Can a Fixed Wireless Last 100m Connection Really Compete with a Wired Connection and Will 5G Really Enable this Opportunity?

New Wireless Spectrum Opportunity: How will this Factor into the MSO Access Architecture with Fixed Wireless Access as a Delivery Option?

A Technical Paper prepared for SCTE/ISBE by

J.R. Flesch
Director, Advanced Technology, CPE
ARRIS
3871 Lakefield Drive
Suwanee, GA 30024
Jr.flesch@arris.com
678-473-8340

Belal Hamzeh, Ph.D.
VP, Wireless Technologies
CableLabs
b.hamzeh@CableLabs.com

Bryan Pavlich
Staff Software Engineer
ARRIS
bryan.pavlich@arris.com

Dorin Viorel
Principal Architect
CableLabs
d.viorel@CableLabs.com

David Virag
Distinguished System Engineer
ARRIS
david.virag@arris.com

Charles Cheevers
CTO/CPE
ARRIS
charles.cheevers@arris.com

Table of Contents

List of Figures

Introduction

For wireless communications, this is an unprecedented time. More licensed and unlicensed radio spectrum between UHF whitespace and millimeter wave mega-block partitions is being made available for commercial interests to invest in and grow business services than at any single prior point in history. The FCC is balancing competitive access for both licensed and unlicensed exploits with innovative dynamic spectrum arbitration promoting shared access in the 3.5 GHz CBRS band. The spectral largesse across all bands has predictably drawn enthusiastic attention from all the major MSO and MNO players with service expansion (or protection) interests at stake. The 5G area of wireless connectivity at scale, 10 Gbps speeds and millisecond or less latency has set in motion a burgeoning and perhaps somewhat pre-emptive set of wireless test trials aimed at establishing both technical merit and posturing some degree of "best stewardship" of the public airwaves.

The use of millimeter wave spectrum has sparked many debates about its architecture and economies — given the physics restrictions of primarily requiring "Line of Sight" to deliver the promise of multi Gigabits of wireless delivery. It is this non-determinism of signal propagation that has generated lots of research, innovation, and testing of solutions to create and define a deployable architecture that will support both Fixed Wireless Access and mobility uses.

This paper focuses on the hot industry topic: can a Fixed Wireless Access solution be developed to compete with or augment the wired broadband solutions today? It will examine the available spectrum options for delivery of a reliable, high-bitrate wireless connection over the last few hundred meters of Front-haul as an alternative to fiber-to-the-home (FTTH). These are the cases where a newcomer wants to overlay incumbent, existing greenfield opportunities, or CAPEX considerations render the latter alternative unsound. Leverage of the best attributes of near-line-of-sight (nLOS), non-line-of-sight (NLOS), and line-of-sight (LOS) signaling will be examined. The opportunity to extend a hybrid fiber/coax (HFC) plant by means of a wireless end network overlay will be analyzed for viability for the last 200m access to a home.

The economics of Fixed Wireless access lie somewhere in the following parameters:

- Cost of the spectrum used
    - As we discussed there are licensed and unlicensed bands to consider. There is also potentially new granular band usage in the 5G space that will follow some of the directions of the CBRS solution based on software based spectrum control
- The size of the cell for bandwidth distribution
    - As we move towards high bandwidth low latency wireless broadband services — the size of the traditional cell size is likely to reduce substantially. This is a function of propagation and distance of technologies like millimeter wave as well as a requirement to provision speeds of Gbps burst levels, which will be required for new Fixed Wireless Access networks
    - While there are some FWA plays that are trying to target 80 foot and higher Towers for 5G deployments — these are not likely to be the architecture for Gbps broadband services as they may scale for coverage at lower bandwidths and MDUs in dense areas — but are expensive in tower real estate lease and also won't deliver the higher headline Gbps speeds. This may not be required for some overlay applications — but if the price of the 200 Mbps level SLA is reduced substantially — the cost of the CPE device dominates the economics of the solution

- The backhaul distribution and connectivity
  - As the cell size gets smaller it still should deliver multiple Gbps to enough customers to make it economically viable. This makes the backhaul to the cell important for speed and scaling to meet the front haul costs to consumers. The ideal solution is that a Fiber connect to every Gbps capacity Small Cell for 5G — likely at least 10 Gbps. There are some intentions and architectures to use Wireless backhaul — also using millimeter wave technology. Today there are backhaul solutions that utilize the unlicensed spectrum in the 60 GHz range. Depending on the Line of Sight of the wireless backhaul — different technologies and frequencies can be used
- The cost of the CPE equipment
  - This is one of the main barriers and inertia contributors to using Fixed Wireless Access. Even in sub 6 GHz access technologies — there is typically an outdoor transceiver to mitigate losses of the exterior walls. For microwave frequencies — like LMDS at 10 GHz — there is also the need for an external antenna and transceiver to mount on the MDU or outside Single Family Unit. This additional cost for CPE is a much debated and analyzed problem for 5G FWA solutions. One of the primary questions for a technology solution is to try and get the CPE transceiver to be self-installable by the consumer and added typically to the upper floor window of the home. The alternative is an outdoor mounted transceiver — which increases install operational costs and has serious ergonomic issues for homeowners and home owners' associations (HOAs). There are technology plays to try and mitigate some of the outside/inside connection problems — typically targeting wireless transmission through windows/walls to try and not have to drill holes for mounting/wires

These topics will be reviewed below to review the physics, architectures, and ergonomics of Fixed Wireless Access solutions. The paper will highlight the CBRS 3.5 GHz sub 6 GHz solution as well. While not a solution typically targeted at 5G (given the 3GPP requirements for 5G (speed and latency in particular) — there is some basis in the likelihood of 5G being a dual PHY or dual standard technology. Millimeter wave is not deterministic in its performance due to the environmental and NLOS issues — and the economics of deploying to the worst condition don't work, therefor there may be likely solutions that:

- Provide Small Cell with both Millimeter wave and sub 6 GHz and CPE that support both PHY
  - This makes the solution more expensive and larger in size and higher in power consumption
  - This makes the solution more expensive for LTE sub 6 GHz transmission for example in the CBRS band — as the small cell will be typically deployed in smaller cell range to meet the speeds and millimeter wave LOS requirements
  - This makes the solution more expensive for Wi-Fi sub 6 GHz transmission as the cell size would have to scale to Wi-Fi EIRP *(*Equivalent Isotropically Radiated Power*)* coverage
  - With dual frequency devices, the solution is more reliable with fallback on sub 6 GHz LTE when the millimeter wave transmission speeds drop due to changing environmental conditions
  - Additionally, there are multiple frequency overlays that may be utilized:
    - <1 GHz for potential NB-IOT applications. Lots of low bandwidth devices at maximum range. Standards running in these frequencies include 802.11ah, 802.11af, LoRA, SigFOX, LTE-M, LTE and others

- 1 GHz-6 GHz for licensed and unlicensed usage: LTE, LWA, LAA and Wi-Fi for mobility and broadband applications
- > 6 GHz for broadband and mobility applications and high bandwidth 5G applications

The 3GPP group is defining the specification around the addition of the 5G NR spec — allowing support for all three general frequency areas above. Most of the current trialing for Fixed Wireless Access solutions has been using the LTE MAC over different frequencies. Some of the trials have been using Wi-Fi MAC over 160 GHz bands and some using 802.11ad MAC at 60 GHz frequencies. The 3GPP standards group has a goal to complete and deploy the 5G NR spec and solutions in 2018 with the 5G MAC being specified by 2019. It's generally believed that Fixed Wireless Access solutions will deploy on the 5G NR specification or earlier — and may move to support the 5G MAC as well — when this is finalized for mobility in 2019/2020. Mobility solutions for 5G are expected to be deployed by 2021.

Content

1. Making the Technical Case

1.1. The Increasing Amount of Available Spectrum in the Sub 6 GHz and Higher Frequency Millimeter Wave Bands

In 2016, the FCC made available nearly 11 GHz worth of licensed and unlicensed spectrum for both mobile and Fixed Wireless exploitation, ostensibly to seed the rapid development of 5G infrastructure. 850 MHz of the new spectrum was located around 28 GHz, 3 GHz between 37 and 40 GHz, and a full 7 GHz between 64 and 71 GHz (this latter segment comprising the only unlicensed block). The year also saw the FCC finalize spectrum sharing rules on the 150 MHz of spectrum allocated to CBRS (3.55 – 3.70 GHz, specifically) in 2015.

From a technology perspective, there is often reference to the 'sub 6 GHz bands' (comprising LTE and Wi-Fi and other services — TVWS, NB-IOT etc.) and the millimeter wave bands (from 28 GHz and higher). For the purposes of this paper we will discuss the importance of both (sub 6 GHz having range and NLOS properties and millimeter wave nLOS or LOS) and the potential for the combination of both to be enablers for reliable 5G based services for FWA and mobile.

Before we discuss the Millimeter Wave bands — it is worth looking at the new CBRS frequencies and their capabilities and relevance to the MSO — as well as the potential for them to be combined with 5G services and also the platform of Software Managed spectrum access used by CBRS (Spectrum Access Service) to potentially also be leveraged by 5G and multiple spectrum solutions.

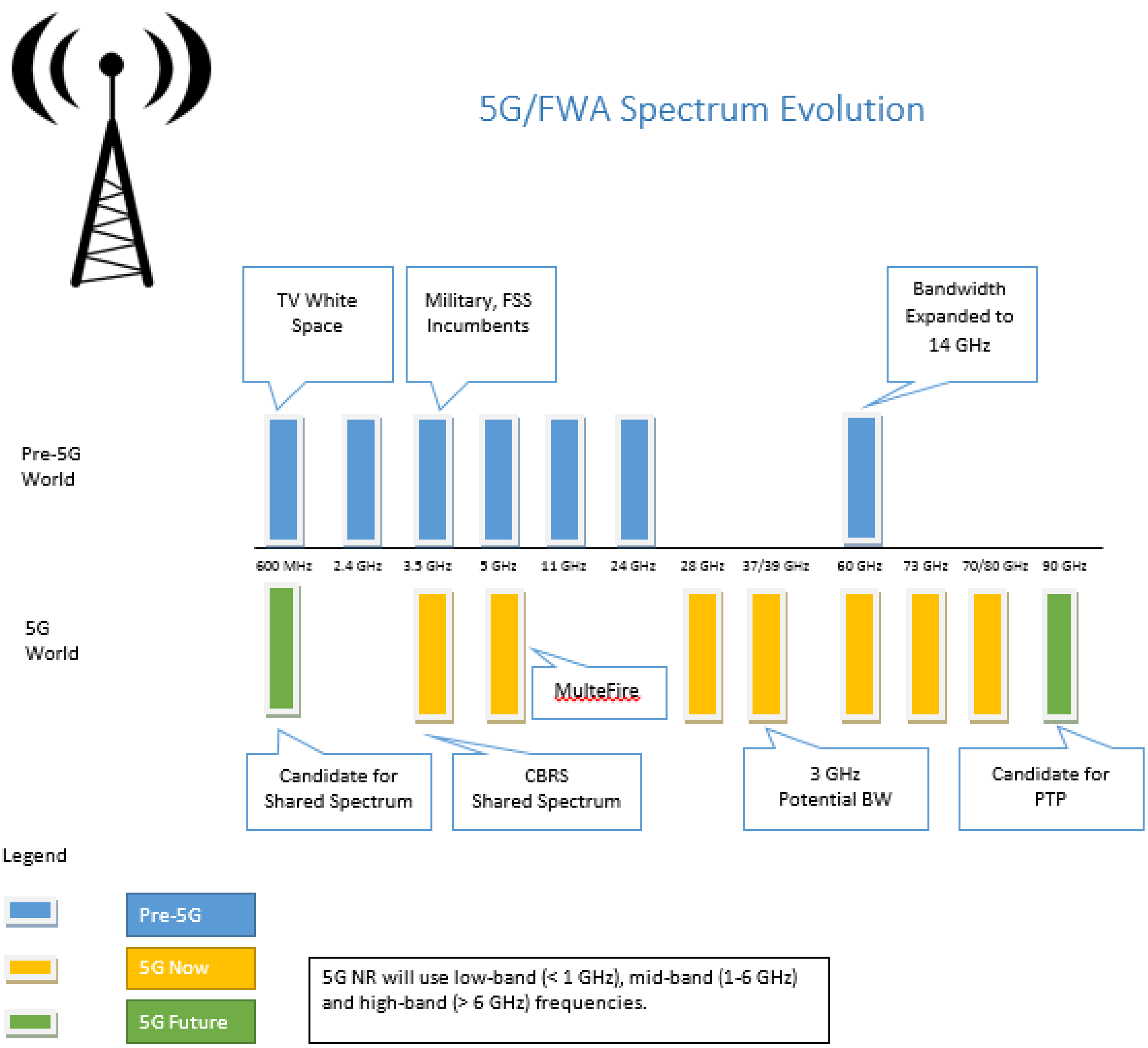


Figure 1 – 2016 FCC Spectrum Allocations

1.2. The 3.5 GHz CBRS Band

CBRS was envisaged by the FCC as an 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):

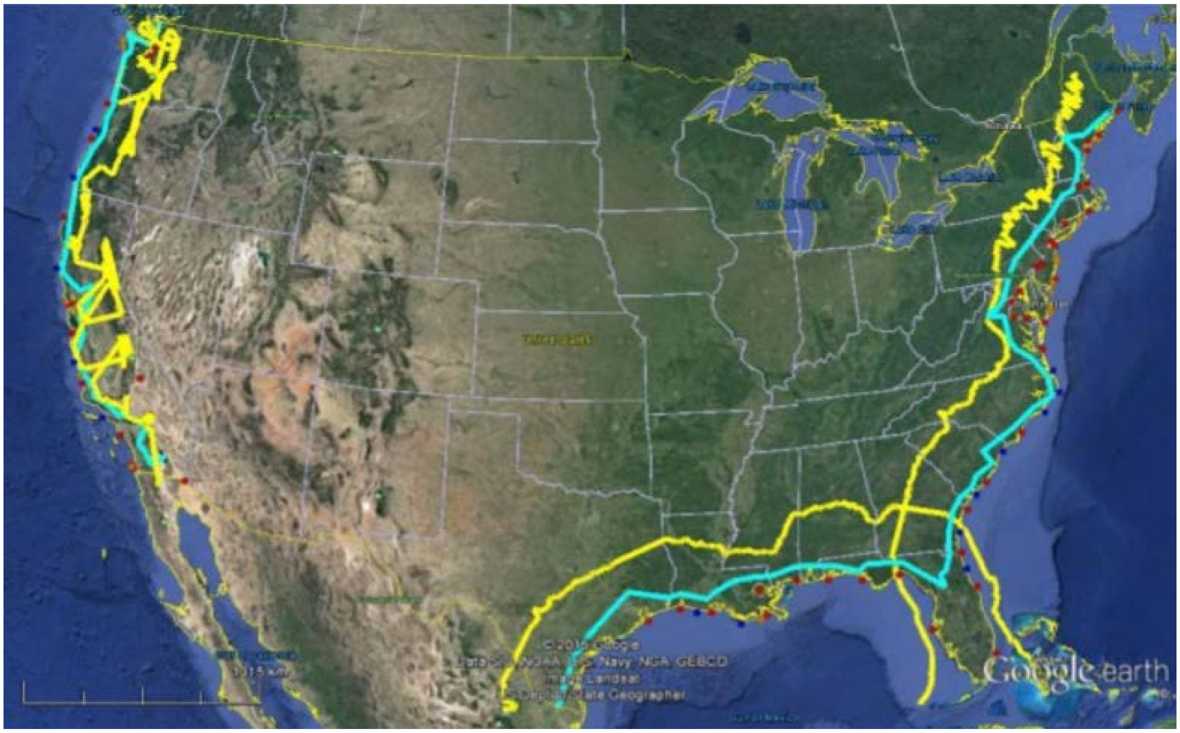


Figure 2 – Shipborne Radar Exclusion Zone (original:yellow, revised:blue)

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 operates on a highly granular geographic basis (census tract cell sized) which permits it to re-use spectrum on a tract by tract basis, 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.

