated by license type and is also informed by an Environmental Sensing Capability (ESC) device — essentially activity detectors for incumbents, such sensors deployed in proximity to the exclusion zone — and uses these information stores to dynamically arbitrate accesses on small-cell boundaries in the 3.5 GHz CBRS band. To underscore the scalable small-cell nature of CBRS, the FCC created the following radiated and conducted power envelopes for Citizens Broadband Radio Service Devices (CBSDs) which intend on levering the PAL and GAA tiers in the band:

CBSD Category	Maximum Conducted Power (dBm/10 MHz)	Maximum EIRP (dBm/10 MHz)	Maximum Conducted PSD (dBm/MHz)	CBSD Installations	Operations in 3550-3650 MHz	Operations in 3650-3700 MHz
Category A	24	30	14	- Indoor - Outdoor max 6m HAAT	Everywhere Outside DoD Protection Zone	Everywhere Outside FSS and DoD Protection Zone
Category B (Non-Rural)	24	40	14	- Outdoor only - Professional Installation	Outside DoD Protection Zone & requires ESC approval	Everywhere Outside FSS Protection Zone and DoD Protection Zone
Category B (Rural)	30	47	20	- Outdoor only - Professional Installation	Outside DoD Protection Zone & requires ESC approval	Everywhere Outside FSS Protection Zone and DoD Protection Zone

Figure 3 - CBSD Category A and B Power Signature Limits

The beauty of leveraging the band with unlicensed LTE means that scale economies for 3.5 GHz radios managed by 3GPP-based LTE narrowband protocols would make the silicon componentry available to minimize both cost and (potentially) battery use of the constrained end devices (CEDs) used in the IoT network. And of course, the LTE small-cell infrastructure in its entirety facilitates carriage of mobile phone services (as replacement for in-home landline dependency or perhaps as proviso of larger footprint, in-neighborhood proximate use scenarios.)

2.1. CBRS/LTE Home Inside/Out Signal AP Reach Analysis

An analysis of available RF link budget for a connection between a mid-home located 3.5 GHz CBRS/LTE AP (modeled as a dual-path device of 3 dBi antenna gain/path with assignable total EIRP of 1W, ½ W or ¼ W and a receiver NF of 6 dB) and a mobile transceiver (modeled as a dual-antenna device with +20 dBm total output EIRP and a receiver NF of 9 dB) was conducted. 20 MHz of channel bandwidth was presumed. A results matrix allowing for three different size home/lot combinations, across three different service grades (Downstream/Upstream Mbps as 25/5, 10/2 and 0.1/0.1 – the latter a voice service presumption but also relevant proxy for NB-IoT signaling) and three types of exterior material construction (wood siding, brick/Hardiplank or stone – all with e-glass windows) was established to test layout sensitivities across several concerns. The end intention of the exercise was to identify potential distribution schemes for exploit of the technology and what complexities might arise.

3.5 GHz propagation characteristics were measured in various open-air environments around Tampa to lump Fresnel and other diffractive effects with bulk loss tangent calculation. Recall that the ~ 10:1 wavelength advantage of the 3.5 GHz band versus mmWave results in a 20 dB lower hit to the link budget and much better nLOS and NLOS propagation. (The free space loss is described by 20 log(d) + 20 log(f) + 20log(4*pi/c) where d is the distance, f is the frequency and c is the speed of light.) A best-fit curve describing generic through-air path losses was extracted from the data:

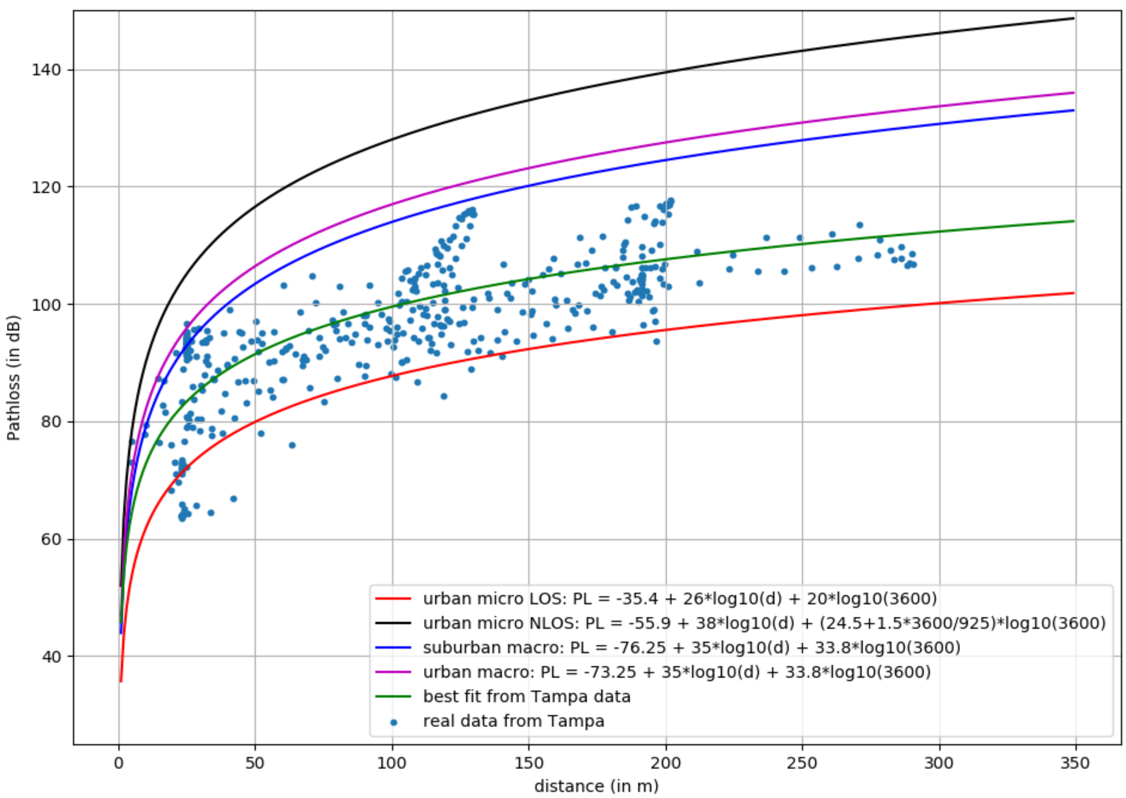


Figure 4 - 3.5 GHz Propagation Study

Lumped-element material transition attenuations from available tabular data were used to peg 3.5 GHz losses as 3 dB for drywall/floor, 35 dB for e-glass, 3-5 dB for wood siding, 13 dB for brick/Hardiplank and 25 dB for 4-6” stone. Average spring/summer foliage losses for a mixed light forest were set in the range of 10-12 dB. Tabular service radii data is available in the section following the illustrations. The illustration below defines the architectural implications of inside/out home reach using CBRS/LTE:

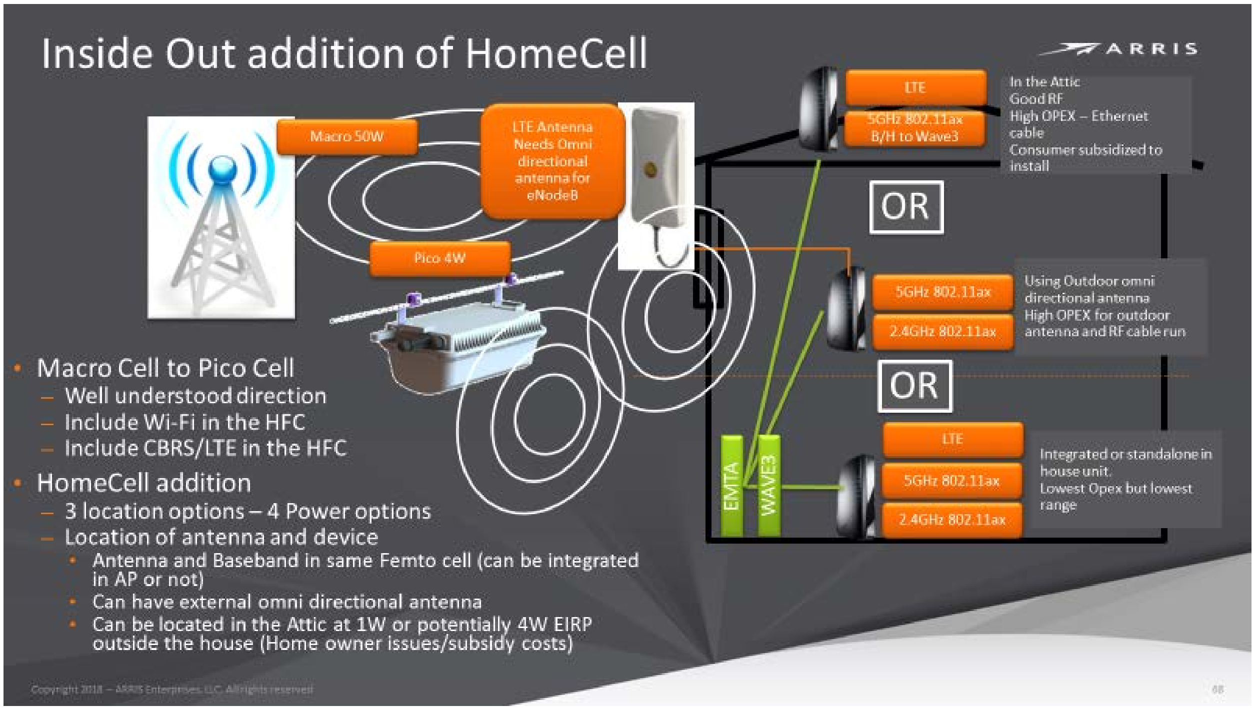


Figure 5 - Schema of Inside/Out Propagation Studies for 3.5 GHz CBRS

In addition to inside/out possibilities, a backbone of 4W strand mount POPs may be used to extend coverage so that CBRS/LTE mobile devices may be used for the case of neighborhood roaming (this lies within the FCC guidelines of 10W maximum for urban areas and 50W for unpopulated rural tracts):