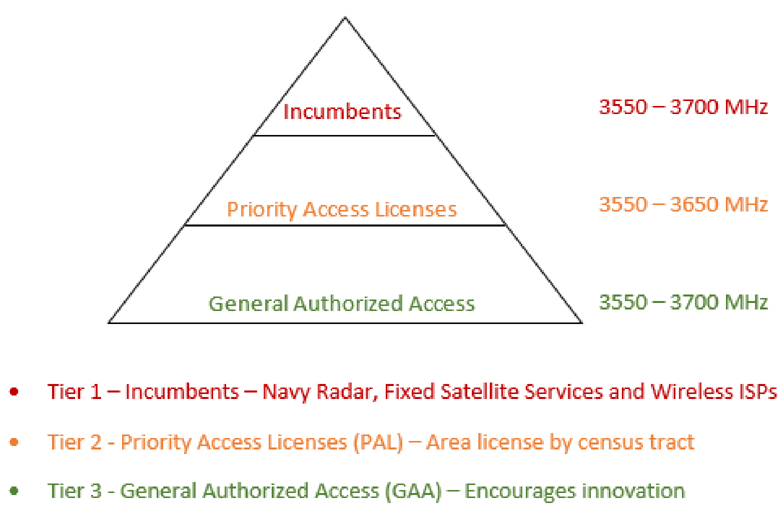


Figure 3 – CBRS Priority Tier Membership Distribution[n]

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 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 (CBSD) 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 4 – CBSD Category A and B Power Signature Limits

1.2.1.1. Distance and Path Loss

3.5 GHz has similar nLOS behavior and propagation characteristics to other sub 6 GHz mobile carrier mid-bands.

$L = 10\,n \log_{10}(d) + C$, where n=2 is the Path Loss (PL) Exponent in Free Space

$PL(d) = 20 \log_{10}(4\pi d \times f/c)$ Note: $20 \log_{10}(4\pi / 300{,}000{,}000 \text{ m/s}) = -147.56$

3.5 GHz, PL (200m) $= -147.56 + 20 \log_{10}(d) + 20 \log_{10}(f)$

$= -147.56 + 46.02$ (@200m) $+ 190.88$ (@3.5 GHz)

$= 89.34$ dB (3.5 GHz, 200 meters)

3.5 GHz, PL (800m) $= -147.56 + 20\log_{10}(d) + 20\log_{10}(f)$

$= -147.56 + 58.06$ (@800m) $+ 190.88$ (@3.5 GHz)

$= 101.38$ dB (3.5 GHz, 800 meters)

2.5 GHz, PL (200m) $= -147.56 + 20\log_{10}(d) + 20\log_{10}(f)$

$= -147.56 + 46.02$ (@200m) $+ 187.96$ (@2.5 GHz)

$= 86.42$ dB (2.5 GHz, 200 meters)

2.5 GHz, PL (800m) $= -147.56 + 20\log_{10}(d) + 20\log_{10}(f)$

$= -147.56 + 58.06$ (@800m) $+ 187.96$ (@2.5 GHz)

$= 98.46$ dB (2.5 GHz, 800 meters)

The overall path loss is similar (~3dB difference) in nature between the 3.5 GHZ and the 2.5 GHz band which is to be expected. Sub 6 GHz delivery at 200m to 800m remains a viable NLOS solution that provides 100s of Mbps of broadband capability. The potential to go to Gbps peak levels with more bands can be realized with CAT16 and CAT18 solutions including Carrier Aggregation and use of Licensed Assisted Access (LAA) within the 5 GHz Wi-Fi bands. Wi-Fi solutions in the 5 GHz band with 8 spatial streams also go to multi Gbps of Wi-Fi capacity.

1.3. Requirements

1.3.1.1. LOS Delivery

Analysis of compound annual growth rate (CAGR) metrics for both average and peak data connectivity demands in the home network indicate that by 2020, service group (SG) downstream (DS) needs — for SGs with a roster of at least 100 clients — will be touching 3 Gbps.

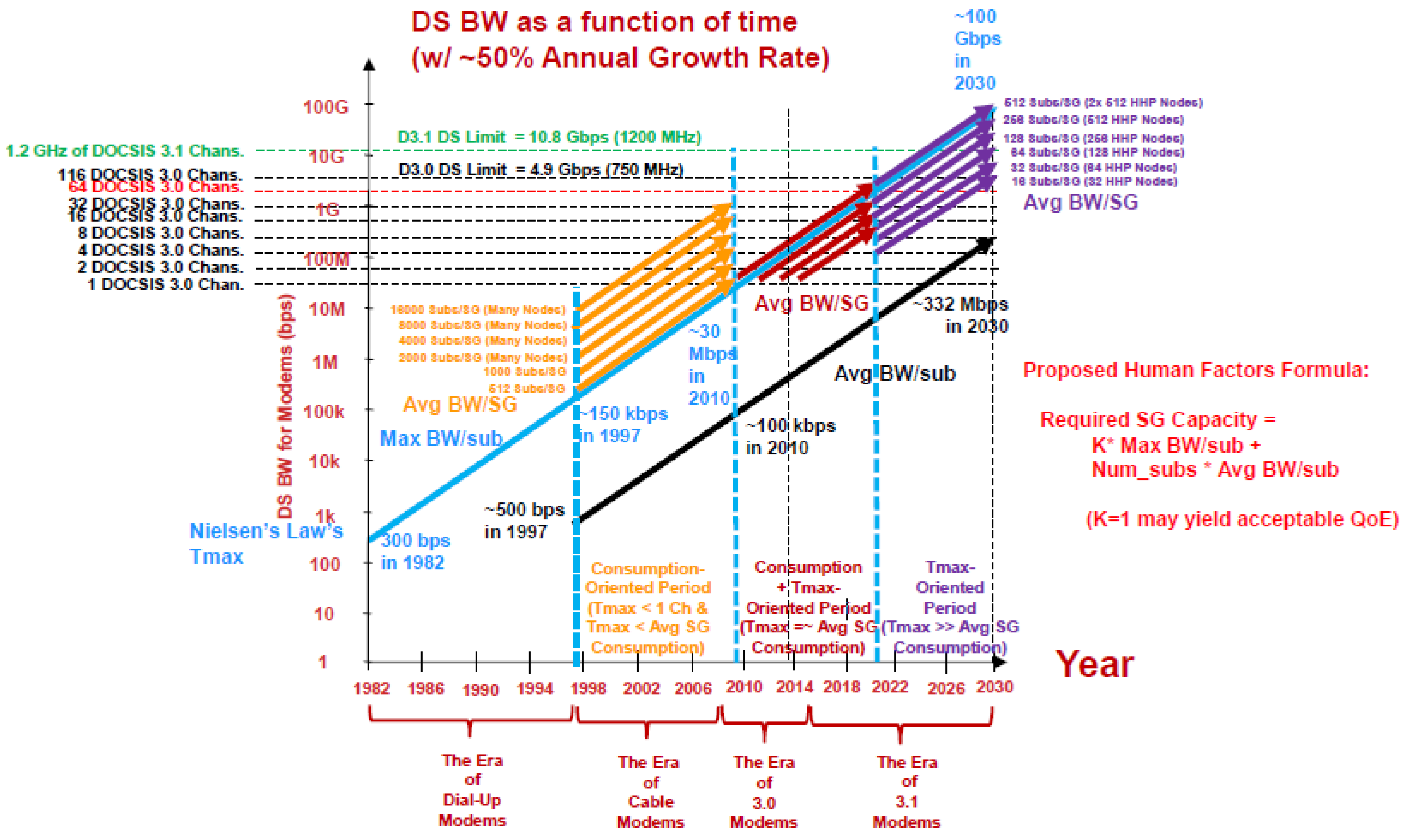


Figure 5 – Historical and Projected Bitrate Consumption Growth at the Service Group (Cloonan's Curve)[1]

The profile of connectivity will dramatically migrate from a "lean" ratio of roughly 9:1 DS:US rates to something approaching a 6:1 ratio, due to client upstream (US) IoT cloud needs (particularly in regards to security camera feeds). For Fixed Wireless Access to be able to compete with Wired Solution, it has to be able to provide Gbps peak rates on both the Downlink and the Uplink. To achieve these peak data rates in a Wireless Access network the only wireless bandwidth available with sufficient contiguous spectrum to meet 3+ Gbps SG downstream service — *if* the spectral efficiencies remain under 10 bps/Hz -- lies well into LOS-delivered (and near millimeter wave) frequencies (28 GHz, 37 GHz, 39 GHz, 60 GHz and 64-71 GHz). These frequencies offer huge amounts of bandwidth (the unlicensed bands alone in the 60 GHz range can deliver 128 Gbps), but these frequencies present some clear technical, operational, and aesthetic challenges.

For example, millimeter wave LOS does not tolerate path loss variation well (as would be the case for smoke, fog, precipitation, wind-driven foliage, or moving bodies which cross the delivery vector to the client). Adaptive modulation schemes see to it that poor SINR signature at the receiver triggers a fallback to less complex constellations (reduced information density — hence, reduced delivered bitrate) to aid the receiver in resolving and decoding the (hopefully temporarily) compromised signal. But physically moving LOS apertures between Point of Presence (POP) — typically the small cell on a pole or street furniture at < 20 feet) — and client to more open pathways to reduce the risk of signal interdiction or attenuation inevitably drives the POP above both terrain and flora masks — and probably requires a similar elevated location for the client's antennae. The increase in vertical height comes with a price tag of extra labor hours to access devices, resolve look angles, align antennae, and verify link performance. There is also the general view that 5G must work at lower street furniture elevations to get the desired connectivity and smaller homes passed cell size. Equally for applications like 5G connected autonomous cars, the addition of 5G small cells along freeways with street lights may be the end game solution to facilitate latency and speed to car requirements. The U.S. for example has 26 million street lights all with power connections. 60% of these street lights are owned and operated by the private sector with 40% owned by city and state municipalities. Public dollars pay for all the street lights to operate with energy costs of $2Bn alone for lighting. Figure 6 below illustrates the simplistic problem of LOS technologies where environmental conditions, terrain, and foliage can affect the performance of any transmitted signal. Higher elevations do not always solve the problem and the erection of new 80 foot and higher towers is in many ways not feasible. There will be of course a macro tower based Cell with fill ins of smaller cells on other emerging POPS — particularly street lighting and other elevated powered locations.

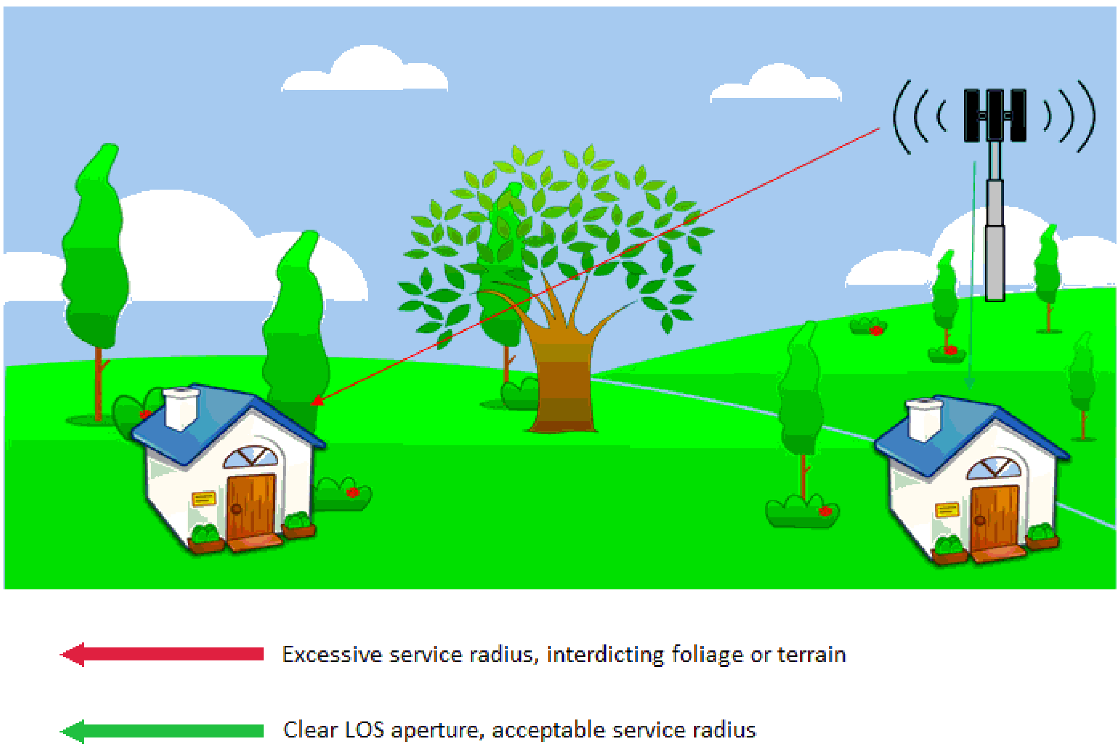


Figure 6 – Terrain and Foliage Masking Effects on LOS Delivery

To illustrate the problem further the following pictures (Figures 7-9) illustrate modeling of LOS millimeter wave propagation in a typical random Georgia residential subdivision at different heights of 2m/6 foot, 10m/30 foot+ and 33m/100 foot pole. The effect that trees and Foliage have is reviewed below in later sections. As you can see — even with the investment a 100 foot tower — the number of houses in the LOS ‘Look’ is still relatively low.

Figure 7 – LOS "Look" Mask from 2-Meter Pedestal (lime green shadow)

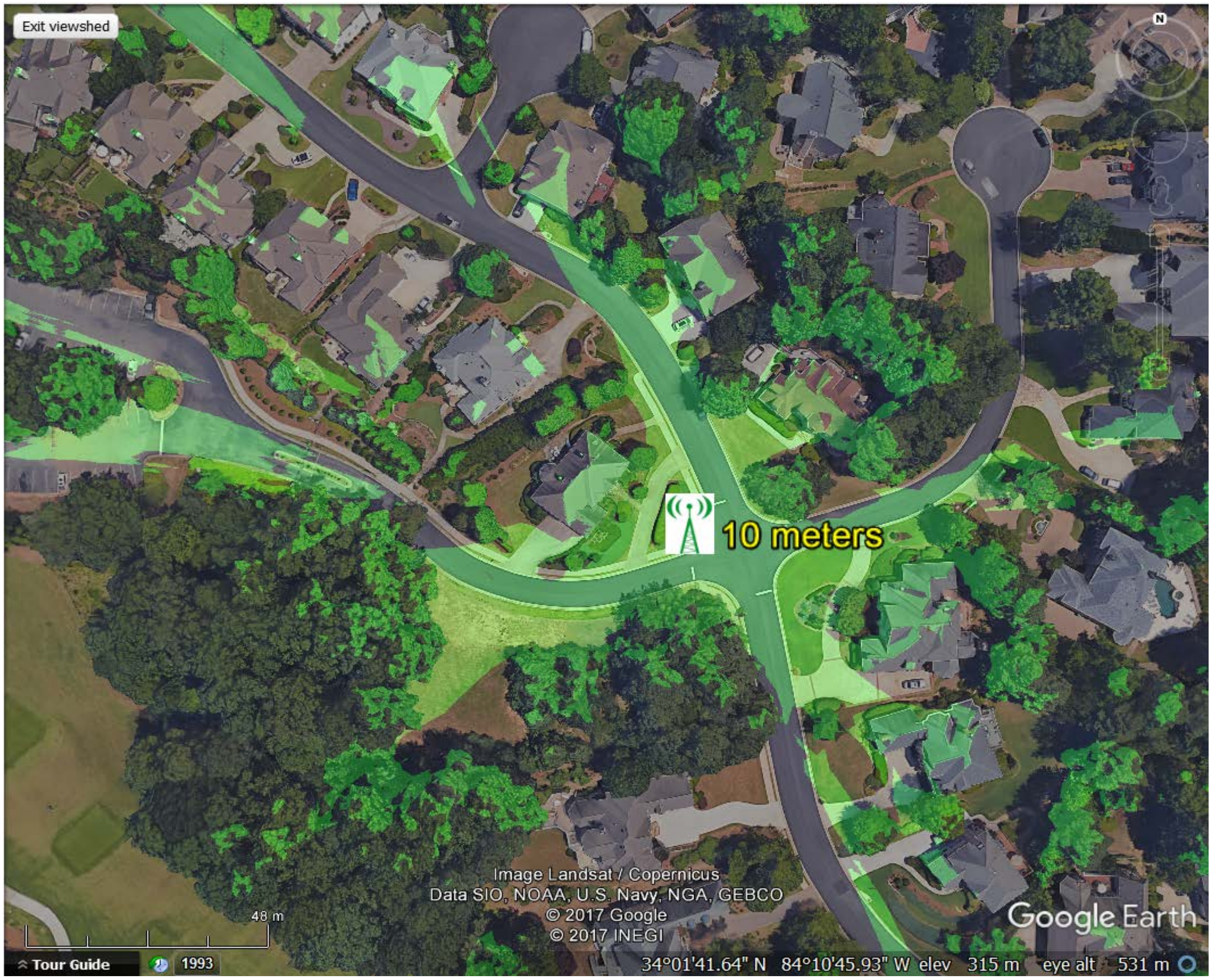


Figure 8 – LOS "Look" Mask from 10 Meter Mast (lime green shadow)

Figure 9 – LOS "Look" Mask from 100 Foot Monopole (lime green shadow)

This is the theoretical LOS "look" mask. In practice, there are other difficult challenges — including the following:

- Planning permission for a new tower to be erected
- Use of street furniture especially street lights as an alternative — foliage can wrap lights and private companies operate many of the lights so deals need to be made with different companies and municipalities
    - Putting more than one Cell on the Light fixture for more than one provider may not be practical and may drive a more neutral host requirement for any investment in street lights for 5G usage
- Adding backhaul capacity to the street furniture or erected tower will also cause disruption
- Adding backhaul capacity using Wireless backhaul increases the Small Cell size and power requirements and requires positioning for both best backhaul and customer LAN side connection

- The question as to whether the client device can be placed inside the consumer's home is one of the biggest open issues for 5G deployment
    - There is high desire to make 5G FWA client self-installable — to improve the economics of 5G wireless as a replacement to incumbent solutions
    - However, the reflection coefficients and penetration losses for building materials in the millimeter wave bands make this a difficult problem to solve and to get any amount of bandwidth into the home even through windows. tinted windows, double and triple glazed windows with energy efficient glass — also pose even larger problems than wooden shingles. Even using 28 GHz (which has lower atmospheric absorption compared to 60 GHz) which is comparable to 1-2 GHz for free space path loss — there is 25dB to 50dB loss when the window is metal coated. Today, external glass is tinted and coated with metal to provide a block to ultra-violet rays and improve insulation. For comparison, clear glass is as low as 2dB and Plasterboard with metal studs is about 9dB loss. Wall construct ranges from low loss 6-7dB for 1 foot of brick to 25dB for a 3 foot brick wall. This makes the challenge of a home self-install difficult at least at the multiple hundred-meter range. Is suggests that 5G small cell must be closer to homes for both self-install and for Gbps capabilities. The tradeoff is to have an external technician-installed antenna and transceiver

There are other issues like HOA covenants regarding external mounted devices and their location — often this forces satellite dishes (or the equivalent outdoor 5G transceiver) to be put on the rear of house. This hinders the economies of deployment on Street Lights, potentially forces new poles to be placed around the subdivision vs. using the interior infrastructure. It does not help that millimeter LOS propagation under even pristine conditions does not survive a service radius much more than 300 meters or so (typically more like 200 meters) in order to deliver more efficient modulation schemes. Such constrained throw feeds directly into a monopole (antenna tower) density calculation where it becomes all-too-clear that these skyline-altering structures would necessarily be much more visible than cell towers -- typical spacing for these latter elements perhaps reaching a 10x more sparse seeding — variously estimated in the literature to around the 1-2 km range in suburban areas). See below Figure 10.

Figure 10 – Example of LOS (left) vs NLOS (right) Monopole Seeding in Golf Community Development

Operationally, the implied Operational Cost overhead on site planning comprises both a shared analytical element (locating the POP to best service the maximum number of clients while maintaining non-overlapped antenna patterns, for example) along with a per-client "tuning" aspect which aligns the antenna elements and determines the best placement solution at the client site from a technical and aesthetic perspective.

However, the downside can be marginalized. The LOS POP which serves the 200-300-meter client radius footprint can effectively be structured to future-proof service bitrate demands such that each POP antenna element / client antenna pairing reuses the entirety of the available millimeter bandwidth (assuming the necessary unicast service switching density in the base station and sufficient wireline backhaul bandwidth to optimize the POP). This suggests that the wireless portion of the delivery architecture can be re-plumbed to upgrade QoE without modification to the endpoint RF frontends (including antennae). The cost and size of the 5G Small Cell POP is then another aspect. Increasing the number of element arrays improves the ability to pair and serve specific clients. That is another area of research to optimize deployment economies and future proofing.

1.3.1.2. nLOS Delivery

Sub-6 GHz carrier radios can be bound with Mu-MIMO smart antenna frontends to effect steerable, beam-formed radiation patterns which can be delivered with per-user-location agility and offer adaptable tolerance for propagation path impediments — while still delivering dense constellation modulation formats over greater distances than those which put paid to mmWave LOS signaling. A canvas of the data provided in the Field Test sections indicates that the nLOS service radius at 3.5 GHz ought to approach 800 meters — and this includes penetration of dwelling walls.

The immediate takeaway is that sub-6 GHz nLOS wireless connectivity requires POP seeding density on the order of 6% or so — $(200/800)^2$ -- of that necessary to insure LOS connectivity. More notably, perhaps, is that this elevated mounting requirement can opportunistically leverage 2nd-story "street furniture" instead of 40-80-foot tree topping monopoles required for LOS installations. Where such leverage is unavailable, shorter wooden masts, strand mounts or pedestals may be used and their location optimized only by considerations of reducing client azimuth contention (and not by clean LOS apertures) — Figure 11 below.

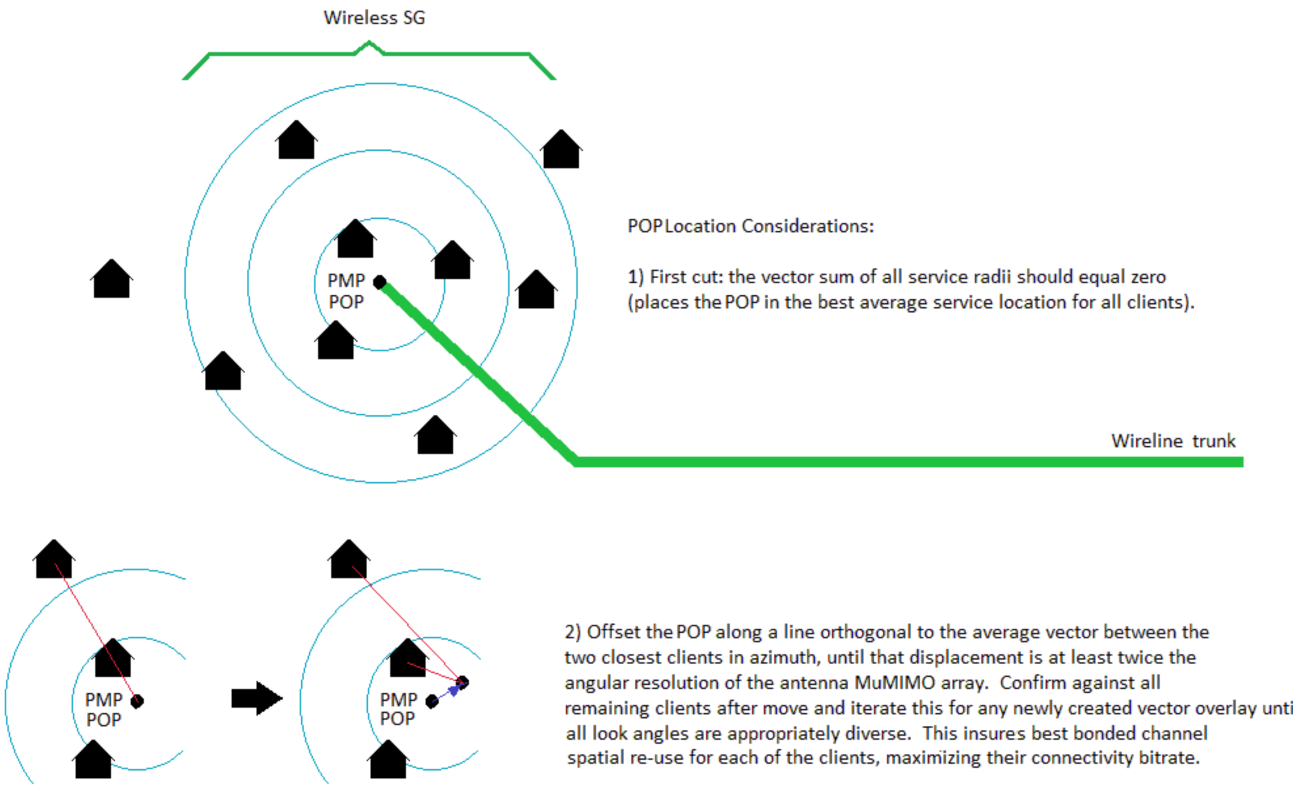


Figure 11 – nLOS Site Survey Fine Tuning of Monopole Axis to Obtain Azimuth Diversity

The remaining issue however, is that 3.5 GHz CBRS, a new useable swath of sub-6 GHz delivery due to its 150 MHz of contiguous (if access-tiered) spectrum, still cannot promise better than 1.5 Gbps if one accepts 10 bps/Hz as an efficiency asymptote. (And this is made slightly worse by the observation that only 70 MHz can be guaranteed by PAL license). Critically, however, this spectral efficiency caveat looks to be rendered "overcome by events" (OBE) by ongoing research into massive MIMO antenna arrays. These arrays offer new potential especially for the client side — allowing the client to host multiple antennas in limited footprints.

On the POP/Small Cell with multiple Antennas, it serves a set of single antenna users and the multiplexing gain can be shared by all users. The good news is that the array geometries, though of daunting size for indoor CPE operating at 3.5 GHz, are eminently suitable for base stations associated with POP antenna masts — and a seminal, demonstrable aspect of massive MIMO signaling in the Fixed Wireless domain (which eliminates sounding offsets due to Doppler effects) is that the channel's MIMO signature can be presumed reciprocal. This implies that, within the bounds of sufficient link SINR, massive MIMO need not be symmetric on link ends to extract benefit. (Refer to the section below on Spectrum Efficiency.) See below some examples (Figures 12,13, and 14) of the different gains of an 8x16 element array and a 4x4 element array at 60 GHz. 8x16 Array yields a 25.3dBi gain — while 4x4 only a 16.4dBi gain.

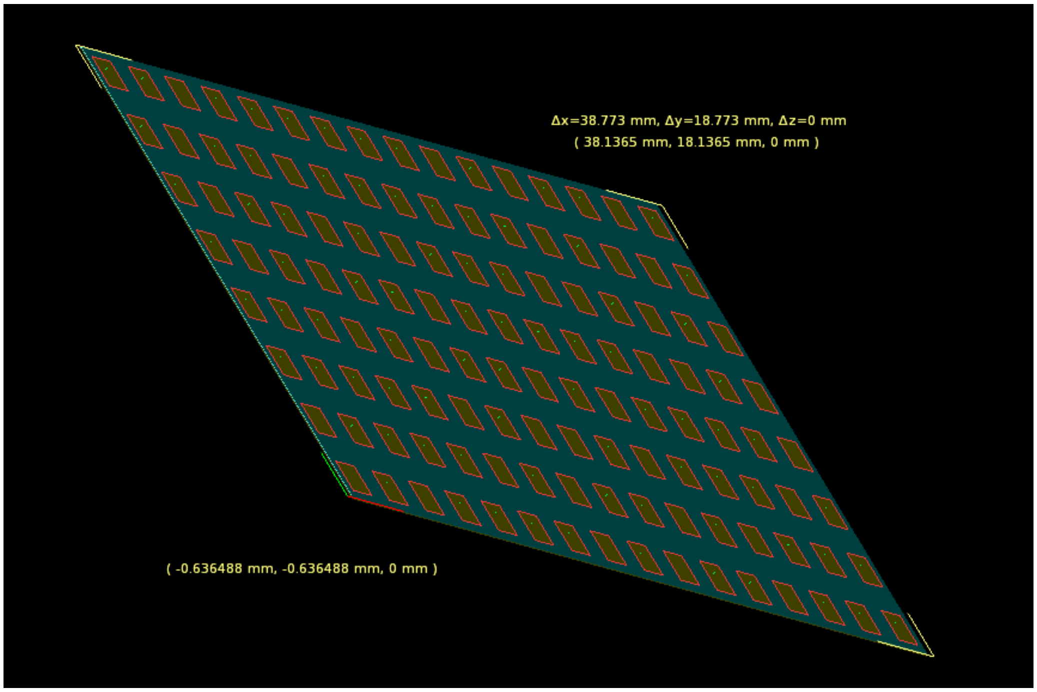


Figure 12 – 8x16 Element Array and Dimensions

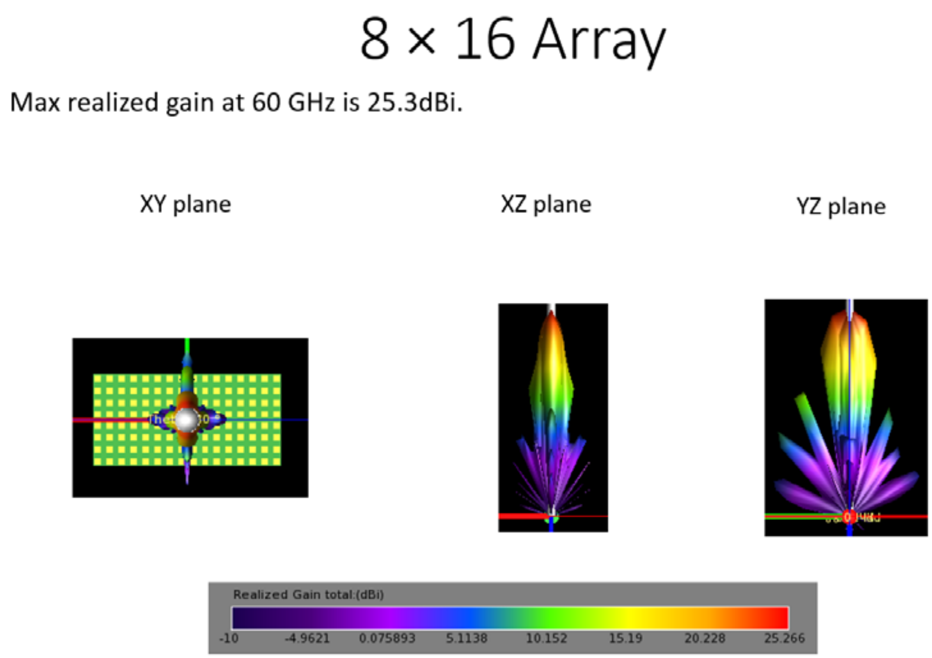


Figure 13 – 8x16 Array - Gain Calculations in the XY, XZ and YZ Planes – Max Gain 25.3dBi