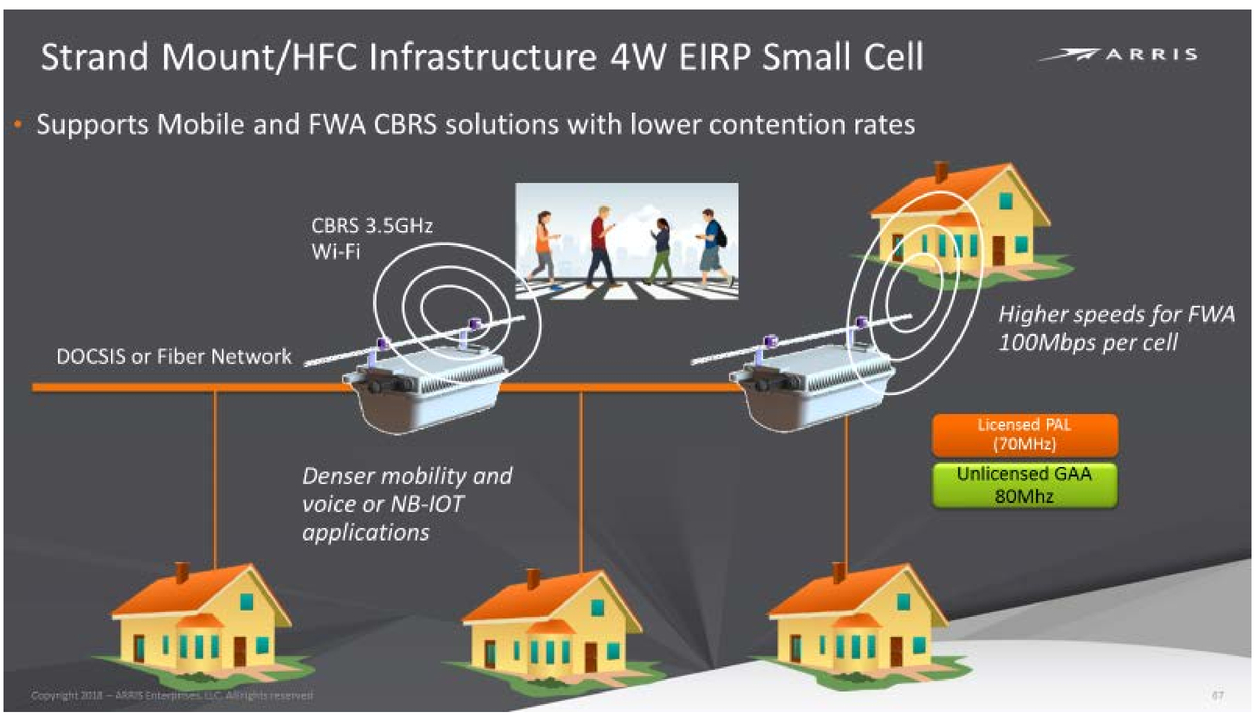


Figure 6 - Defining the Roaming (Home Exterior) Proposition for CBRS/LTE

2.1.1. Bungalow Data and Voice Services

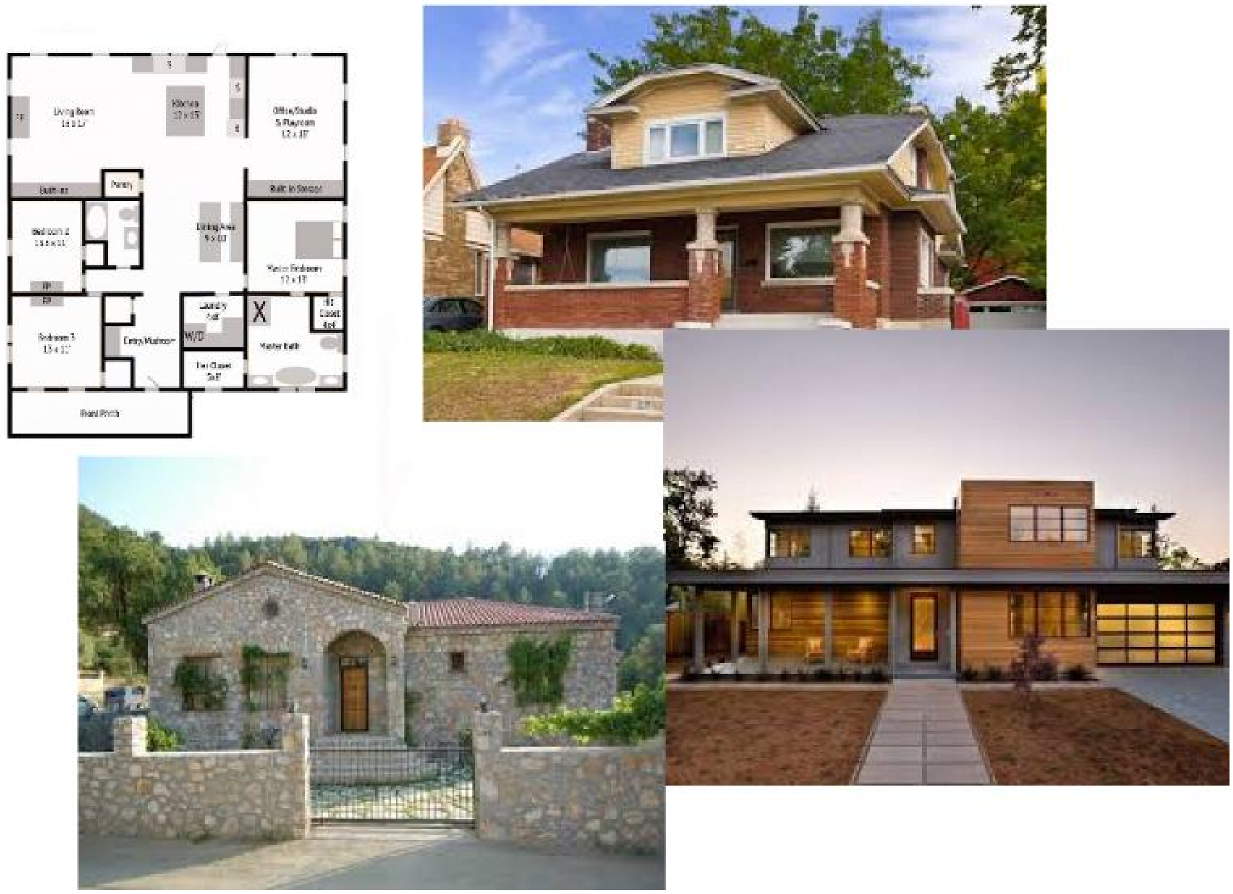


Figure 7 - Sample Bungalows of Various External Construction

The Bungalow portion of the analysis presumed a 1,500 square foot dwelling on a 0.2-acre lot and an internal AP placement which would have met with two internal floor/ceiling transitions and an exterior wall in order to reach outside the home before encountering the foliage costs to propagation. The resultant service radii for the three grades of connection were calculated as follows:

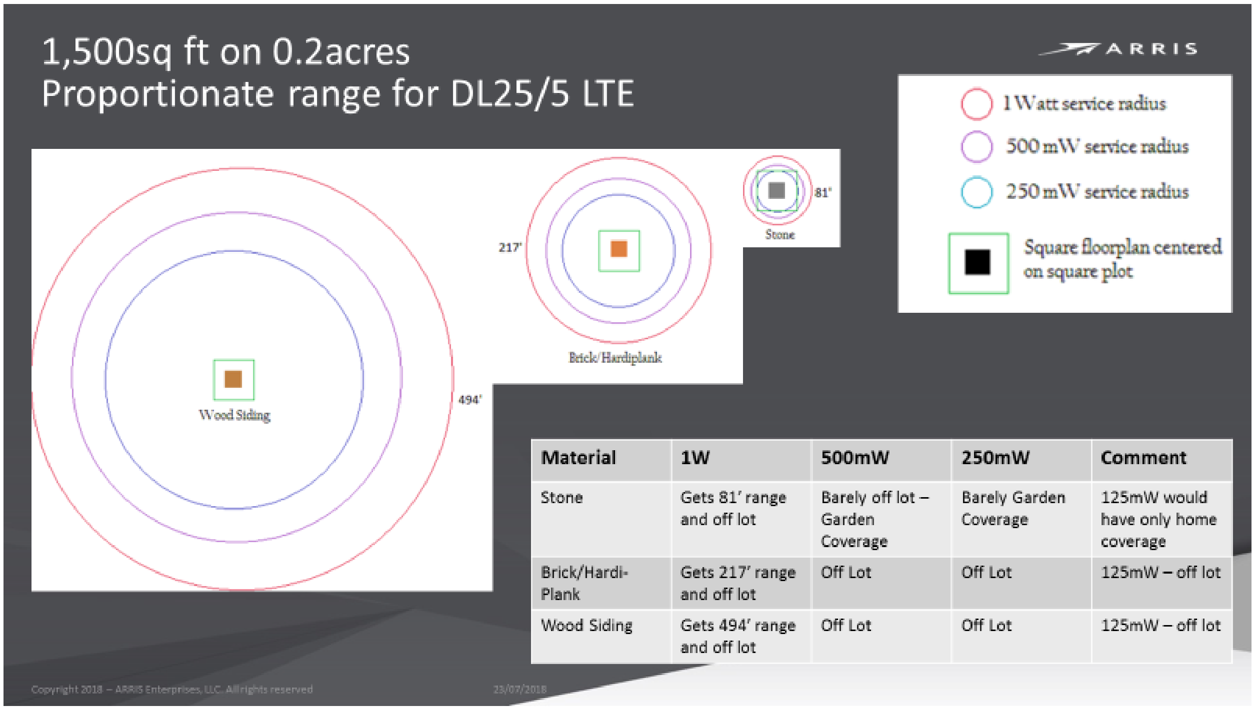


Figure 8 - Inside/Out Bungalow Service Reach @ 25/5 Mbps

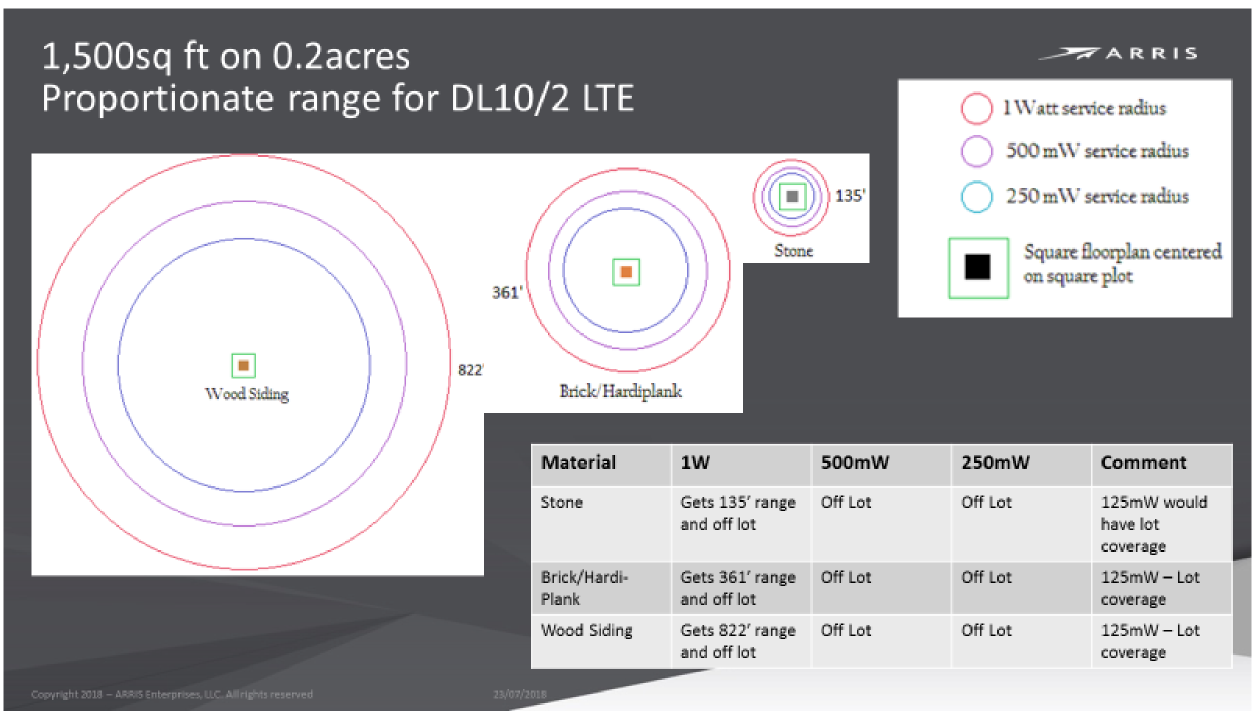


Figure 9 - Inside/Out Bungalow Service Reach @ 10/2 Mbps

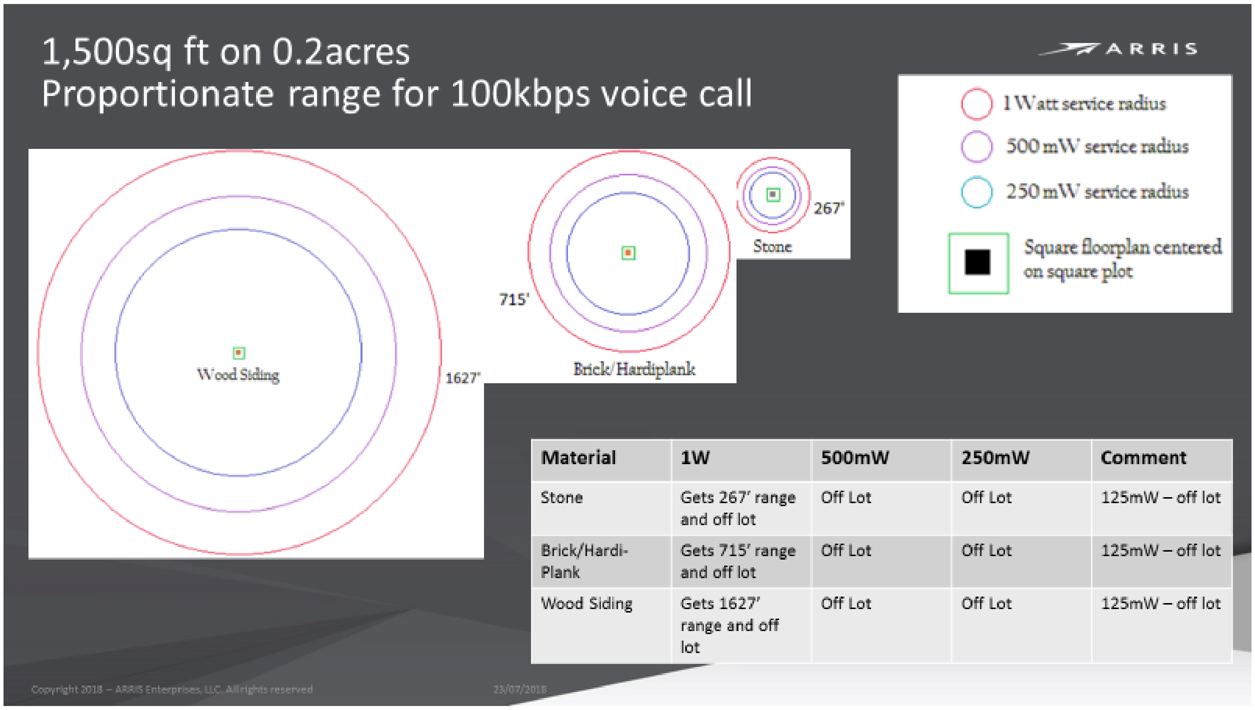
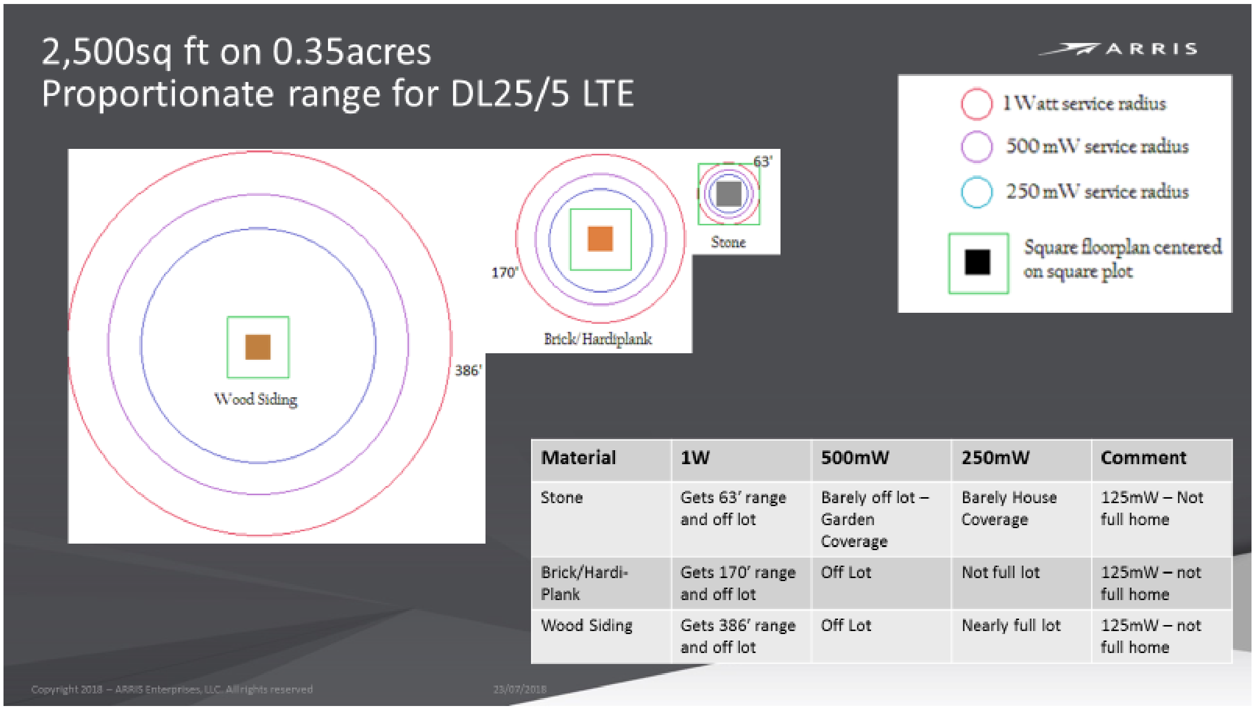