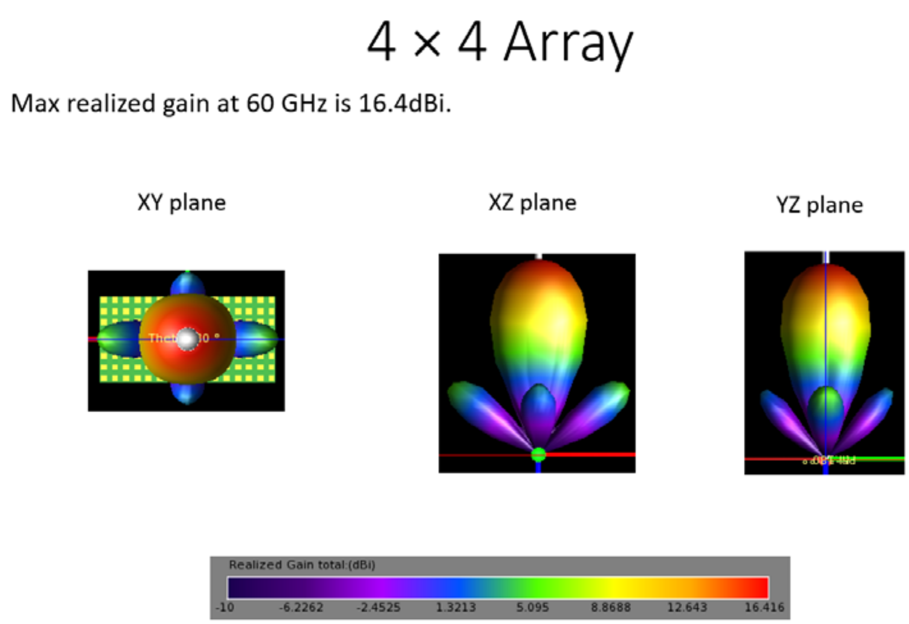


Figure 14 – 4x4 Srray – Gain Calculations in the XY, XZ and YZ Planes – Max Gain 16.4dBi

1.3.1.3. Connections at the Home

External signal propagation characteristics largely define the architecture of the home network connection with LOS millimeter downlinks exhibiting notoriously poor dwelling penetration performance, which is the opposite of sub-6 GHz nLOS. In the case of the LOS solutions, in all but the most (accidentally) favorable of client locations (nearly adjacent to the POP with a clear field of view and predominantly fair weather), an external downlink transceiver (or, at minimum, an external antenna and downconverter) must be employed to capture the LOS external signal and convert it for presentation to the gateway (WAN) agent of an internal home network. This is still to be debated — and as mentioned above in particular if there is investment in the POP/Small Cell with closer proximity to the home perhaps 50M, more element arrays and potentially relaxing the served bandwidths to under Gbps peaks. The potential outside to inside architectural aspects are listed below:

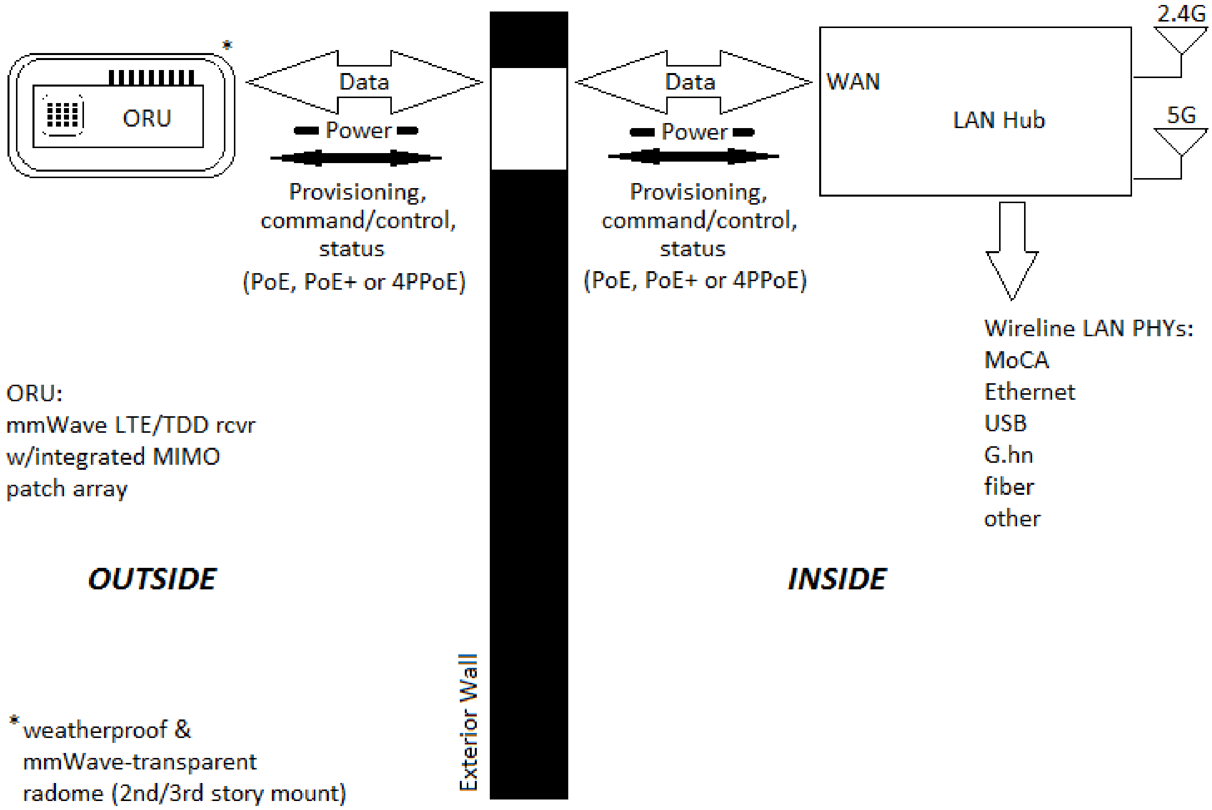


Figure 15 – Implementation Option on LOS-to-Home-Network Interfaces

There is another aspect to this outside mount and inside connection model — that is also problematic and needs to be reviewed. The most optimum location for this outside device is as high up as possible typically. If we assume that roof install is too costly — and the goal is to leverage a Window mount solution — then there are a few considerations that are being worked through.

- Locating the Baseband or Home NTU (Network Termination Unit – LAN HUB above) in a second-floor room typically means an occupied bedroom. Generally consumers don't like Gateways or Routers in bedrooms: the real estate located to them is constrained, Homeowners don't like putting devices on their bedside lockers or in baby's rooms and overall people don't like blinking LED's or bright single LED's in rooms where darkness is desired for sleeping
- The external unit itself if mounted on the window — has the challenge of powering and getting the analog to baseband signal into the home/bedroom
    - There are several companies trying to solve this problem with
        - Window sash mount solutions for conveying the power and data from inside.
        - Window mount on pane using sticky compounds or magnets
        - Inductive Powering through Window — trying to drive to 8W-10W
        - RF technologies to send data through window from outside pad to inside pad
    - Even with these solutions the residential customer must give up the aesthetics on an upstairs window and potentially the view. There are also other issue considerations such as insect screens on windows in warmer states in the USA

The requirement for external signal conversion is not mirrored in nLOS, sub-6 GHz networks. Field reports indicate that 3.5 GHz CBRS propagation, for example, tends to proxy that of 2.4 GHz — making it the home ingress equivalent of legacy 802.11 Wireless Local Loop. The upshot of this good news is that self-contained 3.5 GHz CPE with integrated Mu-MIMO antenna elements can be placed at will in the home and successfully recover signal (though a clever onboarding application would facilitate self-install by leveraging antenna MIMO data to suggest placement and optimize reception). As it proxies the WAN connect afforded by a DOCSIS Cable Gateway/Wireless AP (the sub-6 GHz radio, small MIMO and LTE/TDD receiver substituting for the DOCSIS subsystem), the cost and mechanical footprints of the NLOS gateway ought to mimic that wireline box. And the allowable transmit power of 3.5 GHz CBRS (+30 dBm or 1W) provides enough punch to be able to craft a neighbor mesh to sidecar some amount of opportunistic node+1 network attachment from a functioning neighbor's network feed in the event of failure of the to-home main LOS downlink.

1.4. Data and Analysis from various Field Tests

1.4.1.1. Qualcomm supplied Research data[m]

Qualcomm has investigated propagation and loss behaviors for multiple bands (sub-6 GHz through millimeter) in an ongoing study aimed at determining 5G wireless technology adaptations. Bands and areas of interest are listed below.

Channel Measurements/Simulations

Scenario		Description	Frequency Band
Measurements	Materials	Various construction materials, humans, etc.	22-43 GHz
	Foliage	Various tree species	29 GHz
	Indoor	Residential (interior/exterior walls)	22-67 GHz
	Indoor	Emulated Stadium	2.9 GHz, 29 GHz
	Indoor	Bridgewater shopping mall	2.9 GHz, 29 GHz, 61 GHz
	Urban micro	Street Canyon	2.9 GHz, 29 GHz, 61 GHz
	Indoor	Office	2.9 GHz, 29 GHz, 60 GHz
	Urban micro	New Brunswick	2.9 GHz, 29 GHz, 60 GHz

Scenario		Description	Frequency Band
Simulation	Indoor	Dense office	29 GHz, 38 GHz, 60 GHz
	Urban micro	High density (Manhattan)	29 GHz, 38 GHz, 60 GHz
	Urban micro	Low density	29 GHz, 38 GHz, 60 GHz
	Indoor	Stadium	29 GHz, 38 GHz, 60 GHz

Figure 16 – Propagation Study Subjects by Band

A key study area was the ability of the selected carrier frequencies to penetrate dwelling apertures or materials. As can be seen below, statistical variation over common materials, sidings, and window type were tremendous (and as such, likely defy an “average” characterization of transition losses over client distributions which could include most permutations listed in the tables).

Summary of Out-to-In Propagation Loss

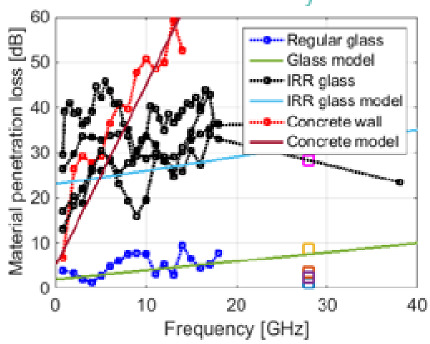
•Measured penetration losses for various materials

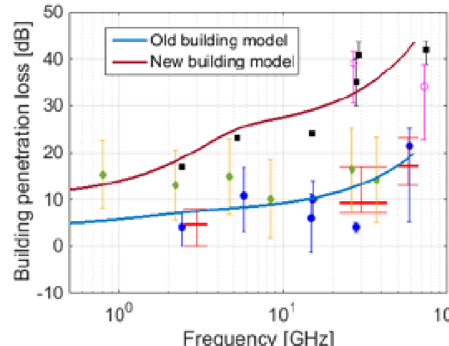
Residential 1	
Material	Loss
Vinyl siding	~6-7 dB
Stone siding	~35 dB
Window glass	~10 dB
Plastic blinds	~2 dB

Residential 2	
Material	Loss
Plywood	~8-10 dB
Hollow sheetrock	~1-2 dB
Wood exterior wall/panel	~10 dB
Brick exterior	~30 dB
Metal doors/window frames	high

Residential & Commercial	
Material	Loss
Commercial Tinted Window	10-20 dB
Clear glass	2.5 dB
Residential Home Exterior	~9 dB

•Results consistent with other industry sources





Confidential and Proprietary - Qualcomm Technologies, Inc.

Figure 17 – Penetration Loss by Material Construction and Frequency

In regards to the wireless propagation environment, however, it is not only client endpoint buildings but interdicting topographical features and weather which can degrade the channel. Channel fade due to weather has been well characterized over the lower parts of the bands in question due to decades of satellite link use and the resort of high ground and towers can be plainly shown to address topology contours. However — in North America in general — large swathes of geography are dominated by trees and other foliage which, depending on seasonal growth and longitude, can interrupt a good many LOS apertures between BS and client and present performance challenges. Data below is captured in two bands — the 2.9 GHz being representative of nLOS/NLOS sub-6 GHz carriers and the 29 GHz proxy's behavior at millimeter wave frequencies. The impact of deciduous and conifer trees (under gusty wind conditions) suggest that the leaf density from the conifer more frequently produces heavy link losses and these, more so at higher carrier frequencies.

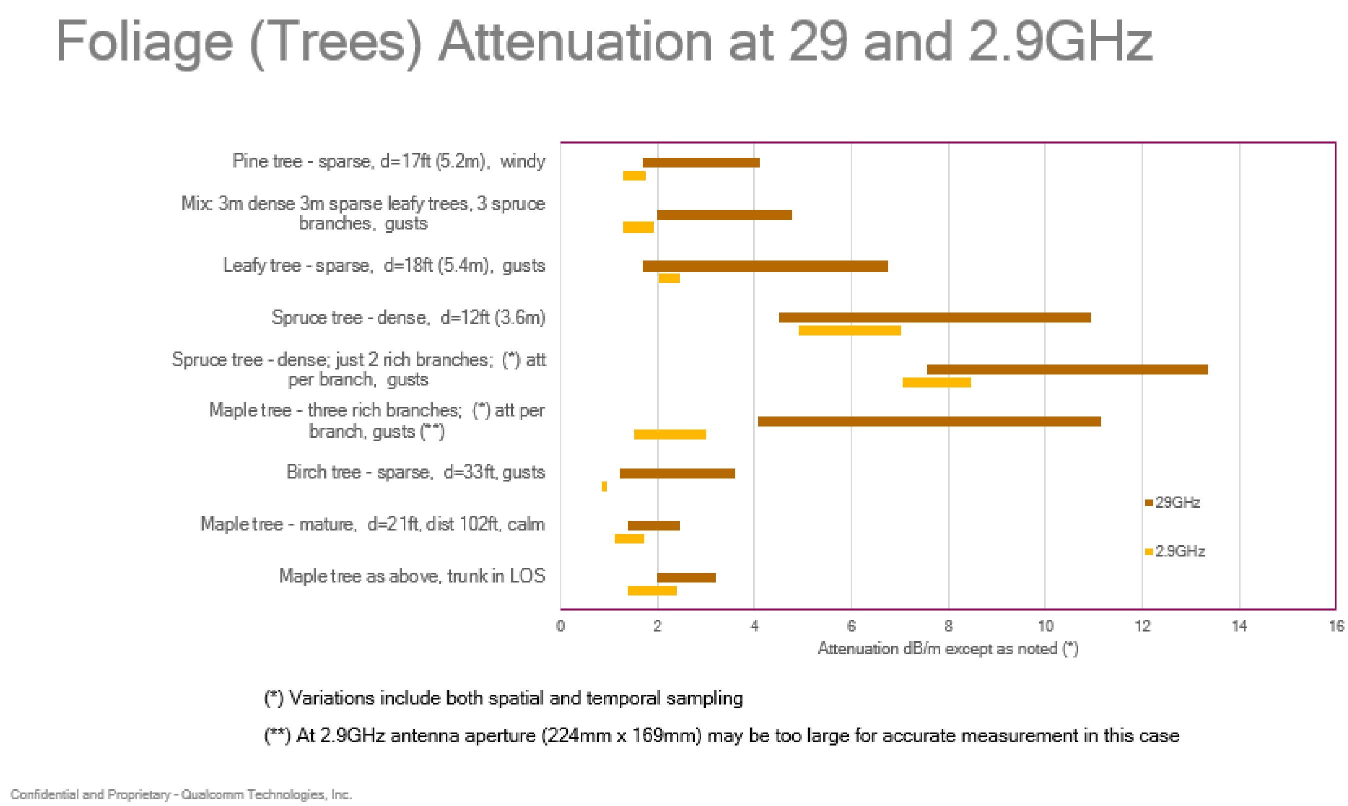
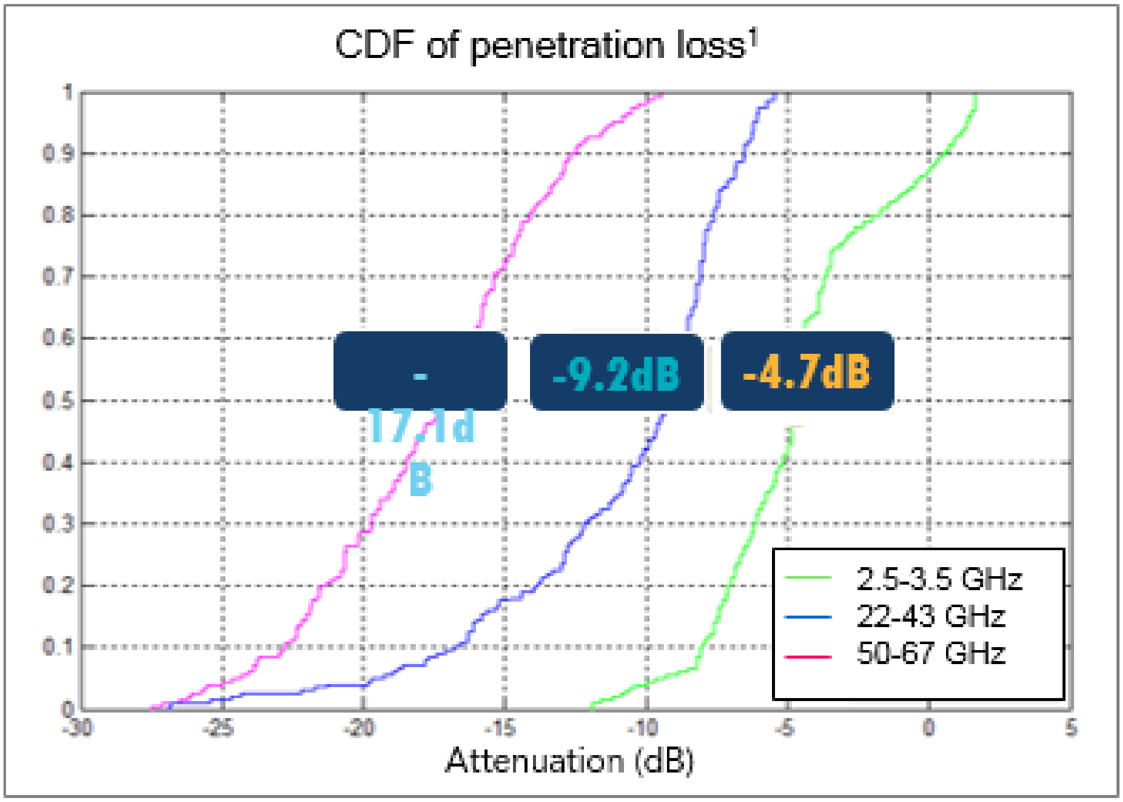


Figure 18 – Scattering Losses at sub-6 GHz and mmWave for Foliage

Signals incident upon exterior construction have a difficult time penetrating exterior walls — more so with brick than siding (refer to data above). However, in even the lowest loss scenarios (lap siding and the like) there is considerable gradient to the losses with frequency (~ 5 dB sub-6 GHz up to 17 dB in the unlicensed millimeter wave band).



Note: Values indicate the low 50th percentile penetration loss for the bands

Figure 19 – Exterior Lap Siding Penetration Losses over Frequency

Internal walls seem more homogeneous whether the construction is residential or office. In both cases, the loss over frequency or construction appears to be in the range of 3.5 dB.

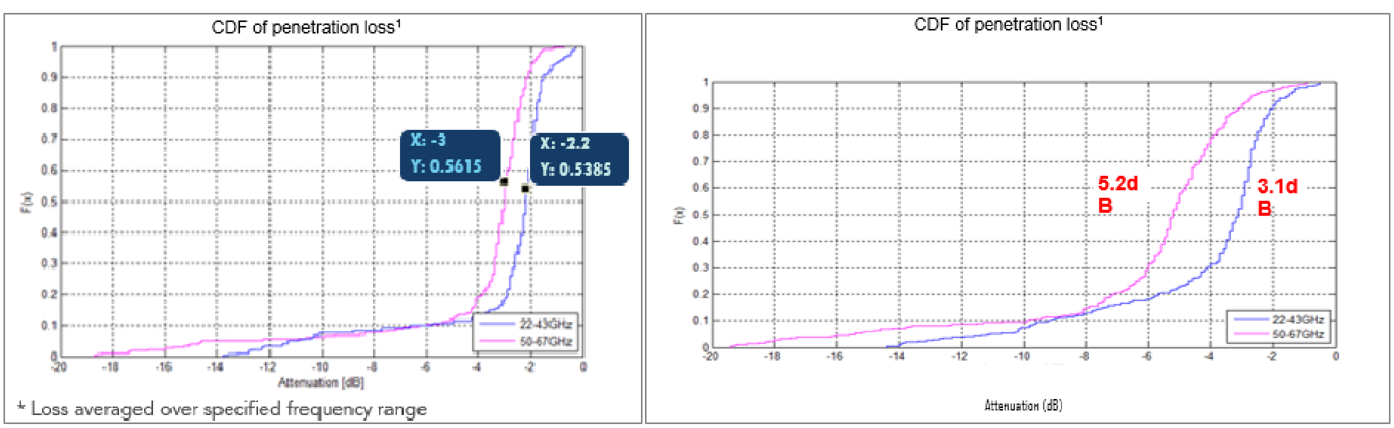


Figure 20 – Interior Wall Penetration Losses, Home (L) and Office (R)

An overall view of interior CPE performance at distances from 50-600 meters from an outside POP/Small Cell operating at 28 GHz was performed and the probability of outage measured for both 8-element (solid lines) and 64-element (dotted lines) MIMO arrays (outage being defined as producing < 100 Mbps). In the graph below, the Y axis is the empirical cumulative distribution function (CDF — jumps of 1/n at each of the n data points) and X axis is the Throughput in Mbps.

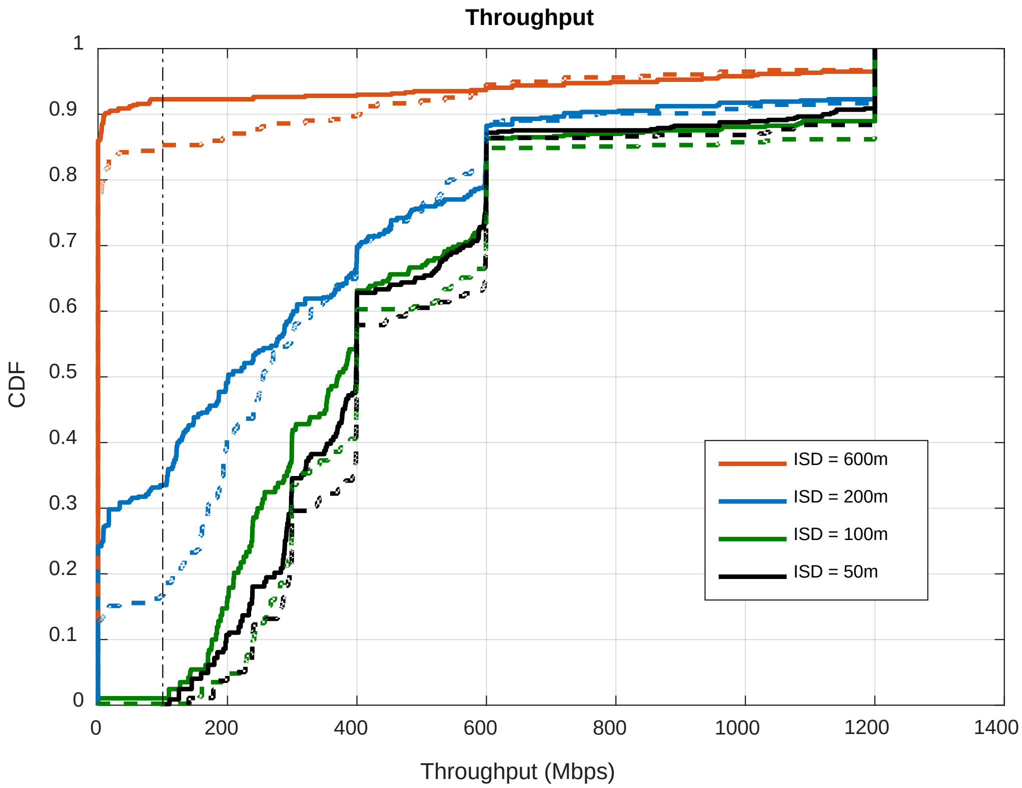


Figure 21 – Probability of Service Outage on Inside CPE Vs Bitrate Demand and Distance to BS

As can be seen, for 50 and 100 meter distances, essentially all CPE could produce at least 100 Mbps (as opposed to 34% outage for the simple antenna array at 200m, falling to 85% outage for even a 64-element array at 600m). Even at 50 meters with the best antenna, however, a full third of the CPE population could not muster the expected 400 Mbps. Moved to 200 meters' distance, another third of the population was throttling back (70% or so experiencing difficulties).

At a fixed service distance to the POP/Small Cell of 200 meters, moving the CPE or at least the Antenna/Transceiver portions outside the dwelling bought back significant performance.

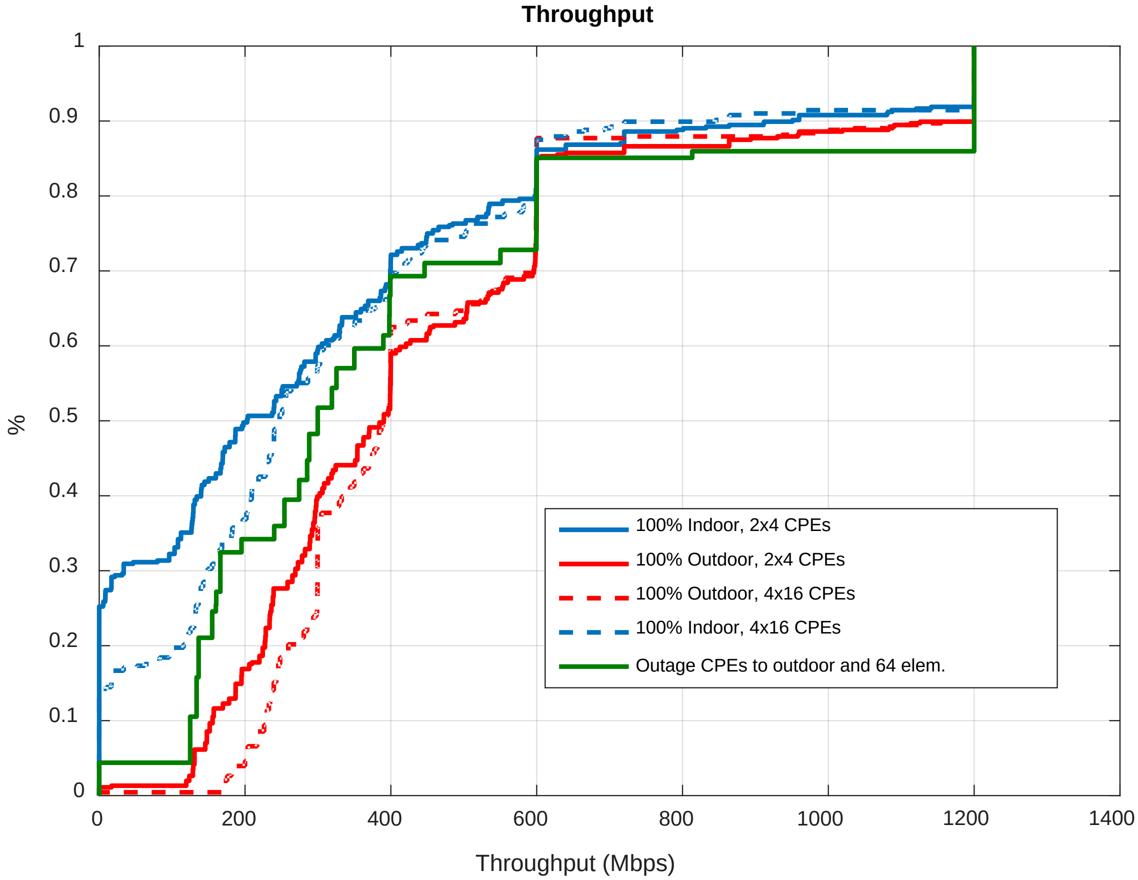


Figure 22 – Comparison of Indoor vs. Outdoor Throughput for 2 MIMO Arrays @ 200m

Getting the *outage* CPE outside the home and equipped with a 64-element array meant 95% of that originally defunct population recovered from outage to consistently produce at least 100 Mbps.