Figure 10 - Inside/Out Bungalow Service Reach for Voice Call

2.1.2. Average Home Data and Voice Services

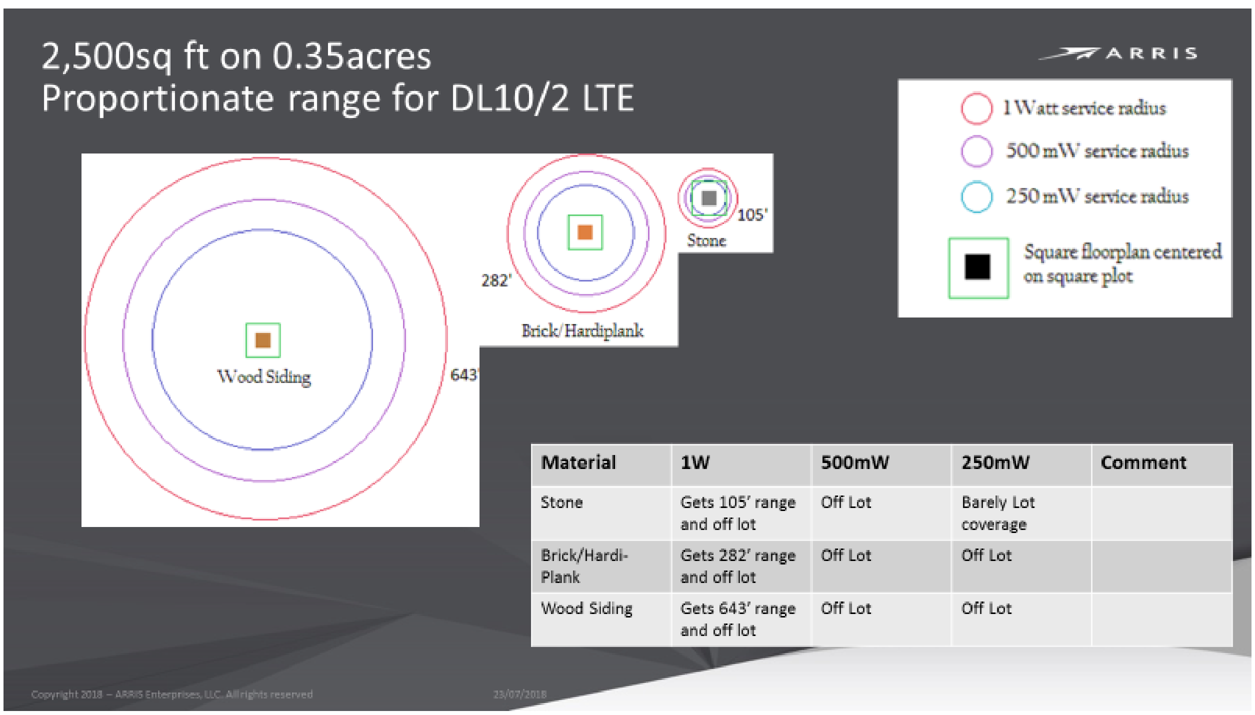
Figure 11 - Sample Average Homes of Various External Construction

The average-sized home portion of the analysis presumed a 2,500 square foot dwelling on a 0.35-acre lot and an internal AP placement which would have met with three internal floor/ceiling transitions and an exterior wall in order to reach outside the home before encountering the foliage costs to propagation. The resultant service radii for the three grades of connection were calculated as follows:



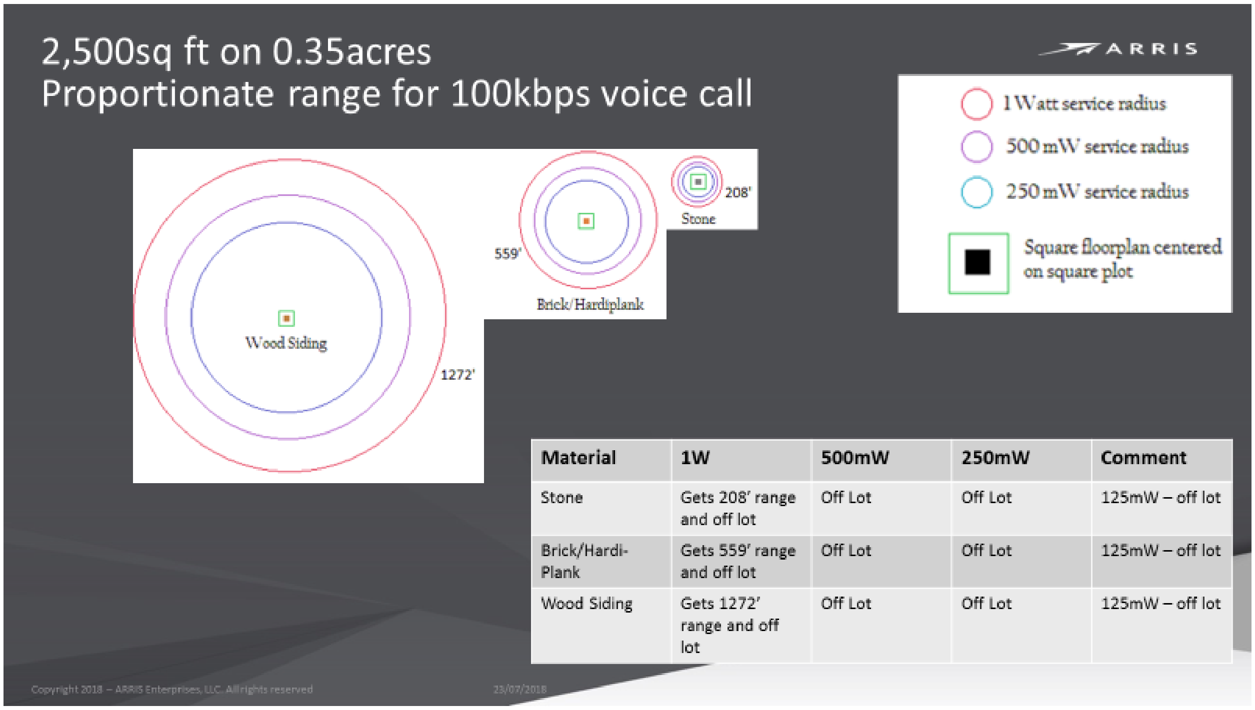
Material	1W	500mW	250mW	Comment
Stone	Gets 63' range and off lot	Barely off lot – Garden Coverage	Barely House Coverage	125mW – Not full home
Brick/Hardi-Plank	Gets 170' range and off lot	Off Lot	Not full lot	125mW – not full home
Wood Siding	Gets 386' range and off lot	Off Lot	Nearly full lot	125mW – not full home

Figure 12 - Inside/Out Average Home Service Reach @ 25/5 Mbps



Material	1W	500mW	250mW	Comment
Stone	Gets 105' range and off lot	Off Lot	Barely Lot coverage	
Brick/Hardi-Plank	Gets 282' range and off lot	Off Lot	Off Lot	
Wood Siding	Gets 643' range and off lot	Off Lot	Off Lot	

Figure 13 - Inside/Out Average Home Service Reach @ 10/2 Mbps



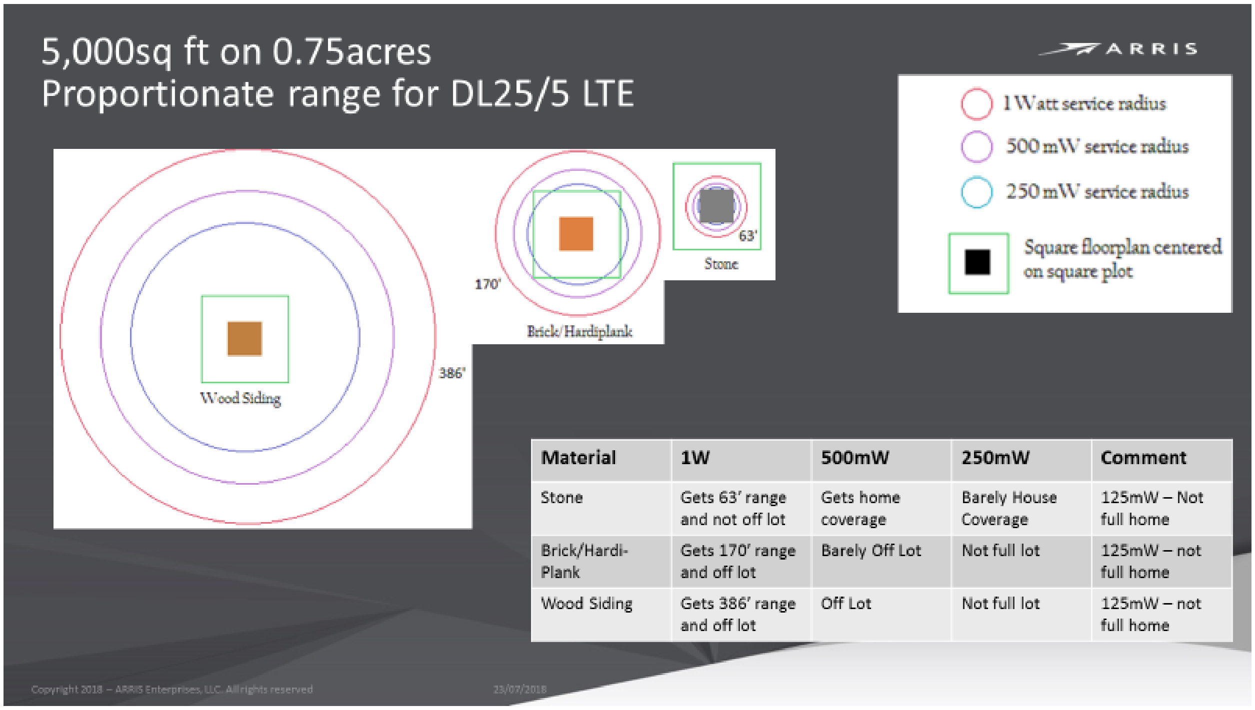
Material	1W	500mW	250mW	Comment
Stone	Gets 208' range and off lot	Off Lot	Off Lot	125mW – off lot
Brick/Hardi-Plank	Gets 559' range and off lot	Off Lot	Off Lot	125mW – off lot
Wood Siding	Gets 1272' range and off lot	Off Lot	Off Lot	125mW – off lot

Figure 14 - Inside/Out Average Home Service Reach for Voice Call

2.1.3. Large Home (Mansion) Data and Voice Services

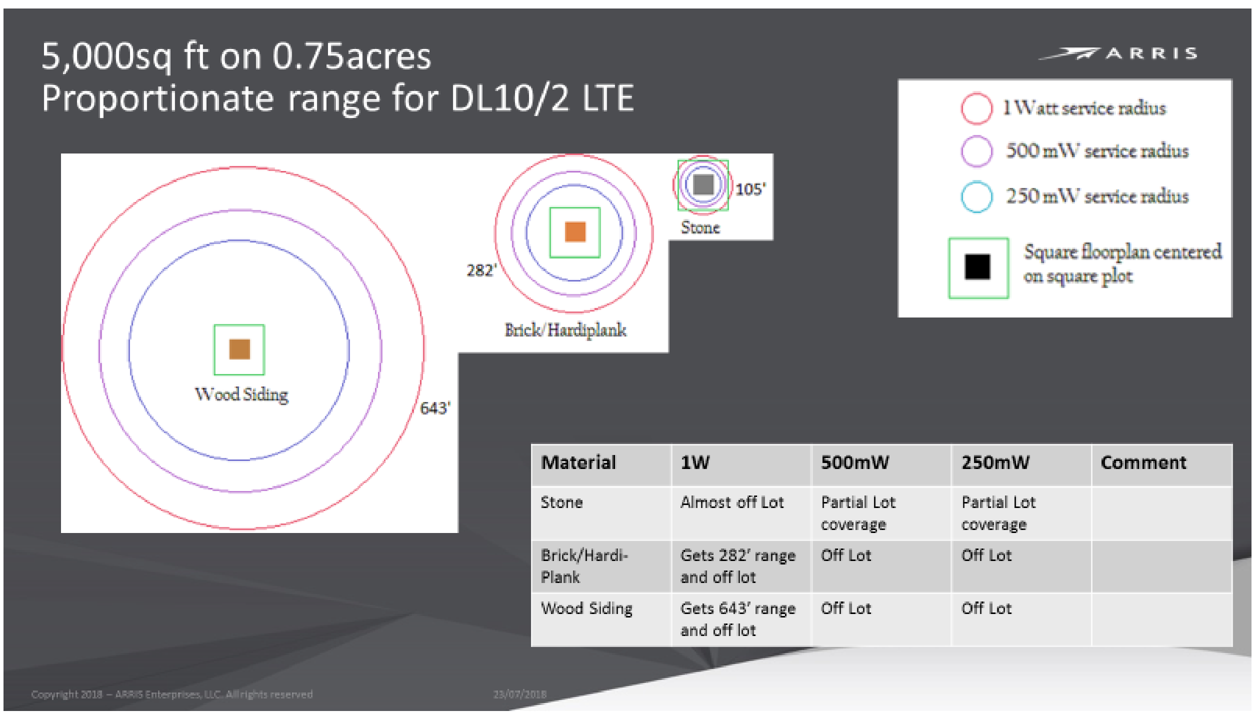
Figure 15 - Sample Mansions of Various External Construction

The mansion portion of the analysis presumed a 5,000 square foot dwelling on a 0.75 acre lot and an internal AP placement which would have met with three internal floor/ceiling transitions and an exterior wall in order to reach outside the home before encountering the foliage costs to propagation. The resultant service radii for the three grades of connection were calculated as follows:



Material	1W	500mW	250mW	Comment
Stone	Gets 63' range and not off lot	Gets home coverage	Barely House Coverage	125mW – Not full home
Brick/Hardi-Plank	Gets 170' range and off lot	Barely Off Lot	Not full lot	125mW – not full home
Wood Siding	Gets 386' range and off lot	Off Lot	Not full lot	125mW – not full home