1.4.3 CableLabs Analysis and Testing

CableLabs has been engaged in multiple 5G (millimeter wave) field trials to evaluate the opportunities and limitations of using millimeter wave 5G Fixed Wireless links to provide Multi-Gbps services to the end user. Based on the developments in the 5G ecosystem, the field trials focused on the 28 GHz, 39 GHz, and 70 GHz bands. An extensive list of KPIs was collected during the field trials, but for the scope of this paper, we will limit the discussion to spectral efficiency and link length.

Channel bandwidths in the mm-wave bands are significantly larger than typically used wireless channels. For example, the 28 GHz band is divided into 425 MHz wide channels, the 39 GHz band is divided into 200 MHz wide channels, and the 70 GHz band is divided into 1.25 GHz wide channels. Thus, even under modest spectral efficiencies, such bandwidths can potentially enable multi-Gbps services to the end user.

It is worth noting that the field trials were performed using systems that are still under development, thus further performance improvement can be expected as the systems mature.

1.4.3.1 28 GHz vs. 70 GHz Performance Comparison

CableLabs conducted a millimeter wave link field trial focused on evaluating the impact of millimeter wave spectrum on link performance. 28 GHz and 70 GHz bands were selected as they represent the lower and higher bands of the millimeter wave spectrum.

The test setup mimicked a wireless drop scenario to a residential household; the transmitter and receiver were placed approximately 240 foot. apart, and a single spatial stream was used in the evaluation. The evaluation focused on the impact of simple channel impairments (single impairment at a time, no compound impairments) on the link performance relative to a line of site link.

Figure 23 below summarizes the impact of single channel impairments on the link's spectral efficiency. The link under evaluation was a SISO link, thus for MIMO links (for example 2x2 MIMO), the spectral efficiency can be scaled accordingly.

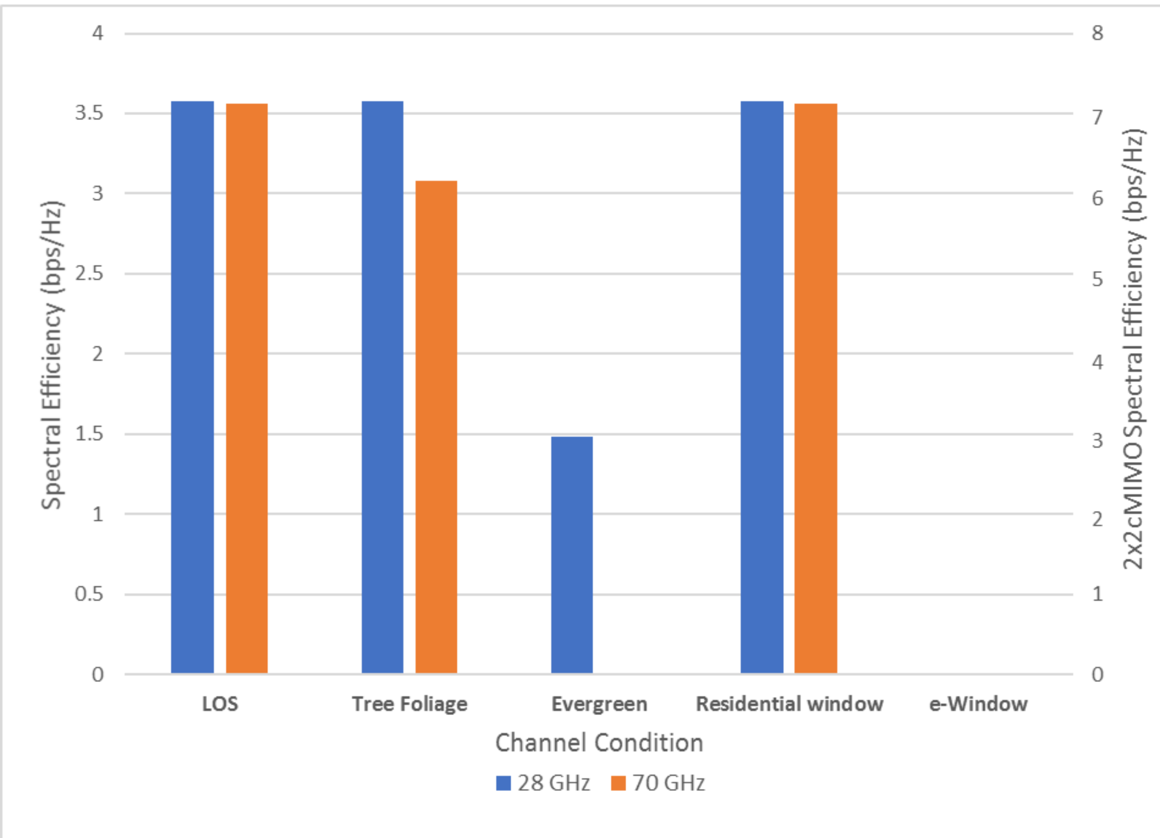


Figure 23 – 28 GHz vs. 70 GHz Spectral Efficiency

As can be seen in Figure 23, in LOS conditions and slightly obscured channels, a MIMO system can achieve ~ 7 bps / Hz, which translates to a minimum requirement of 150 MHz of channel bandwidth to be able to support 1 Gbps link capacity. As mentioned previously, current regulations provide 425 MHz wide channels in the 28 GHz band, and 1.25 GHz wide channels in the 70 GHz band.

The performance of the 28 GHz and 70 GHz links in short distances are comparable in favorable channel conditions, but the 70 GHz band is more susceptible to channel impairments, especially moisture bearing channel impairments. As seen in Figure 23, the 70 GHz link's spectral efficiency drops by 15% due to tree foliage, and the link is completely lost when going through an evergreen tree.

The difference between the 28 GHz band and 70 GHz band becomes more observable upon evaluating the cell edge of the link. Figure 24 below represents simulated results for the maximum distance from the transmitter to achieve a target modulation order. As shown in Figure 24, the link length (defined by the lowest achievable MCS) is reduced by 75% in the 70 GHz band in comparison to the 28 GHz band, which in turn means a ~16x increase in cell density to achieve the same coverage.

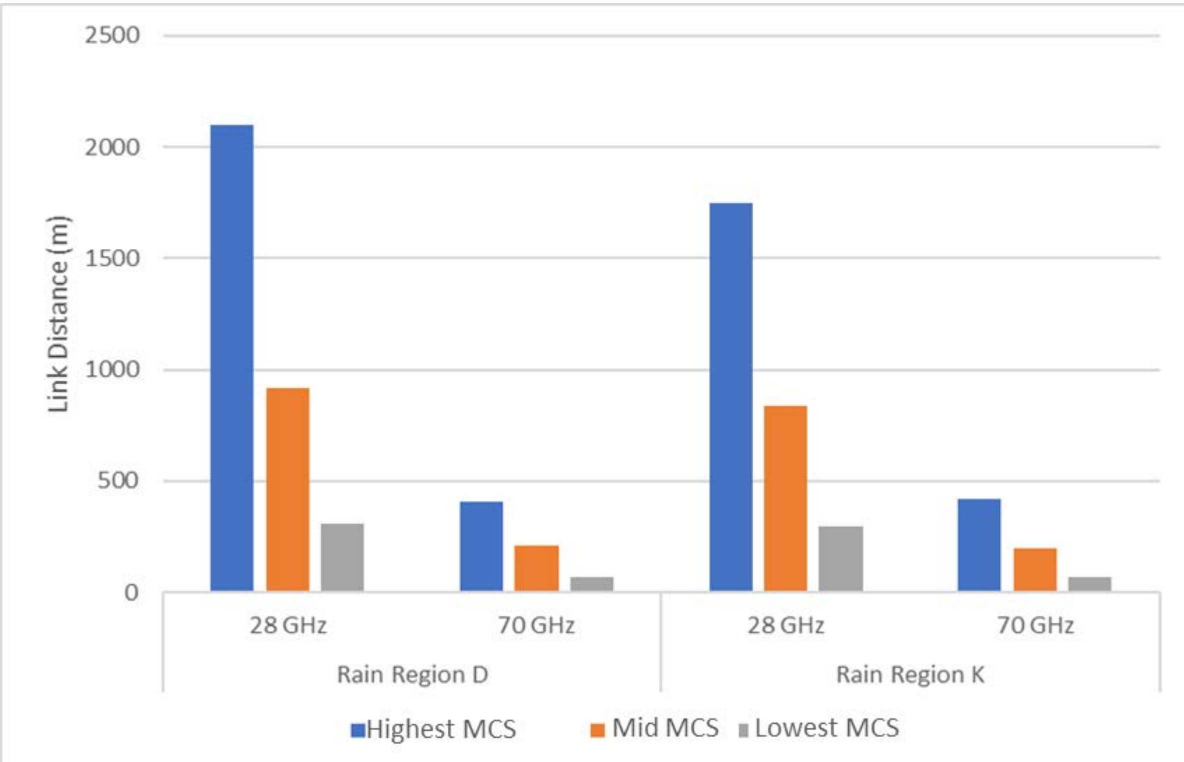


Figure 24 – 28 GHz vs. 70 GHz Link Distance

Based on the results from Figure 24, one would assume that deploying a wireless network based on 70 GHz band would incur a much higher deployment density in comparison to 28 GHz. This would be true if advances in antenna technology are not considered. For the same size antenna panel, a 70 GHz antenna panel can have 6 times the density of antennal elements compared to a 28 GHz antenna panel, which translates to ~7 dB gain for the same panel size. A 7-8 dB gain allows for 70 GHz links to have similar link lengths as 28 GHz links (assuming favorable channel conditions); thus 70 GHz remains a viable option for delivering multi-Gbps connectivity to end users.

1.4.3.2 37 GHz Field Trial

In addition to the 28 GHz and 70 GHz field tests, CableLabs conducted a 37 GHz field trial using millimeter wave system under development. The objective of the field trial was to evaluate the coverage and capacity of 200 MHz wide links operating in the 37 GHz band under various channel conditions.

The system under test had advanced MIMO and beamforming capabilities which are some of the fundamental features in 5G. The benefits of MIMO and beamforming can be leveraged to deliver high capacities and/or extended coverage even in the presence of channel impairments.

As shown in Figure 25, link capacities of approximately 750 Mbps were achievable in LOS conditions, which were degraded to just under 490 Mbps in adverse weather conditions. Also of particular interest was the maximum link length that can be achieved to deliver service where a LOS link extending approximately 2600 feet while delivering nearly 190 Mbps was demonstrated.

As shown in the 28 GHz and 70 GHz field trials, the 37 GHz links are also highly susceptible to channel impairments, where a 70% link capacity reduction was observed due to foliage and a reduction of approximately 90% in link capacity due to dense foliage.

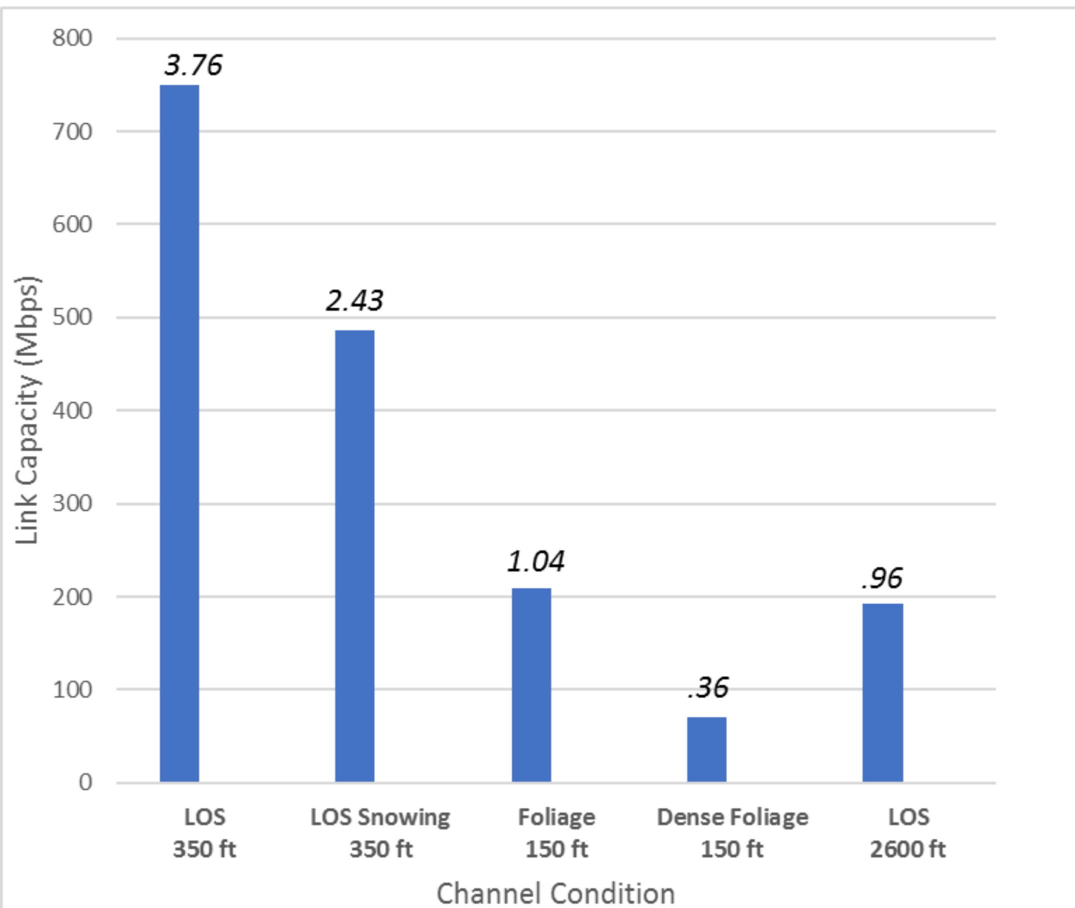


Figure 25 – 37 GHz System Performance & Spectral Efficiency (values above columns)

1.4.3.3 Field Trials Summary

Based on the results of the field trials, Fixed Wireless networks leveraging millimeter wave links hold the potential of delivering high speed service to end users. Large channel bandwidths and advanced signal processing techniques such as MIMO and Beamforming are key enablers.

Nonetheless, the susceptibility of millimeter wave links to channel impairments such as tree foliage adds an amount of complexity in deploying such networks. Channel impairments can significantly reduce link and system capacity.

The results from the 70 GHz field trial indicate that the unlicensed spectrum extending from 64 GHz to 71 GHz can potentially be used to deliver Multi-Gbps Fixed Wireless services, without the need to acquire licensed spectrum.

1.5 nLOS/NLOS Advantages in Reach and Setup

Despite modest available spectrum (relative to that liberated for use from 28-71 GHz), sub-6 GHz maintains a key benefit over millimeter wave in terms of wavelength-related propagation improvement (~ 20 dB lower losses over the same distance), more birefringent than outright scattering behavior with respect to encountered materials in the spatial delivery channel and much lower tendency towards absorption by atmospheric particles or moisture. From POP/Small cell to client, through the air and around or through man-made or natural interdicting materials, sub-6 GHz based signal delivery provides a much more robust probability of successful recovery at the receiving end. Real-world numbers suggest a usable service radius of ~800 meters for the power budget allowed (1W for the client and 50W for POP/Small Cell Category B, in the case of 3.5 CBRS) and may permit indoor use without resort to a piped outside antenna provided a capable enough BS is employed. LOS systems seem bound to perhaps a quarter of that distance (and dare not risk inside-home antenna mounts much past 50-meter range).