Figure 16 - Inside/Out Mansion Service Reach @ 25/5 Mbps



Material	1W	500mW	250mW	Comment
Stone	Almost off Lot	Partial Lot coverage	Partial Lot coverage	
Brick/Hardi-Plank	Gets 282' range and off lot	Off Lot	Off Lot	
Wood Siding	Gets 643' range and off lot	Off Lot	Off Lot	

Figure 17 - Inside/Out Mansion Service Reach @ 10/2 Mbps

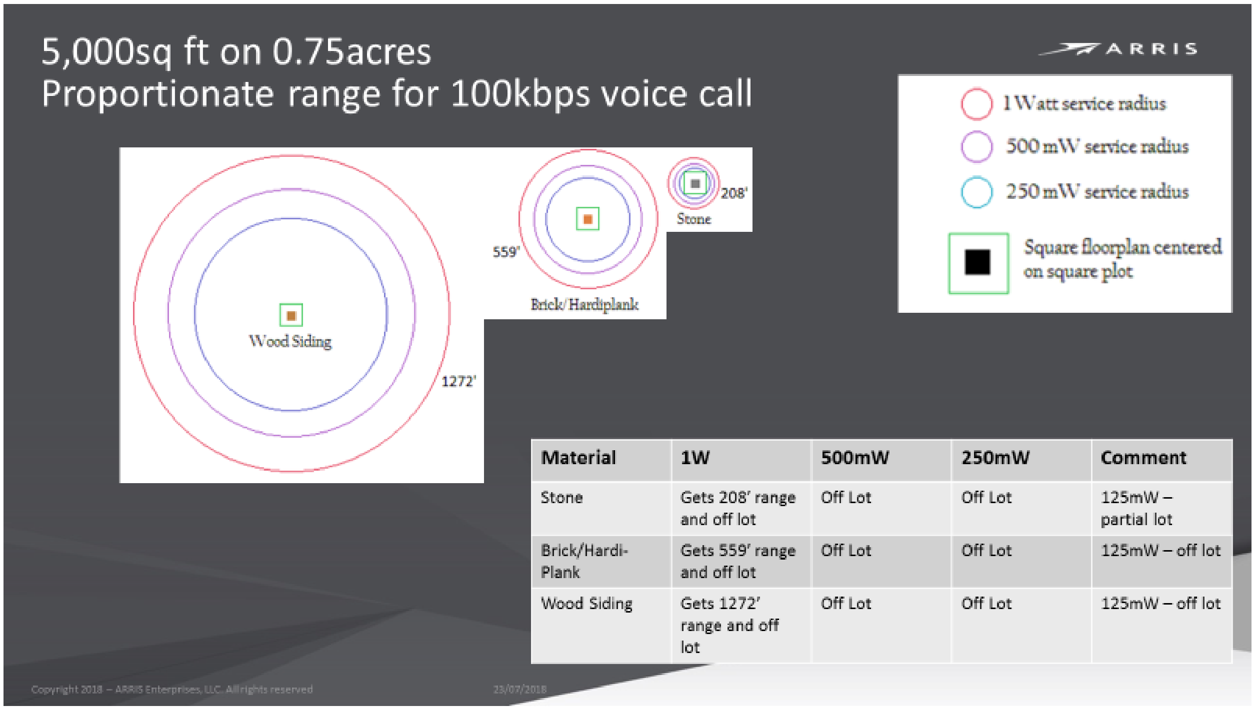


Figure 18 - Inside/Out Mansion Service Reach for Voice Call

2.2. Tabular Summary of Inside/Out 3.5 GHz CBRS AP Reach

AP Service Radius (feet)
25 Mbps (D) / 5 Mbps (U)

	Size (sq ft) \ Exterior	Stone	Brick	Wood
1W AP	1500	81	217	494
	2500	63	170	386
	5000	63	170	386

	Size (sq ft) \ Exterior	Stone	Brick	Wood
500mW AP	1500	63	170	386
	2500	49	132	302
	5000	49	132	302

	Size (sq ft) \ Exterior	Stone	Brick	Wood
250mW AP	1500	49	132	302
	2500	39	104	236
	5000	39	104	236

Figure 19 - 25/5 Mbps Service Radii Performance

AP Service Radius (feet)
10 Mbps (D) / 2 Mbps (U)

1W AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	135	361	822
2500	105	282	643
5000	105	282	643

500mW AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	105	282	643
2500	82	221	502
5000	82	221	502

250mW AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	82	221	502
2500	64	172	392
5000	64	172	392

Figure 20 - 10/2 Mbps Service Radii Performance

AP Service Radius (feet)
100 kbps (D)/100 kbps (U)

1W AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	267	715	1627
2500	208	559	1272
5000	208	559	1272

500mW AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	208	559	1272
2500	163	437	994
5000	163	437	994

250mW AP

Size (sq ft) \ Exterior	Stone	Brick	Wood
1500	163	437	994
2500	127	341	776
5000	127	341	776

Figure 21 - Voice Call Service Radii Performance

2.3. 3.5 GHz CBRS Neighborhood Roaming Via HaaT (Home as a Tower)

Reviewing the data for inside/out coverage indicates that extremely dense exterior home construction (stone) puts paid to the notion that one might be able to roam outside very far with a band 48 (CBRS) mobile device – potentially not even being able to reach the limits of the property for a large (>= 0.75 acre) lot before losing all but voice connection even with the most powerful 1W interior AP (not that such devices are all that desirable for an interior environment, with a ~ 400 cubic inch volume dissipating an estimated 26 W).

There is a qualifier which must be noted here regarding visible antenna placement within the home and the accurate observation that horizontal propagation from a low height within the dwelling (or even from the second floor) does indeed prove problematic. However, if the home is viewed as effectively a radome of sorts, then some amount of propagation relief can be had by elevating the antenna into the attic. This typically would involve a fair amount of cabling loss (say, 5 dB for 20 feet of coax at 3.5 GHz) and necessarily involve the use of an antenna element with sufficient gain to at least overcome the cabling losses. This is largely wasted effort in the case of wood-sided homes, since the roof aperture for the antenna pattern still involves end plates which cannot be mitigated and the relieved surfaces (as transition of roof sheathing, insulation and shingles) are not much less lossy than the wood siding itself. But for brick or stone homes, the pattern would certainly improve along the horizontal access where the dense siding is replaced by roofing materials (unless, for example a slate, formed concrete or tile roof is involved). Aesthetic and access objections aside, the elevated interior antenna should show greatly improved footprint along at least one horizontal access compared to the buried case, presuming typical North American materials (since even composite, asphalt or stone materials are thin enough to reduce the comparative effects of several inches of masonry or stone.)

The potential of attic placement aside, the effect of ever-denser exterior construction in a real sample neighborhood on distribution of high power interior-only APs – and the resultant collapsing coverage footprint for high value data services are shown in this sequence of illustrations:

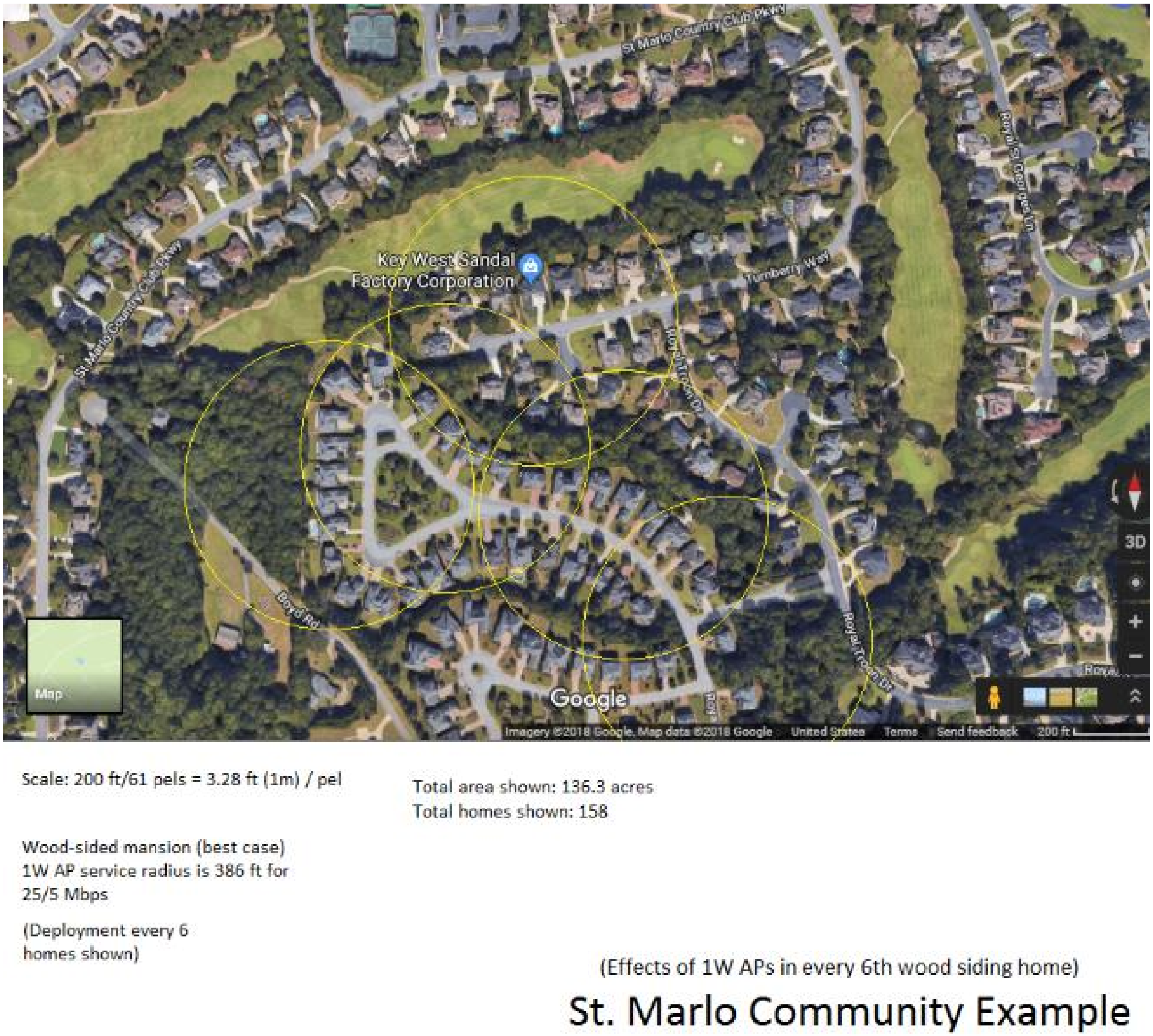


Figure 22 - Inside/Out Coverage for 25/5 Service Assuming Wood Sided Homes (1 x 6 Homes)

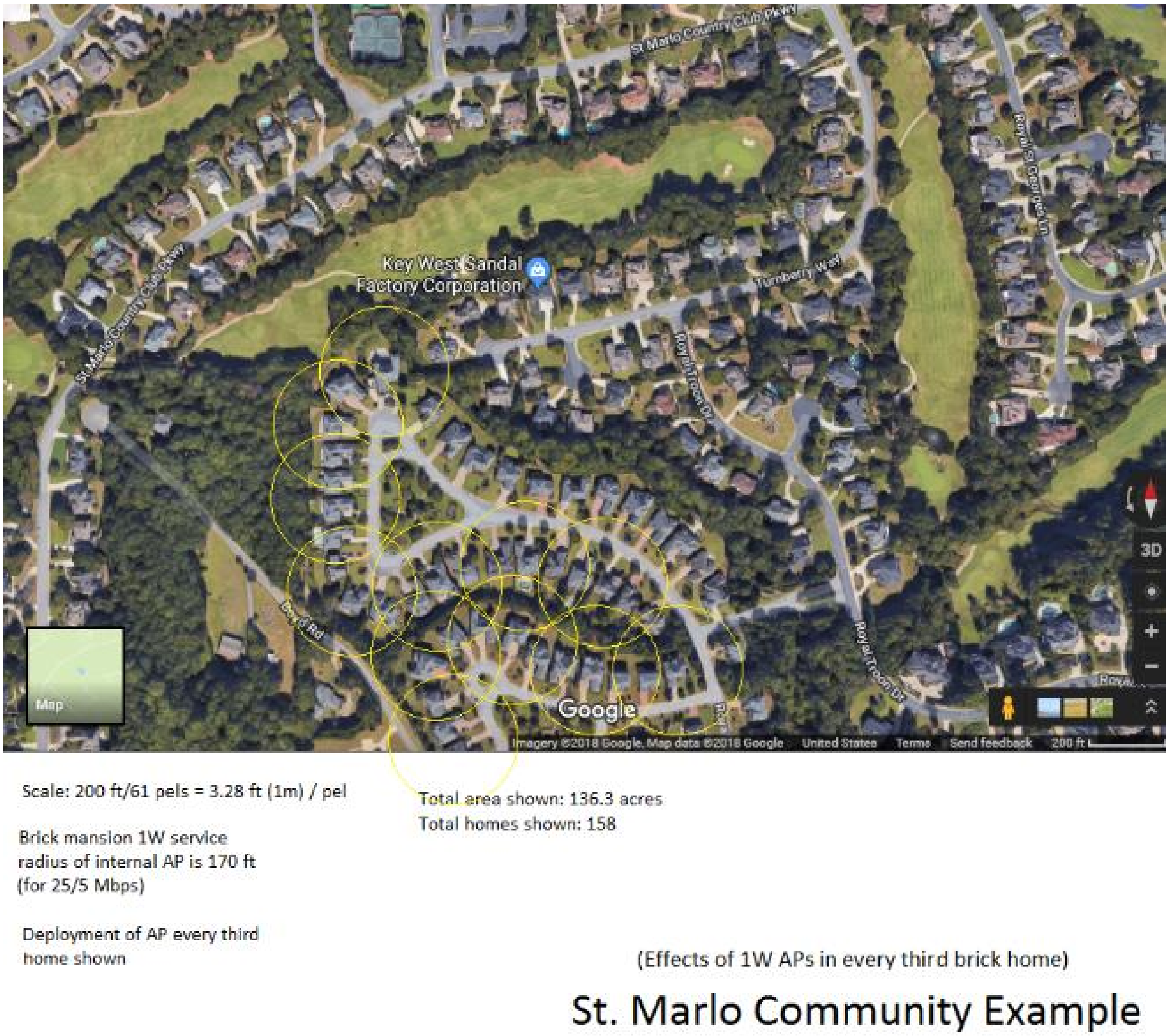


Figure 23 - Inside/Out Coverage for 25/5 Service Assuming Brick Sided Homes (1 x 3 Homes)

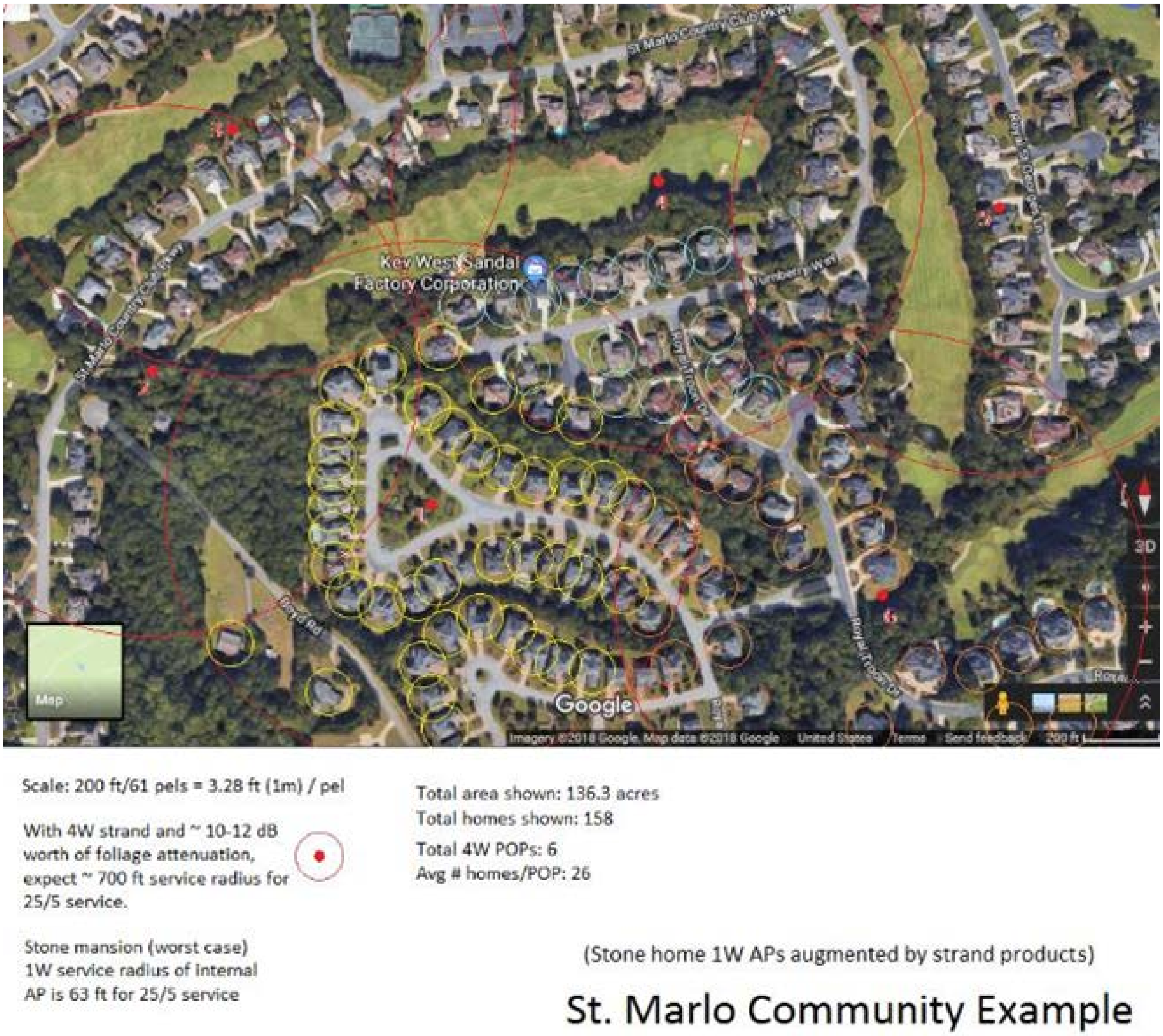


Figure 24 - Inside/Out Coverage for 25/5 Service Assuming Stone Homes (Yellow) and the Need to Augment with 4W Strand Mount APs (Red) (1 x 1 Home + 6 x 4W POPs)

As is evident in the progression above, significant roaming coverage gaps for premium data services begin to occur once exterior materials approach the density of brick and become unusable for cases where stone home placement become spaced by large lots – unless the coverage is augmented by exterior high-power APs.

This leads to a solution where we examine the separation of interior-home and neighborhood roaming coverage by employment of a scaled picocell internal AP in each home (to accept handoff of the mobile from its outside roaming) and a network of outside mast- or second-floor mount APs of either 1 or 4 W power (using the acronym "Home as a Tower" or HaaT) every N houses to provide the "outside home" (neighborhood roaming) data coverage. Coverage maps of the same sample neighborhood are shown:

Figure 25 - 1W HaaT Coverage for 25/5 Service (1 x 10-16 Homes)

If the exterior AP power is raised to the CBRS allowed maximum of 4 W, the HaaT RF coverage permits even less density. However, the per-user data coverage now might become limited by the number of roaming customers (data pipe-sharing) as opposed to bitrate throttling (loss of spectral density):

Scale: 200 ft/61 pels = 3.28 ft (1m) / pel

With 4W external roof mount and ~ 10-12 dB worth of foliage attenuation, expect ~ 700 ft service radius for 25/5 service.

Total area shown: 136.3 acres
Total homes shown: 158

Roof-top mounting easily supplies > 20 homes per mount roaming support

Figure 26 - 4W HaaT Coverage for 25/5 Service (1 x 20-40 Homes)

2.4. Roaming User Considerations

Some data traffic notes are worthwhile here. As mentioned, the exterior AP's service reach also needs to scale with the potential number of roaming users within the service radius. Use of premium data does not necessarily suggest that downlink speeds are continuous (as in streaming). In fact, connected browsing users may exhibit duty cycles of only 25% or so, but we will assume worst-case streaming by all simultaneous users. Assuming further that the AP under study can be backhauled to the limit of its PAL channel carriage (70 MHz) and each of the simultaneous users is a different distance from the AP (but none outside the expected service footprint required for the 25/5 service – so in round terms at signal levels no worse than -80 dBm for the mobile device under consideration if we include the upstream data carriage considerations).

Next, we allow for distribution of the users equal distances from the AP (so the effective average signal level drives an MCS on their mobile devices to between 16- and 64-QAM – figure an average spectral density of around 4 bps/Hz). If the antenna is tri-sectored (and again, the users don't gather in a single sector) then you get a "x3" multiplier for the delivered spectrum. Under all of these (admittedly ganged) assumptions, your 4W AP would be delivering an ensemble to-mobile bitrate of 840 Mbps (280 Mbps to each of 3 sectors) and you could be supporting 33 roaming users per AP (which ends up being roughly ~1 per household in the service area).

2.5. 1W HaaT Simulations

In order to corroborate the inferences produced by the lumped model calculations, direct simulation of existing Ruckus 1W devices (arrayed as those coverage calculations suggested above) was performed in order to validate the roaming footprint proposed. This type of simulation permits the otherwise averaged effects of multipath propagation, antenna pattern, and topological interactions to be directly calculated via aggregation of ray-trace power measurements. A side-by-side comparison of the two 1W HaaT findings is immediately below:

Figure 27 - 1 W HaaT Simulation Vs Calculation; ~ 2:1 Service Radius Improvement in Sim

The 2:1 service radius differential (~ 800 ft vs ~ 400 ft) amounts to roughly 7-8 dB worth of pessimistic additional link loss in the lumped calculations (shift in the path loss vs distance curve fit, or overly excessive foliage losses, for example). This might also be indicative of the differences between the environment measured in Tampa and the neighborhood characteristics outside Atlanta. The simulation also provides greater granularity in the topographic feature effects associated with bitrate support degradation with increasing distance from the AP, better showing how radially non-homogeneous the coverage can actually be:

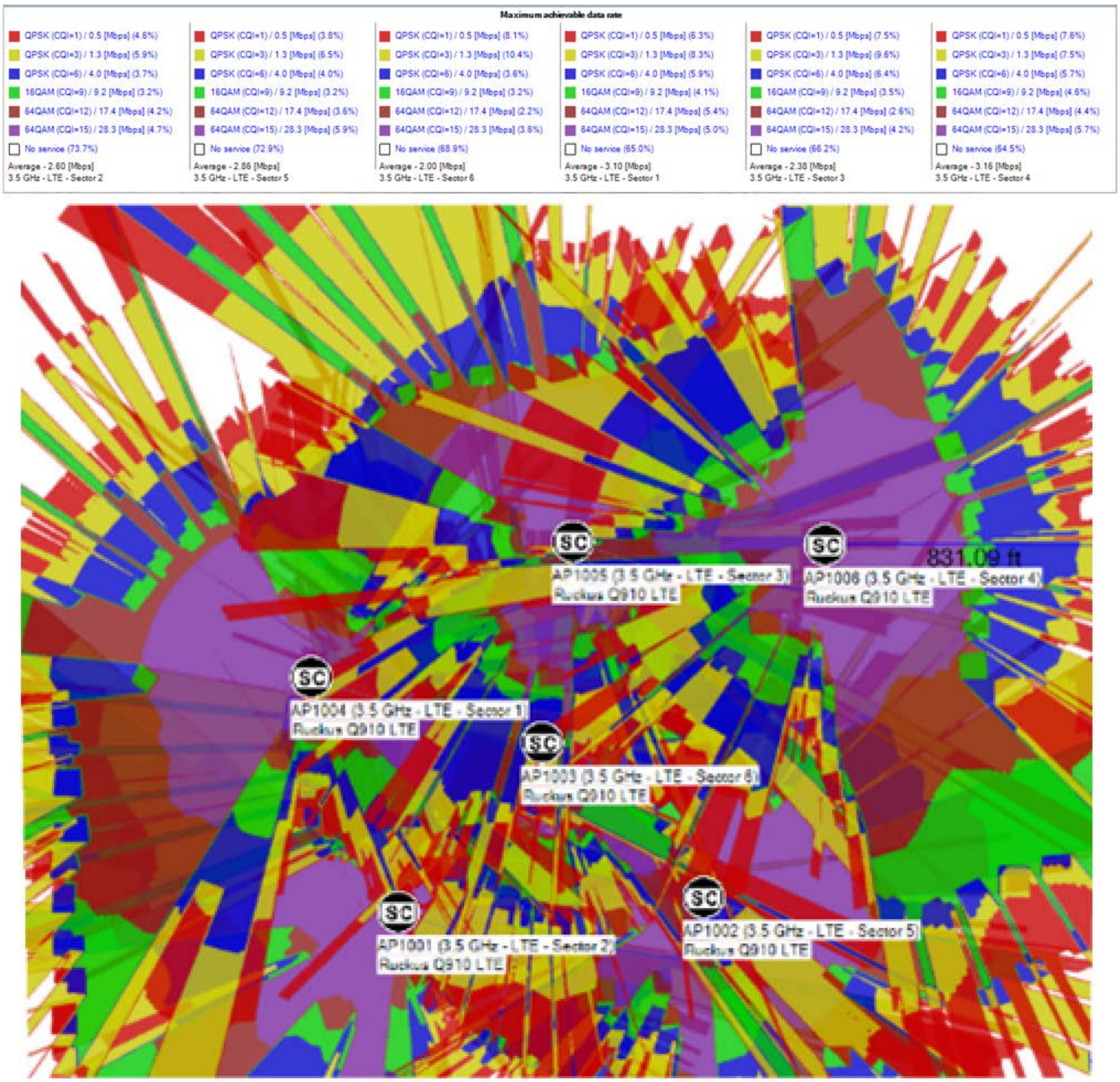


Figure 28 - 1 W HaaT Simulation, Bitrate Variance in Coverage Map

If we presume that the lumped calculations serve as a reasonable indicator of the service level available at every intermediate point within their bounded radius, then a rough estimate of the mesh density required for 3.5 GHz 4W strands or pedestals for the cases of open range distribution and mildly forested scenarios can be made:

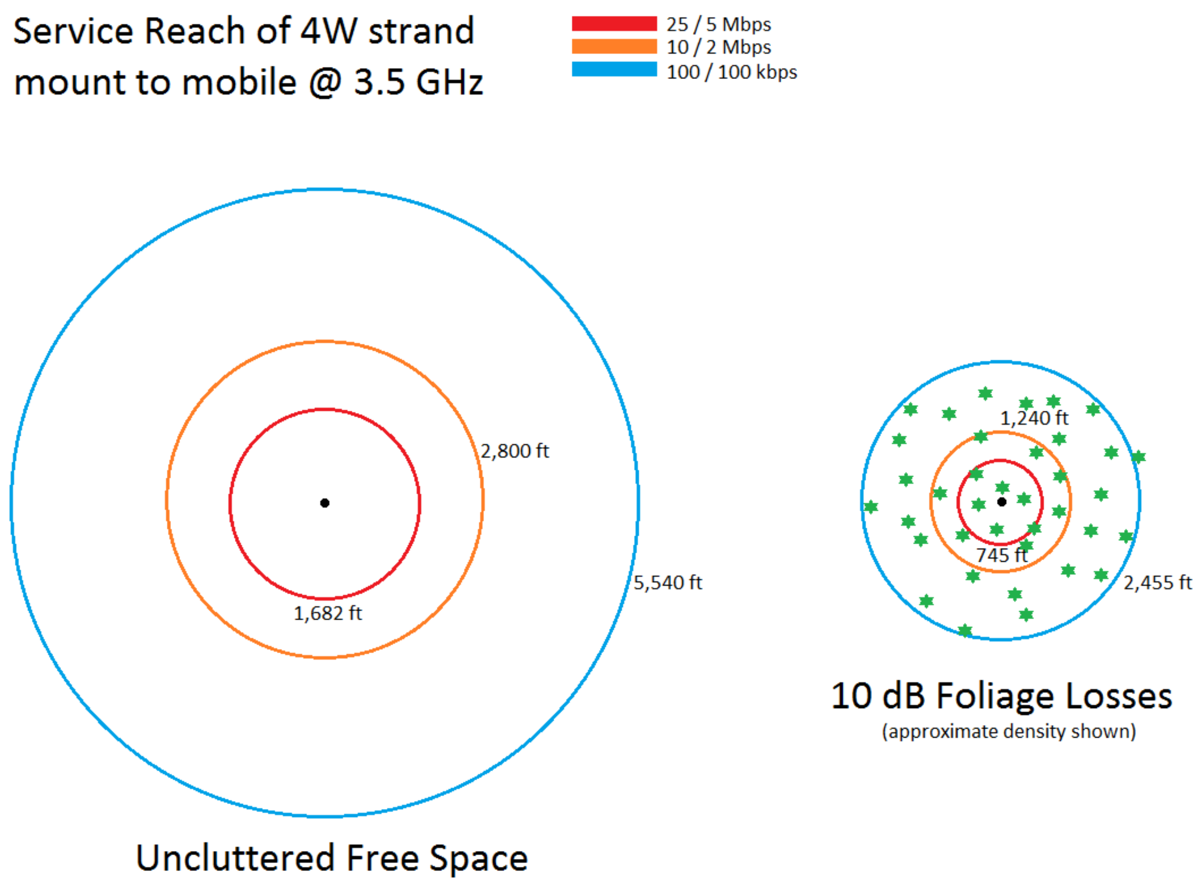


Figure 29 - Service Mounting Potential for Outdoor 4W CBRS Mesh

Recall that the simulation difference to the lumped estimation calculations yielded a 2x improvement; applied to the estimates above, it suggests that in open range conditions, 2 kilometer AP spacing might yield fairly good data coverage.