In terms of equipment setup, CPE with only a rudimentary MIMO (say, 2x2) ought to be able to pilot, or sound, the channel such that the home user can be iteratively guided to the best in-home location and orientation with an out-of-box onboarding application which levers the CPE’s interpretation of the smart antenna tuning parameters relayed by the BS. The upshot here is that new clients for a given nLOS POP ought to be capable of self-installation without the service provider resorting to a truck roll. However, in the event of a technician-assisted install, such should be possible with the complications associated with placing or aligning outside pole-mounted antennae.

1.6 Bandwidth Advantages in mmWave

There is no question that for sheer available bandwidth, the bands above 20 GHz provide instantly scalable, multi-Gbps bitrates at only modest spectral efficiencies. Even with the “narrow” channel bandwidth of 200 MHz assigned to the 39 GHz band (a 33% uptick over *all* the channel BW available at 3.5 CBRS), a pedestrian 7 bps/Hz yields nearly 1.5 Gbps (the equivalent of 35 or so bonded DOCSIS 3.0 channels). And while issues of service radius and link availability (due to atmospheric or topographic masking) give pause, the PHY’s raw capability might prove an exploitable contingency in certain use case scenarios where alternate means are either too expensive or not yet ready.

1.7 Spectrum Efficiency: the Power of Massive MIMO

The two-species wireline legacy of cable — coax and fiber — provide a loss gradient and ingress protection which promote E2E spectral efficiency about 10 bps/Hz. A full and fair comparison to the prospect of wireline delivery needs to acknowledge the rather precipitous and (to-date) unappreciated impact of massive MIMO antenna arrays (rather loosely defined as those T x R matrices in densities larger than 8 x 8) in achieving an order of magnitude better spectral density over short-haul (< = 800 m) wireless links.

For example, wireline's DOCSIS 3.1 pride (4K-QAM-based) promises a 12 bps/Hz spectral efficiency (before overheads are invoked). However, in the wireless space, one year ago, academic proof-of-concept (POC) work has yielded data which confirms that a 160-element planar antenna array (its area befitting a mount on a short monopole — see below) could support over 20 fixed and walking-pace mobile, single-antenna clients to the tune of nearly *150* bps/Hz (this, leveraging 256-QAM over a 20 MHz channel at 3.7 GHz)[6]. The extensibility to a 3.5 GHz CBRS POP/Small Cell is obvious and if one were to include channel aggregation of the full available PAL-guaranteed bandwidth of 70 MHz, the result would amount to ~ 10 Gbps. Additionally, if one were to instead apply this to a LOS solution at 37 GHz, the planar array size would collapse to an area of 1% of that used for the 3.7 GHz POC (due to the wavelength shrinking by a factor of 10) and, assuming just the 200 MHz of single-channel spectrum, produce a yield in bitrate of more than 30 Gbps. obviously scalable to whatever channel-aggregation scheme one might apply there and subject to lease considerations). It is noteworthy that Massive MIMO is implementable at both the client and POP/Small Cell ends of a LOS link due to the constrained geometries required (1/2 wavelength spacing, element-to-element).

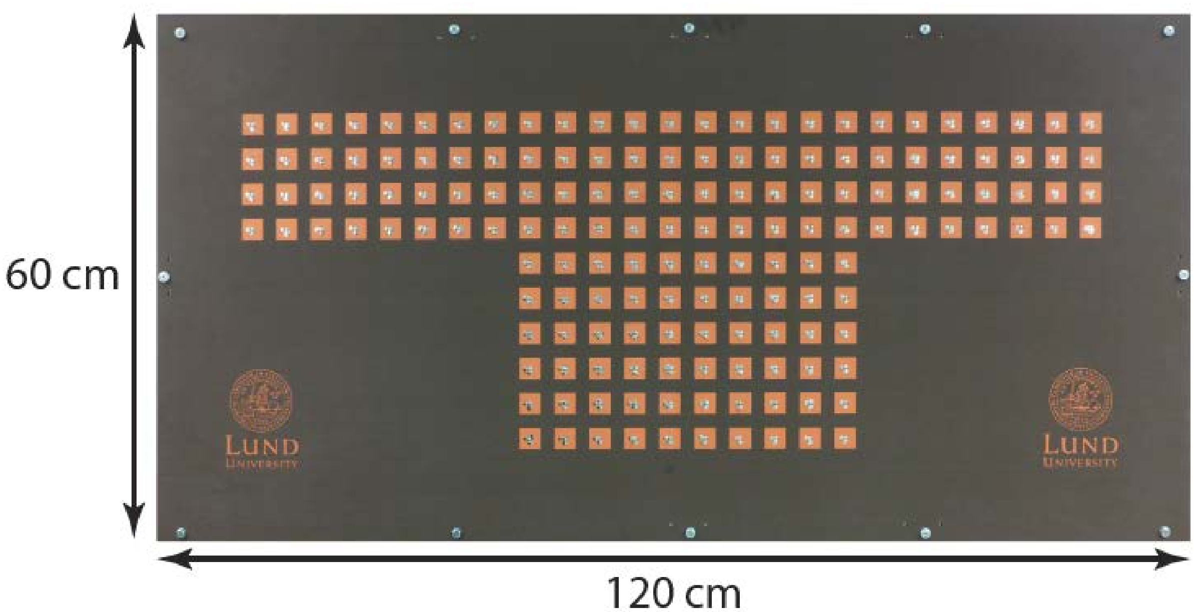


Figure 26 – Lund University Massive MIMO Array (3.7 GHz)

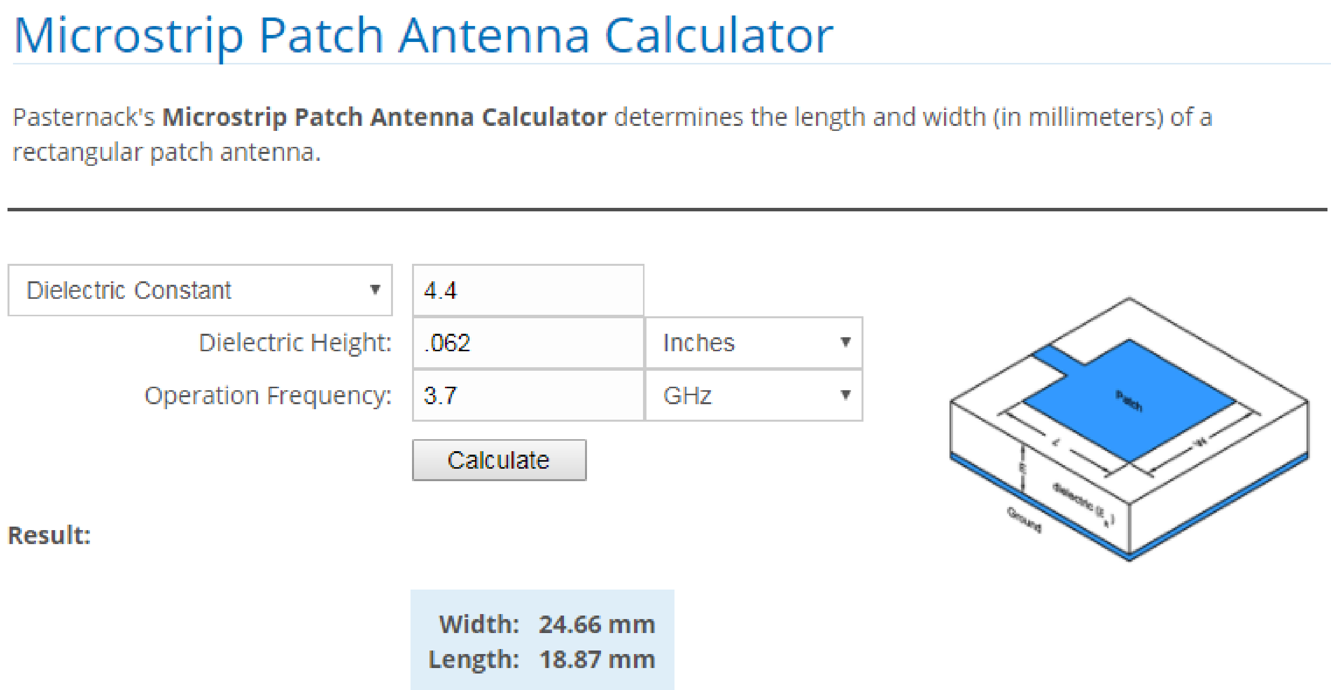


Figure 27 – Example of a Single Microstrip Patch Antenna Element @ 3.7 GHz – as Would be Represented in an Array Similar to the Lund Above (courtesy: Pasternack Website)

1.8 Hardening the Delivery

To expand more on the problem of millimeter wave transmission susceptibility to atmospheric absorption or scattering -- the availability past 2 nines (99%) usually implies redundant, orthogonal signaling paths and persistent monitoring of link quality. In the case of a FWA solution, 3.5 GHz and nLOS smart antennas provide both transmit power reach and backup link azimuth tuning which facilitate near-instantaneous switching of the connectivity path when signaled via meshing protocols to the nearest local peer (peer piggyback or peer repeating) in the case of primary loss-of-link. An example of this 3.5 GHz meshing is shown below in Figure 28. This is a potential elegant architecture for sub 6 GHz nLOS solutions.

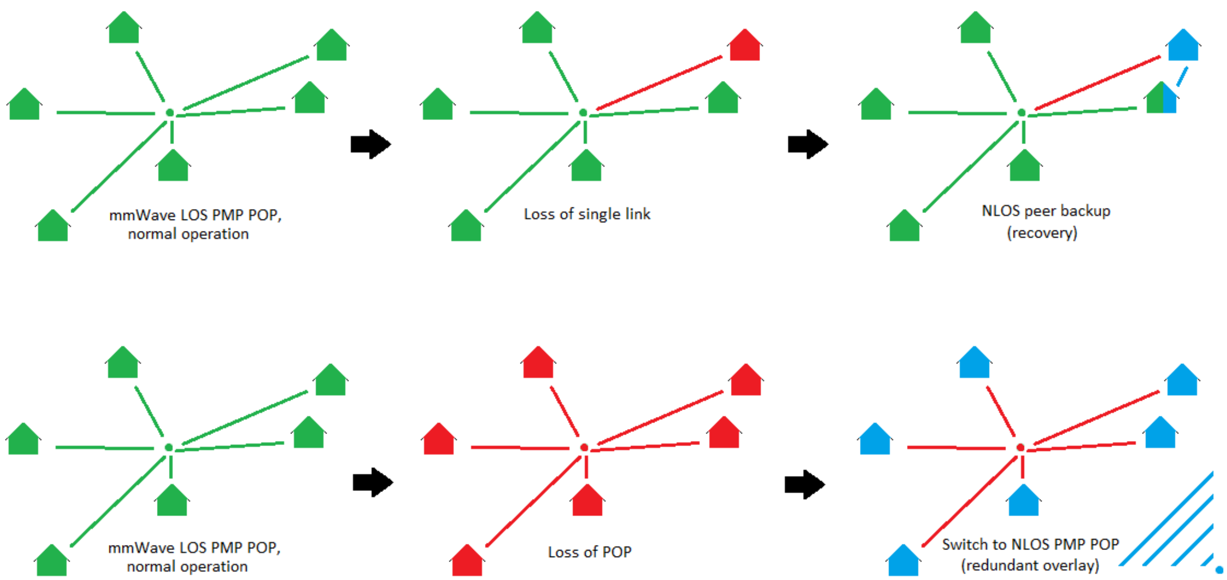


Figure 28 – Example of a 3.5 GHz Backup Signalling Mesh

LOS delivery redundancy is a much more difficult and expensive proposition, however. While it may be possible to establish dual LOS apertures (to separate monopoles) and even allocate emergency front- and backhaul POP/Small Cell wireline resources, redundant antenna solutions at the client sites would be required to affect a purely LOS backup scheme — and this presumes that a convenient LOS aperture to, and a serviceable radius from, a standby LOS base station exists.

A much more sensible scheme — perhaps an evolutionary goal past NLOS delivery at 3.5 GHz — would be to backstop the broad if less reliable LOS downlink with an NLOS "emergency" overlay which advantages itself of the scheme described above for NLOS delivery and provides a reliable uplink (pruning the link failure analysis tree in the process). Broad failure across multiple LOS downlinks in a single POP service group — as would happen for atmospheric interference — would of course tax the backup downlink bitrates; the presumption is that parametric performance reduction is better than complete loss of link.

From a purely qualitative analysis, the availability numbers for LOS wireless delivery versus nLOS should be comparatively worse, given a) its higher susceptibility to service interruption in the first place, b) the possibility that a redundant LOS signaling path is either unavailable or of compromised performance, and c) the potential for thrash or hang in the management of separate frontends (and hence, loss of link) under what may be a common propagation path impairment (rain or fog, for example). Concerns (b) and (c) are obviously mitigated in the case of NLOS downlink redundancy — with the performance hit as noted above.