2.6. CBRS/LTE and IoT

A quick address of the implications of using 3.5 GHz CBRS as a potential out-of-band solution for IoT is in order. As might be expected, CEDs operating at the 2.4 GHz ISM band via the NFC MAC of choice would certainly benefit from either less competition in-band or the emergence of another band option outright. At issue is the cost of MAC/PHY in the new band and in particular, the availability of scale economies from widespread leverage of that new band (better still, from that standpoint, if the band use is unlicensed). CBRS may offer some relief in this aspect, since its tiered SAS support anticipates both licensed users (who might then bear the cost of scale economies in question) and GAA participants (who then benefit as an "interested second market" from MAC/PHY chip solutions which have to be developed for the license-based crowd).

At the moment, there is a cost penalty associated with CEDs moving from a legacy 2.4 GHz NFC radios and onto NB-IoT support offered by LTE at 3.5 GHz. (Hence, the interest in coupling other services – voice and premium data – into the move). However, catalytic cost benefit from licensed spectrum leverage requires watching to see when/if a cost inflection point is reached. Certainly, there is market pressure building which seeks to resolve the wireless service contention at 2.4 and it must be solved in some fashion. This is a situation whose dynamics beg monitoring.

2.7. Timing Considerations Across LTE and Cable Domains

The issue of transit between an LTE-based domain (roaming) to a home interior which is beholden to DOCSIS timing considerations is under active consideration by CableLabs. Without exposing intellectual property interests in this area, it can be said that the two domains' synchronization in general is covered by a common reference to GPS timing. However, the LTE domain (and in particular, 5G) is set to trigger on a finer granularity of latency than DOCSIS (roughly one order of magnitude, if not almost two). This difference is bridgeable, as a general rule, if the LTE network apprises DOCSIS of the impending handoff so that the latter can schedule the required wireline packet availability (essentially slaving, via alert messaging, the DOCSIS network's chunkier operation to the LTE's near-1 msec latencies.)

3. LoRa

LoRa has been more of an unknown commodity than 3.5 GHz CBRS due to its recent adoption timeline and lack of MVNO interest. LoRa amounts to a purpose-built out-of-band IoT service network scheme supporting very low-power endpoints and a native distributed star topology designed for robust and (somewhat) timely relay of IoT small-packet, spread-spectrum narrowband communications. On the cloud network edge, LoRa operates in the USA at the very well characterized ISM 900 MHz band which features an improved through-air loss tangent and better materials penetration than 3.5 GHz CBRS or any of the Wi-Fi bands – as would attend inside-out communication.

LoRa also promotes an opportunistic leverage of any conveniently available wireline IP network backhaul due to its ability to curate and cache repeat IoT packets at its edge aggregation points. This, plus its deep RF link budget, seem at first blush to facilitate an organic location protocol for its base stations. As more IoT clients get seeded, only rough triangulations should be needed to calculate where best to locate new bases (and the proximity of suitable wireline backhaul nodes can be baked into the estimations).

Furthermore, LoRa projects a naturally hardened aspect given the "repeated packet" culling and roundtrip latency calculus which can be done at its base stations.The effective star topology by default should then define a best-path solution based upon first successful edge discrimination even though there may be redundant receptions at multiple base stations. More to the point, perhaps, is that <u>LoRa allows network service providers to abstract IoT management considerations away from operation of the main IP network</u> (IoT verticals are constructed as a secure tunnel of application server(s) x addressable CEDs – the 'x' proxying the IP network backhaul as mere crosspoint switch). Such a schematic is captured below:

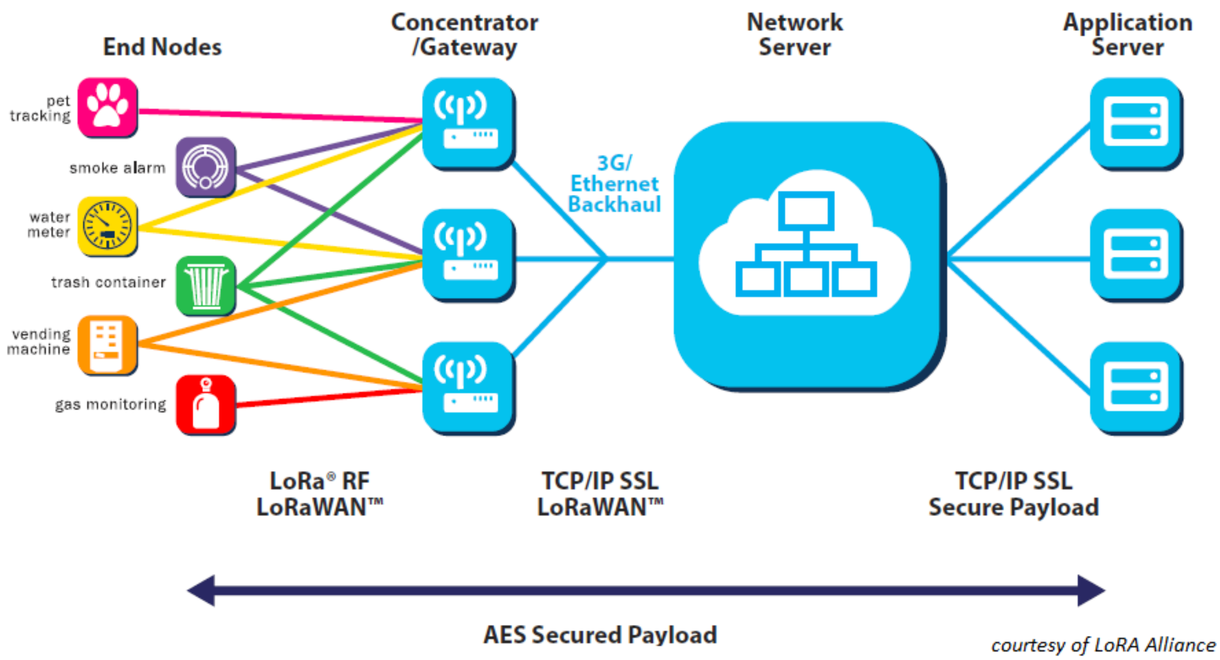


Figure 30 - Schematic of LoRa Edge Network

LoRa's approach to leverage of the ISM 900 MHz band involves the use of randomly channel-hopped, low-bitrate CSS (chirped spread spectrum). The approach is essentially chipping a data stream and then uses that to modulate a chirp waveform on an uplink-prioritized band bifurcation which places 500 kHz downlinks in the upper ~ 5 MHz of the band and two classes of uplink (64 x 125 kHz or 8 x 500 kHz channels) in the lower ~ 13 MHz of the band. The arrangement renders itself as follows:

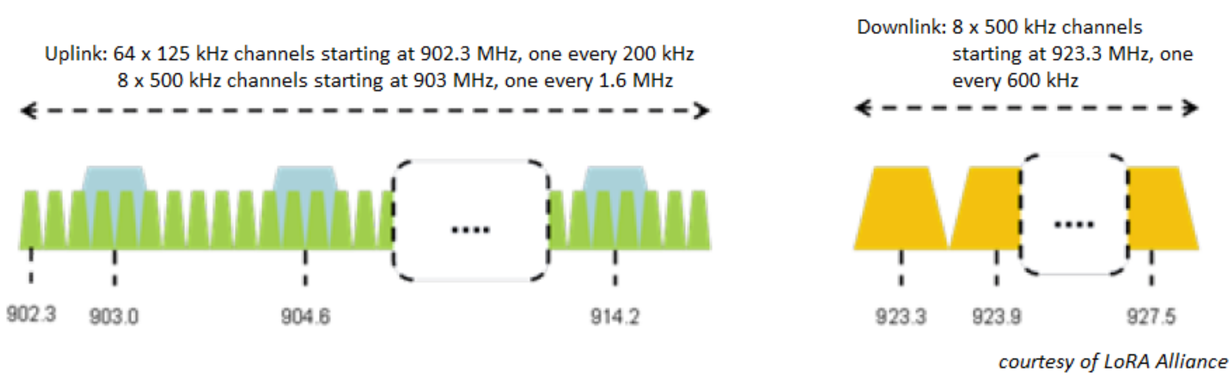


Figure 31 - LoRa US ISM 900 MHz Band Occupation

As mentioned above, from a link noise management perspective, LoRa uses a spread spectrum chirp and chipping of the underlying data to perform constant-envelope modulation of the selected channel carrier. Part of its noise adaptation mechanism is to apply additional spreading of the signal by essentially chipping a lower rate stream with a higher sampling rate and buying discriminator margin in (very) roughly similar fashion to an OFDM/QAM stream backing off its constellation density (MCS reduction –

lowering its spectral density). The cost to bitrate versus noise margin for some of the spreading factors is listed in the following table:

SF (Spreading Factor)	Chips/Symbol	SNR limit	Time on Air for 10 byte packet (ms)	Bit Rate (bps)
7	128	-7.5	56	5470
8	256	-10	103	3125
9	512	-12.5	205	1758
10	1024	-15	371	977

Figure 32 - LoRa US Spreading Factor Implications to Noise Margin and Bitrate

Another illustration of the relationship between higher rate chipping, threshold of acceptable performance, and the impact of these parameters on sustained bitrate and range is captured here:

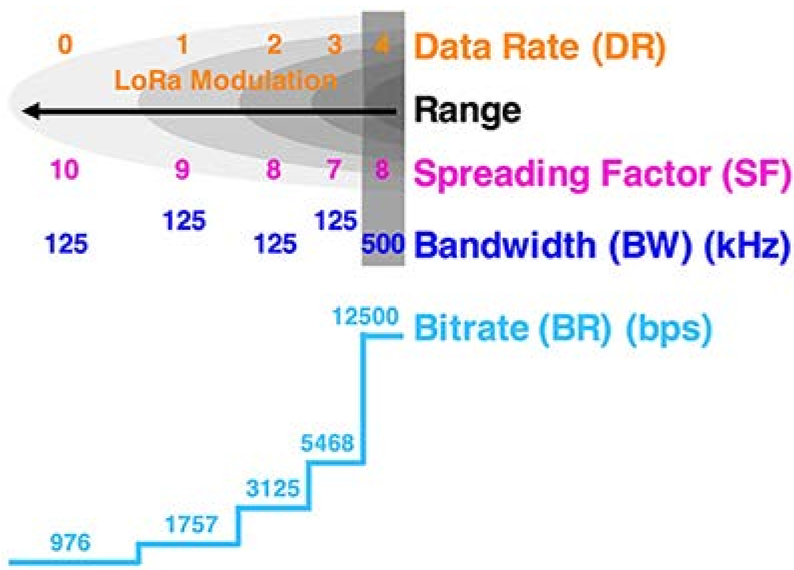


Figure 33 - LoRa Tradeoff of Sustained Bitrate for Better Range

3.1. Base Stations and CEDs

The LoRa cloud-edge base stations (which can use various backhaul technologies to attach to the cloud) serve as one terminus of the 900 MHz link. At the IoT actuator or sensor end lie three types of client devices, partitioned per their respective battery draws and communication latency needs. Type A devices are strictly the very lowest power sensors which randomly transmit (based upon event or internal watchdog timing) and wait two slotted periods for a base station ACK. (This specified random access behavior generates some quite-unwanted 2nd order effects, about which more later.) Type B devices are also battery powered devices but higher energy consumers as they are actuators which must process a timing beacon to constrain control loop latency (and establish wake/sleep periods). And Type C devices are high power actuators expected to operate off AC mains and thus maintain a constant wake state. The implications of the parsing are expressed below:

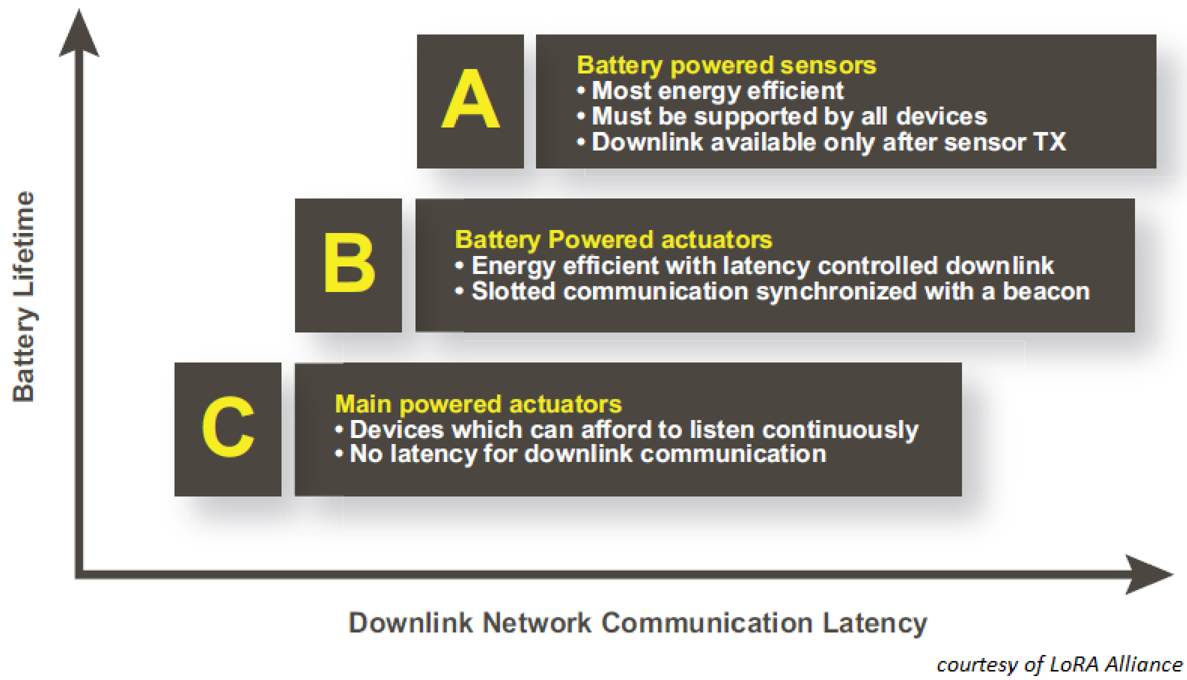


Figure 34 - LoRa Client Mix: Sensors and Actuators

3.2. Link Specifics

The associated link parameters are tabulated below. Considerations of integrated RF power under different spreading considerations suggest an actual maximum power of perhaps +21 dBm (and such is in keeping with maximizing battery life). Note especially the deep link budget even with such modest transmit power:

Frequency band	902-928MHz
Channels	64 + 8 +8
Channel BW Up	125/500kHz
Channel BW Dn	500kHz
TX Power Up	+20dBm typ (+30dBm allowed)
TX Power Dn	+27dBm
SF Up	7-10
Data rate	980bps-21.9kpbs
Link Budget Up	154dB
Link Budget Dn	157dB

courtesy of LoRA Alliance

Figure 35 - LoRa US ISM 900 MHz Link Parameters

3.3. Link Budget and Service Throw (Range)

LoRa offers two compelling recommendations for its consideration: 1) it operates in the recently (1985) created and sparsely used (as in: only partial band exploits) 903-928 MHz ISM space and 2) it employs a robust CSS modulation scheme with coding gain and random (though mask-controlled) channel assignments to extract link budgets approaching 160 dB in some cases – promoting huge potential operating range for the RF link from base station to addressable CED (and more importantly, back).

The following is tabular performance data of a LoRa endpoint device using commercially available silicon:

Mod	Data rate	Frequency (MHz)	Sensitivity (dBm)
LORA	SF7BW125	902.3	-125.1
LORA	SF7BW125	908.7	-125.8
LORA	SF7BW125	914.9	-125.9
LORA	SF10BW125	902.3	-133.7
LORA	SF10BW125	908.7	-134.5
LORA	SF10BW125	914.9	-134.7
LORA	SF8BW500	903	-122.7
LORA	SF8BW500	907.8	-123.4
LORA	SF8BW500	914.2	-123.6

courtesy Semtech

Figure 36 - Measured Sensitivity of Commercial LoRa Product

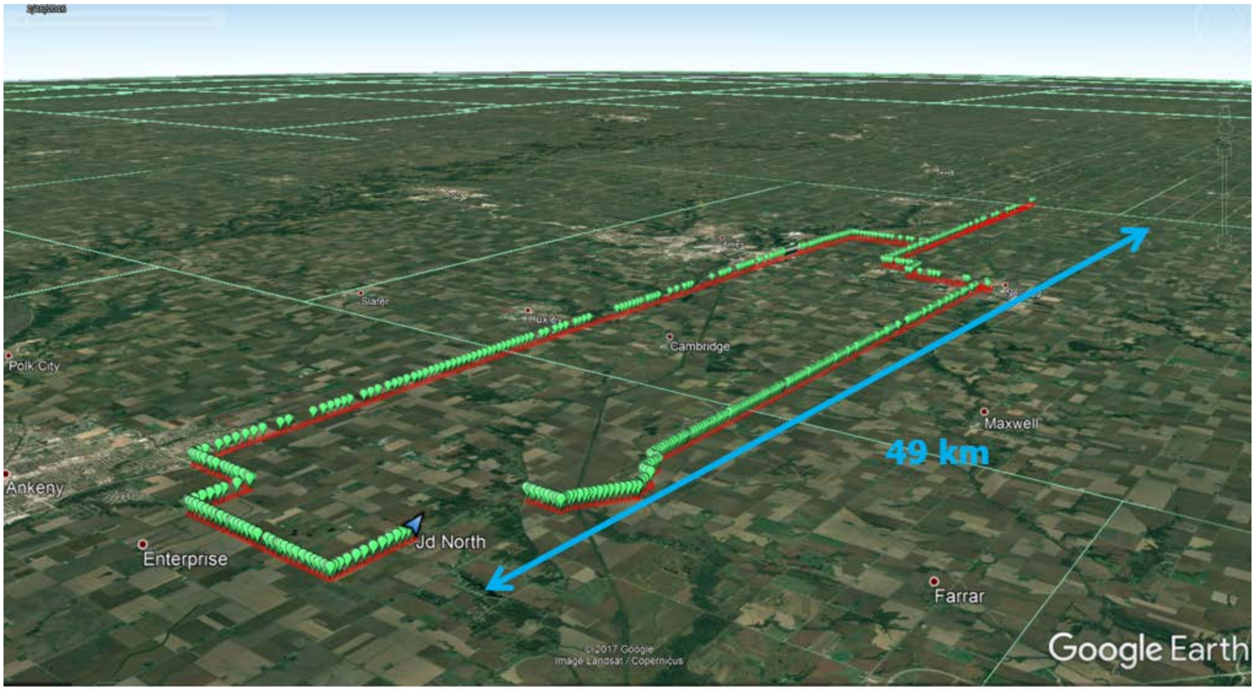
The numbers above correspond to operation at a PER threshold of 10 %. Using a web-available LoRa calculator for receiver sensitivity (http://www.rfwireless-world.com/calculators/LoRa-Sensitivity-Calculator.html) and seeding it with the appropriate spreading factor and BW numbers yields a calculated NF of 4 dB (averaged across all 9 data points). This is an excellent implementation. More to the point, the realizable bounds of +20 dBm transmit and -134 dBm receiver sensitivity play out as easily surpassed 20+ km LOS reach. (City reach is topography-specific: as in all NLOS wireless propagation calculations, the link budget is reduced by through-material transitions – getting out of the CED’s housed environment – and lost scattering in addition to the classic frequency-dependent free-space losses.) Propagation models to handle multiple diffractive paths are beyond the scope of this paper yet are worth separate investigation – the Egli model with its VHF/UHF television heritage seems a reasonable choice in areas where tree/building interferers are not common. The long story short is that 20 km LOS is a reasonable range for LoRa and this might be reduced by a factor as high as 10 in extremely dense urban environments.

As an example set of calculations and observations, there is an Egli model calculator available on the internet (https://www.commscope.com/calculators/qegli.aspx/). Using this resource and seeding values for 4 meter heights for both the base station and CED (so, 2nd residential floor for both) yields a loss estimate of 142 dB at 915 MHz and 3 km spacing. (This provides a generous 12 dB budget of lumped losses to transit buildings, for example).

Semtech builds silicon for LoRa radio implementations and offers the following performance observations (green balloons are successfully exchanged transmissions; had there been dropped packets these would have been shown in red):

courtesy Semtech

Figure 37 - Sample LoRa Suburban Mobile Inside/Out Connectivity @ 1300' Radius



courtesy Semtech

Figure 38 - Sample LoRa Rural Mobile Inside/Out Lossless Connectivity @ 49 Km (!) Radius

3.4. Geolocation of Clients as Calculated Benefit

The LoRa network topography is accurately termed an extended star. However, the fact that multiple base stations receive transmitted CED packets offers an opportunity to use packet arrival statistics (timestamp and RSSI) to build a triangulated representation of their location since base stations are GPS timed and located themselves. As long as at least 3 base stations receive a particular packet, rough estimates of client locale can be built from the near-intersections of weighted radii – the weights associated with signal strength (RSSI) or what is called TDoA (timed difference of arrival). As shown in the following figure, both techniques are inherent in LoRa and so do not represent costly appropriation of additional capability but merely exploit of a simple calculus on existing message data. The scale of the drawing is a bit misleading; examination of the error terms makes it plain that the accuracy of the TDoA exploit is roughly 10x that of the triangulated RSSI. As might be expected, the addition of additional base stations – particularly in a geographical pattern which yields as close to equal path lengths as possible – produces the most accurate results.

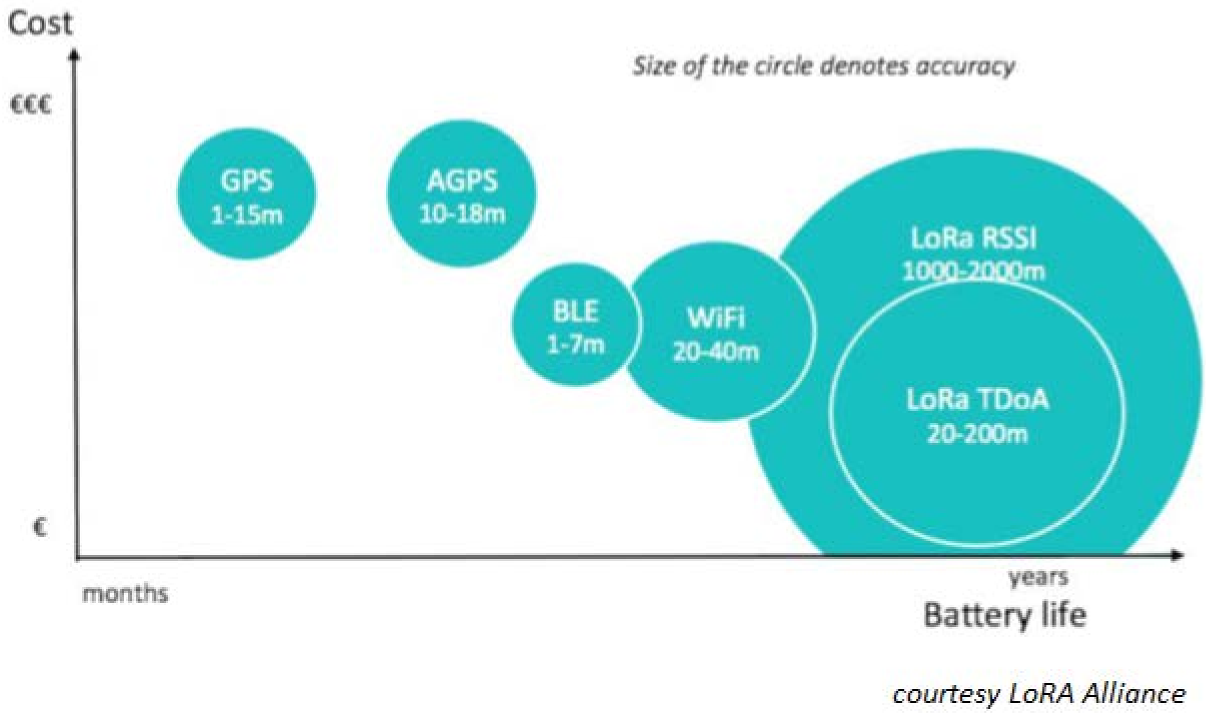


Figure 39 - LoRa TDoA (Time-Difference of Arrival) and RSSI Geolocation Accuracy

The tracking capability has only recently become the subject of interest from the LoRa Alliance; a formal whitepaper regarding implementation details was released in 1Q 2018. Part of the engineering studies performed to validate error sources (and thus, suitability) of the GPS-based timing in what could be problematic multipath environments yielded the following estimations for circular error probability (CEP) in the location estimates produced. Noteworthy (and expected) aspects confirmed that long-throw rural estimations produced tighter CEP results than progressively more spread/scattered results as path diffractions densify in more urban settings:

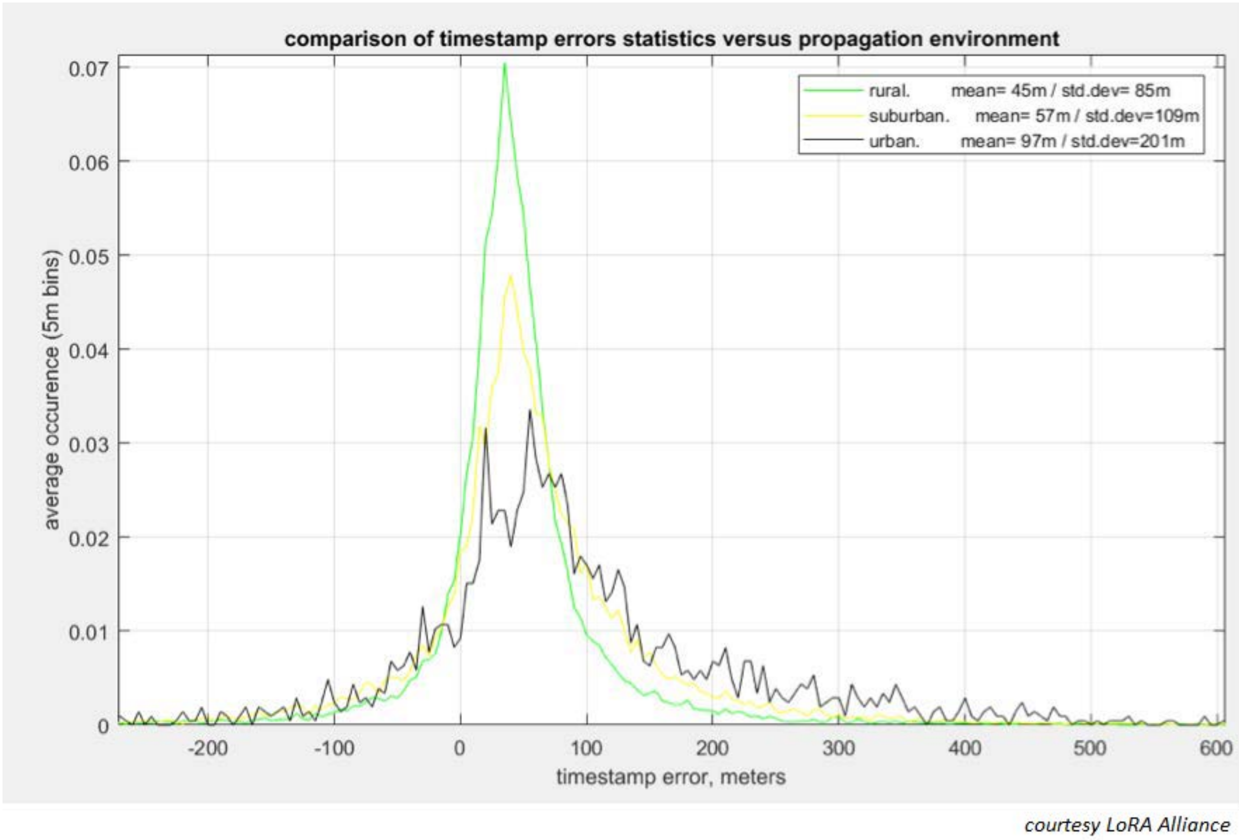


Figure 40 - LoRa Timestamp Error Contribution to Geolocation Error

3.5. The Issues of Scale

In the client device description in this paper, a bookmark regarding class A devices employ of what amounts to ALOHA signaling was lodged. This is perhaps the most cringeworthy shortfall in the LoRaWan protocol, as of course the damage to throughput (even under the condition of randomized channel selection) bears the unmistakable imprint of an ALOHA asymptote. Though the convergence to poor throughput is mitigated by the random channel hopping scheme and the orthogonality of the chirping modulation (essentially, your throughput approaches the sum of multiple simultaneous ALOHA schemes, one for each channel and spreading factor). In the IEEE Communications Magazine of January 2017 the research paper "Understanding the Limits of LoRaWAN" addressed the standard's shortfall in regards to scalable applications and some of it is referenced here.

Note that it is not only an ALOHA congestion issue but one that is subject to FCC rules on band occupancy dwell and duty cycle. In brief, the FCC puts occupancy restrictions on the CSS spectrum employed by LoRa. For the 125 kHz channels, this specification is no more than 400 msec of per-message transmission every 20 seconds. For the 500 kHz channels, the restriction is less restrictive: no more than 400 msec every 10 seconds. This impacts the time on-air, packet sizes and spreading factor as follows:

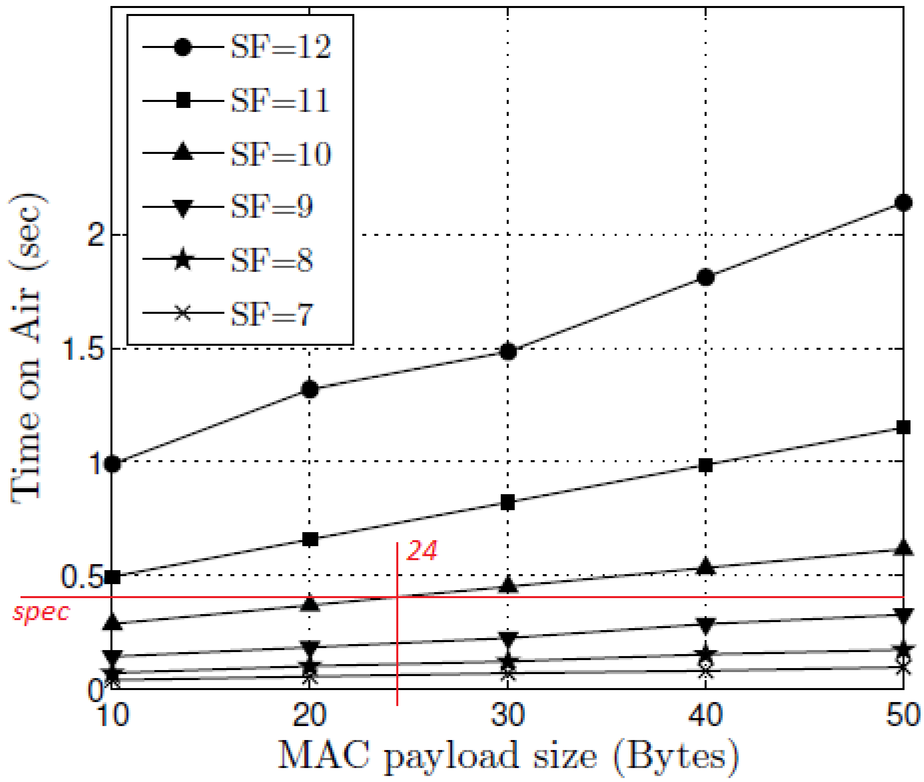


Figure 41 - LoRa Message Dwell Time Implications to Payload and SF

Note that the dwell time specification precludes use of spreading factors 11 and 12 in the US. Furthermore, the most noise-immune SF left to use (10) must be restricted to the transport of no more than 24 MAC payload bytes.

The resultant ensemble, asymptotic throughput behavior looks very familiar to those familiar with ALOHA congestion – albeit with the inclusion of a hard limit due to duty cycle off time restriction:

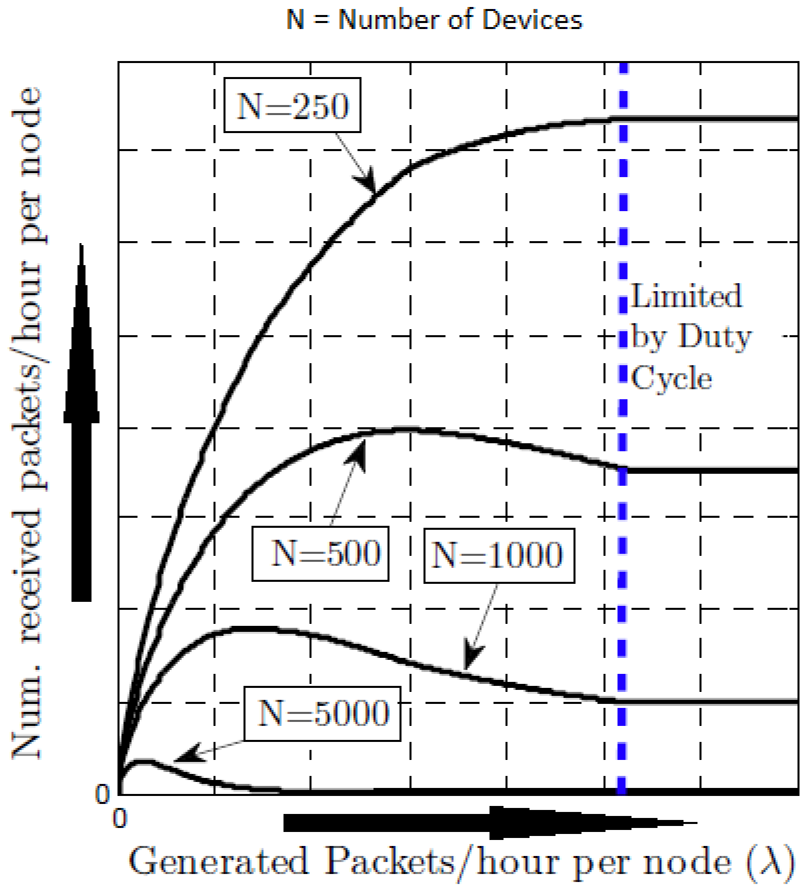


Figure 42 - LoRa Congestive Behavior Due To Closed Loop ACK of ALOHA Upstream Messages

4. LoRa Compared Vs LTE Narrow Band IoT Options

LTE has taken several swipes at establishing a scheduling mechanism to handle IoT signaling needs, appearing originally to accept that radio costs and power draws would likely disqualify it from ever scaling down to CEDs themselves. A shared LTE host (mobile phone) for 2.4 GHz ISM NFC-based CEDs has been one key driver for establishing the necessary small-packet handling priorities in the larger network. The other, much more critical aspect, has been the need for extremely low latency industrial IoT (IIoT) control environments to be in place to handle the real-time needs of the manufacturing sector(s). As it turns out, the lack of determinism in control loop latency and very modest signaling bitrates for LoRa disqualify it from competing in that role, so there appears to be a natural gap between high value/high accuracy/low-latency commercial IoT applications with LTE support and cost-sensitive, light industrial, asset-tracking or consumer-end (and, as regards latency, more casual) IoT support which LoRa can underpin. On the plus side for LoRa are its much less expensive implementation BOM (for both ends of the RF link) and extremely usable low-current modes (principally for class A CEDs, though some B's might qualify). A tabular breakdown of the differences follows:

Feature	LoRaWAN	LTE Cat-1 2016 (Rel12)	LTE Cat-M 2018 (Rel13)	NB-LTE 2019(Rel13+)
Modulation	SS Chirp	OFDMA	OFDMA	OFDMA
Rx bandwidth	500 KHz	20 MHz	20 - 1.4 MHz	200 KHz
Data Rate	**0.98 - 21.9 kbps**	10 Mbit/sec	200kbps – 1Mbps	~20K bit/sec
Max. # Msgs/day	Unlimited*	Unlimited	Unlimited	Unlimited
Max Output Power	**20 - 30 dBm**	23 - 46 dBm	23/30 dBm	20 dBm
Link Budget	154 dB	130 dB+	146 dB	150 dB
Batery lifetime - 2000mAh	105 months		18 months	
Power Efficiency	Very High	Low	Medium	Med high
Interference immunity	Very high	Medium	Medium	Low

*** < 400 msec / msg dwell. Ultimately capped by FCC duty cycle limits. (upstream limit)**

courtesy of LoRA Alliance

Figure 43 - US LoRa Comparison to LTE as LPWAN

Conclusions

The home's casual and largely organic adoption of Wi-Fi as its favored brand of wireless communications has seen this haphazard marketing play challenged first by self-handicapping via unmanaged standards supersession, then peer overcrowding and pre-emption (the penalties for success), and now finally by direct competition from unlicensed co-participants in the 2.4 GHz ISM band associated with the emergence of various IoT vertical businesses. While Wi-Fi's assimilation of the 5 GHz band and the introduction of airtime management have begun the process of distributing and scheduling RF energies in and out of the old band, such relief-valving involves a protracted remediation schedule and does not completely resolve some of the service competition issues associated with sharing 2.4 GHz among so many perspective clients. Two new band opportunities have become available for consideration, both as options in the service contention solution space and as outright disrupters as regards the ability they give providers to mine new opportunities in the home: 3.5 GHz CBRS/LTE and 900 MHz LoRa.

Both wireless technologies provide options to move at least IoT data out of the crowded Wi-Fi space and into alternate bands for backhaul and in doing so, either harden the IoT services involved against casual or perhaps even targeted interruption. Both feature new radio packaging for CEDs (though LoRa's is less expensive). Both involve investment in the overlaid wireless portion of the backhaul – though LoRa's longer wavelength and throw indicates that the distribution of concentrators (base stations) can be sparser than the seeding of 3.5 GHz support. Scale economies seem to favor LoRa as well – but only to the limit where upstream ALOHA-based congestion throttles the star aggregation scheme. For its part, however, 3.5 offers a much broader support bandwidth which would enfranchise a wider palette of IoT devices (most specifically cameras – whose ad hoc home utilization seems to easily outstrip other smart home connected appliances of more modest signaling requirement.)

As the pitch of complaints against oversubscription of the 2.4 GHz ISM space mount, it will do well for operators to examine other band solutions for the hosting of emerging smart home and aging-in-place businesses which will demand (perhaps life-critical) service availability at the three nine's level and beyond; 3.5 GHz CBRS/LTE and LoRa offer potential solutions to this problem.

Abbreviations

AC	Alternating current
ACK	Acknowledgement message
AP	Access point
BLE	Bluetooth Low Energy
BOM	Bill of material
bps	Bits per second
BW	Bandwidth
BYO	Bring-your-own
CBRS	Citizens Band Radio Service
CBSD	Citizens Band Radio Service Device
CED	Constrained end device
CEP	Circular error probability
CPE	Consumer premises equipment
dB	Decibel
dBm	Decibel referenced to 1 milliwatt
DOCSIS	Data-over-cable service interface specification
DoD	Department of Defense
EIRP	Effective isotropic radiated power
ESC	Environmental sensing capability
FCC	Federal Communications Commission
FDM	Frequency Division Multiplex
FEC	Forward error correction
GAA	General authorized access
GHz	Giga-hertz
GPS	Global positioning system
HaaT	Home as a Tower
HFC	Hybrid fiber-coax
HD	High definition
Hz	Hertz
IoT	Internet of Things
ISBE	International Society of Broadband Experts
ISM	Industrial, Scientific and Medical
ISP	Internet service provider
kHz	Kilo-hertz
Km	Kilometer
LTE	Long Term Evolution
MAC	Media Access Control
Mbps	Mega-bits per second
MCS	Modulation

MHz	Mega-hertz
Msec	Milliseconds
MVNO	Mobile virtual network operator
NB	Narrowband
NF	Noise figure
NFC	Near-field Communication
OFDM	Orthogonal frequency division multiplexing
PAL	Priority access license
PER	Packet error rate
PHY	PHYsical Layer
QAM	Quadrature amplitude modulation
RF	Radio frequency
SAS	Spectrum Allocation System
SCTE	Society of Cable Telecommunications Engineers
SF	Spreading factor
SNR	Signal-to-noise ratio
TDD	Time division duplex
TDM	Time division Multiplex
UHF	Ultra high frequency
VHF	Very high frequency
W	Watt

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