1.9 HFC Wireless Extension: the New Trunks

Tapping into the HFC plant to supply wireless POPs amounts to an organic extension to the existing network (see below):

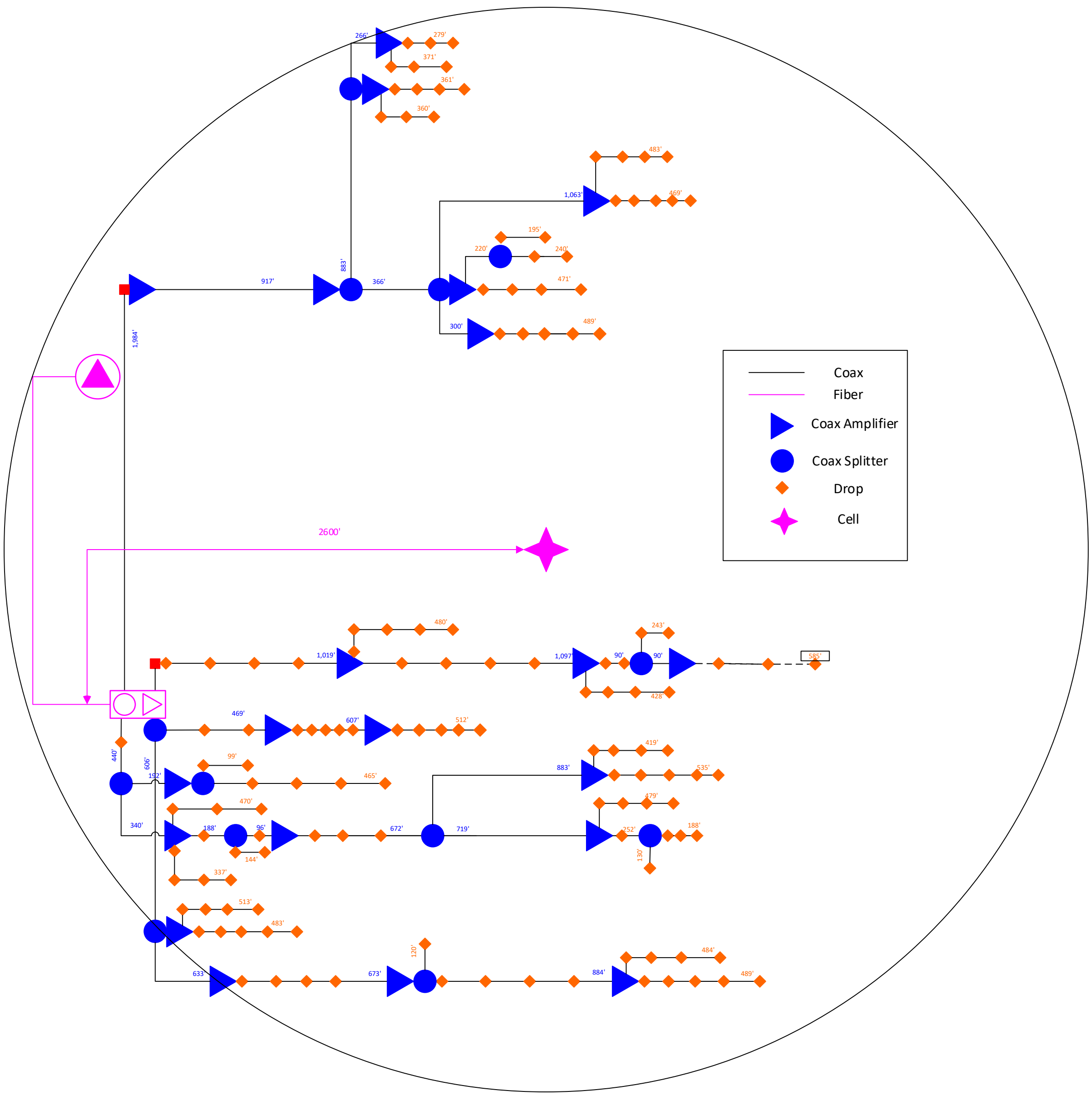


Figure 29 – Straightforward Tap of Fiber Trunk for Single Wireless Service Group

Previous analysis has evaluated options for enhancing the HFC plant capacity by pushing fiber deeper into the network [Ulm 16]. The analysis looked at a small number of fiber node service groups in one fiber service group.

In a full-service group overlay the 5G may be deployed to enhance or offload services from the HFC plant for subscribers. Depending on the geography of the service group, this may be a lower cost alternative to the more traditional methods of extending the capacity of the plant - i.e. node splits, fiber deep, etc. However, it should be noted that it is still likely that some costs (in addition to tower construction) will be incurred in the fiber distribution system to support a full-service group overlay.

Figure 29 depicts the same node from [Ulm 16], overlaying with an 800m radius small cell transmitter. Placing the cell at the existing fiber node, the CBRS signal does not cover the entire service group area. In the figure, the tower is placed more central to the service area, approximately 800m or 2600 feet from the fiber node requiring new infrastructure development.

This diagram is intended only as a hypothetical example of how a converged network may look on an existing node. Note that the node diagram has been updated to reflect the geographic distances between elements, however, it still may not reflect the directional depiction accurately.

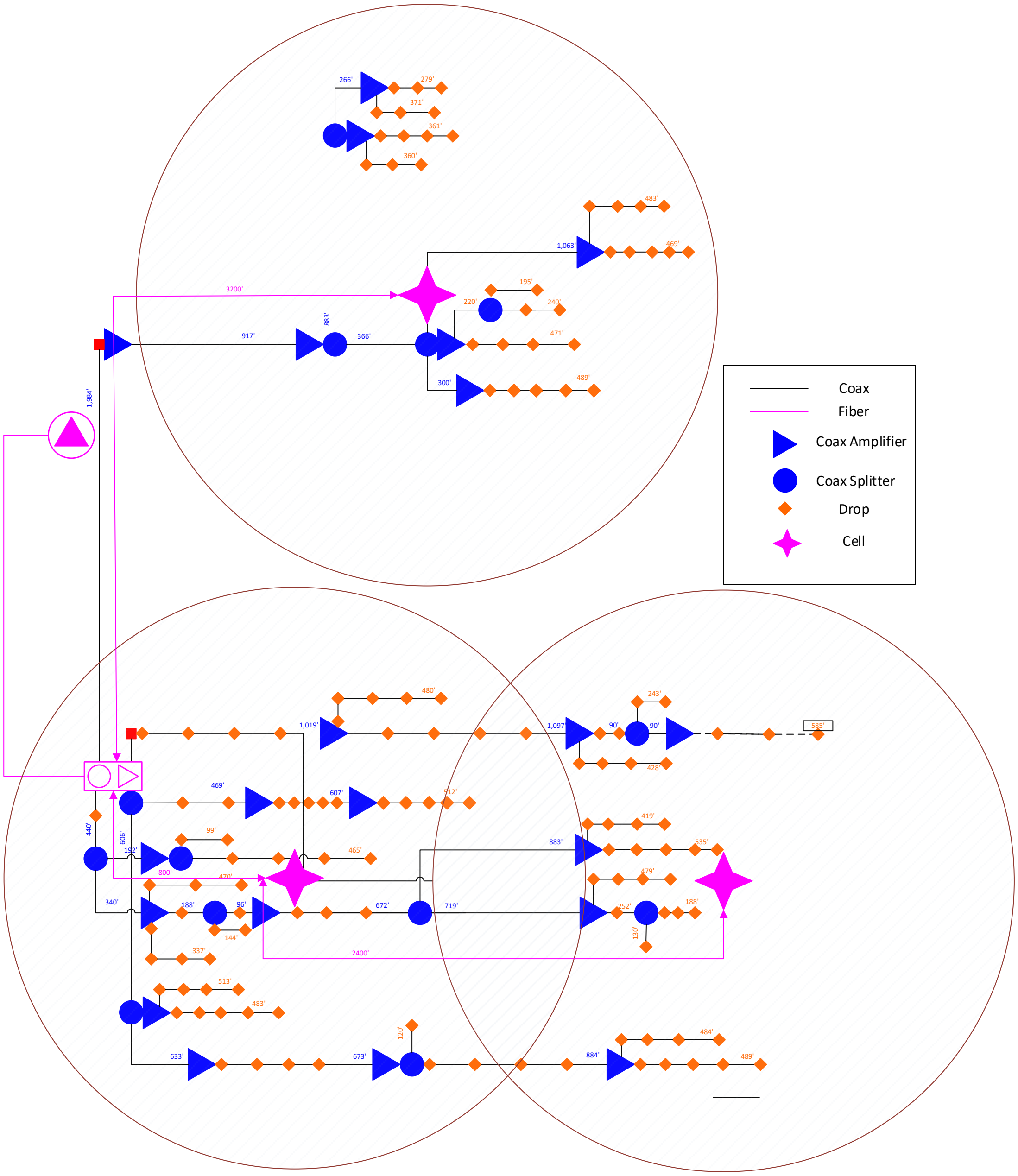


Figure 30 – Feed to Multiple POPs in a Large Overlaid Wireless Service Group

Figure 30 shows the same service group with 200m small-cell towers. The location of the transmitters was chosen to cover the service area with the fewest small cell towers. Alternatively, the location of the small cell transmitters could be placed to allow the reuse of the existing buried or aerial rights within the existing plant as much as possible. Note that in this situation, it may require a larger number of small-cell transmitters to cover the overall node service group, thus trade-off analysis should be done to determine the overall lowest cost configuration. Considerations may include whether the plant modifications will require new aerial or underground distribution feeds and availability of site locations.

2 Cost Considerations

Finding a common reference for the infrastructure investments implied in any of the options listed is difficult due to differentials in regional labor rate, site topography, client population density, relative accessibility of client and tower end points, antennae complexity, back- and front-haul piping to the POP, lease costs, and availability of shared BS infrastructure (like power and tower), the nature and type of the residential CPE and HN interface, and the complexity of installing and setting up the link. The following represents average estimates based upon input from industry professionals, publicly available cost studies and extrapolated CPE costs founded on similar complexity cable devices.

2.1 FTTH Costs

The presumptions applied to, and classifications for service enumerated in, CSMG's 2009 FTTH Deployment Assessment for Corning, have been examined and found no objectors among MSO senior staff solicited for commentary. Of the three company experiences referenced in that paper, a spread of ~ 35% in cost for connecting homes in "dense" population territories were noted. Applying an aggregated 3%/yr Cost of Living Adjustment (COLA) to those 2009 estimates seems advisable. In that case, for "dense" portions of the client population (~880 households/$mi^{2)}$, the average cost to pass and connect with fiber amounted to $1,153 (Figure 31 - $1,460 in adjusted 2017 dollars). When this density fell to ~175 households/mi^2, there was a cost premium of 40% — which applied to our adjusted for cost of living number above — implies $2,050 per household. Allowing the client population density to fall to ~72 households/mi^2 imparts a 71% premium to the "dense" connectivity cost, yielding a "pass and connect" charge of $2,499 per household.

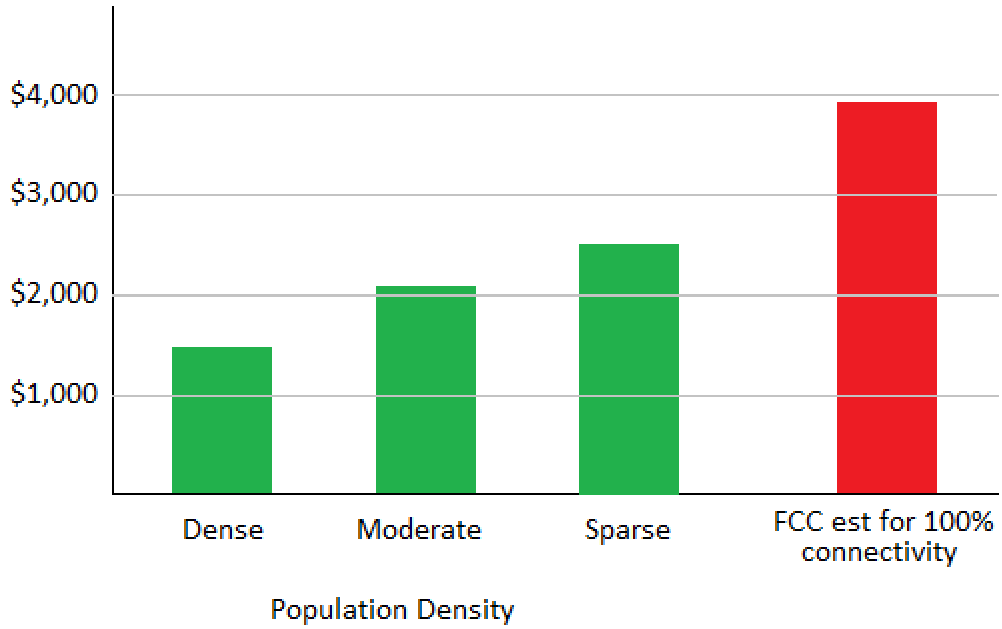


Figure 31 – FTTH Cost in 2017 to Pass and Connect Per Household

Note that the rapidly rising cost to enfranchise ever-more-rural customers motivated the study to recommend against ever enfranchising the last 20% or so of the customer base. (In fact, the CSMG paper targets a goal of 41.5% of potential clients.) It is noteworthy that the FCC estimate for 100% connectivity in 2009 raised the connection tariff to an *average* of $3,084 (estimated $3,907 in current dollars) — so the weighted contribution of that final 20 percentiles is indeed staggering. Figure 32 captures the CAPEX and OPEX considerations.

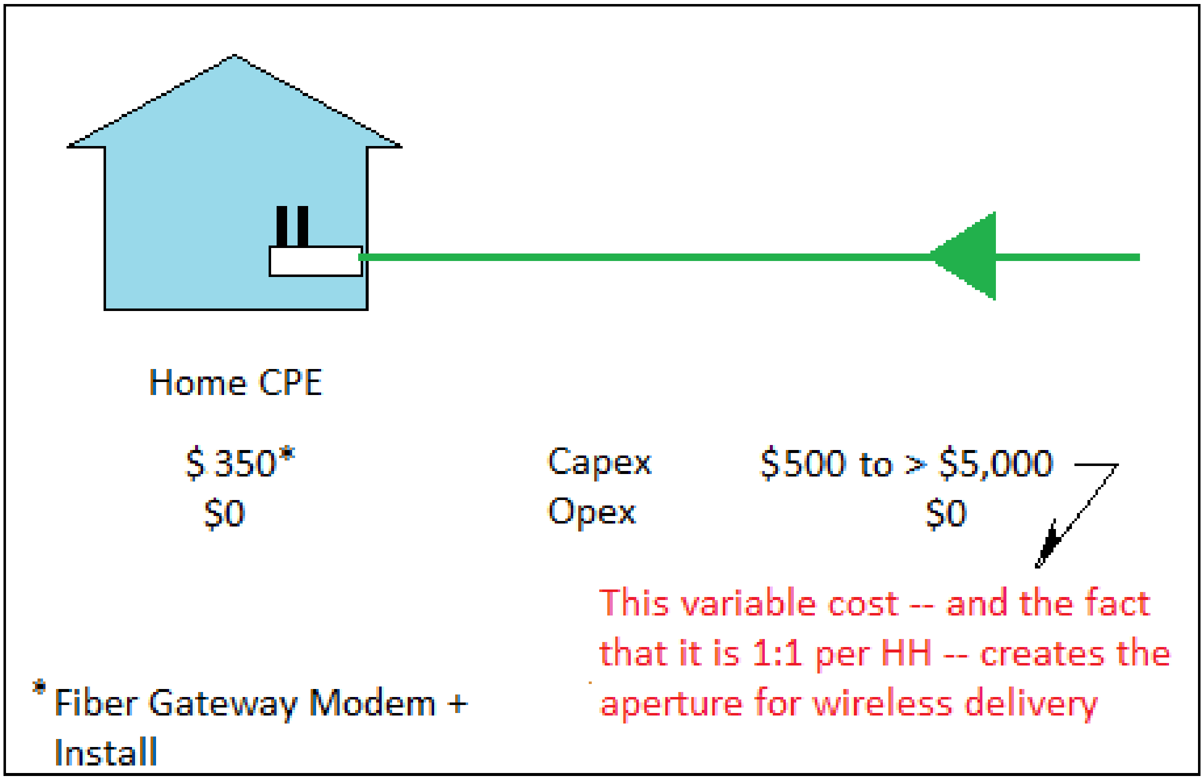


Figure 32 – FTTH Connection Costs at the HH

The upshot of this is that a significant percentage of US data customers could find themselves beyond the reach of high capacity wireline data services and seek an option to connect via Wireless services.

2.2 3.5 GHz CBRS Costs

As mentioned, NLOS 3.5 GHz does not require tall masts to facilitate antenna mounts but can settle for opportunistic 2nd-story types of elevations within 800 meters of its client base. In this way, it is extremely like legacy WLL strand and pedestal plays. Home CPE tends to look very much like existing gateway equipment with a different WAN attachment and the base station consistent with strand product (though with a more sophisticated, massive MIMO antenna array). Costs are anticipated to run as follow in Figure 33.

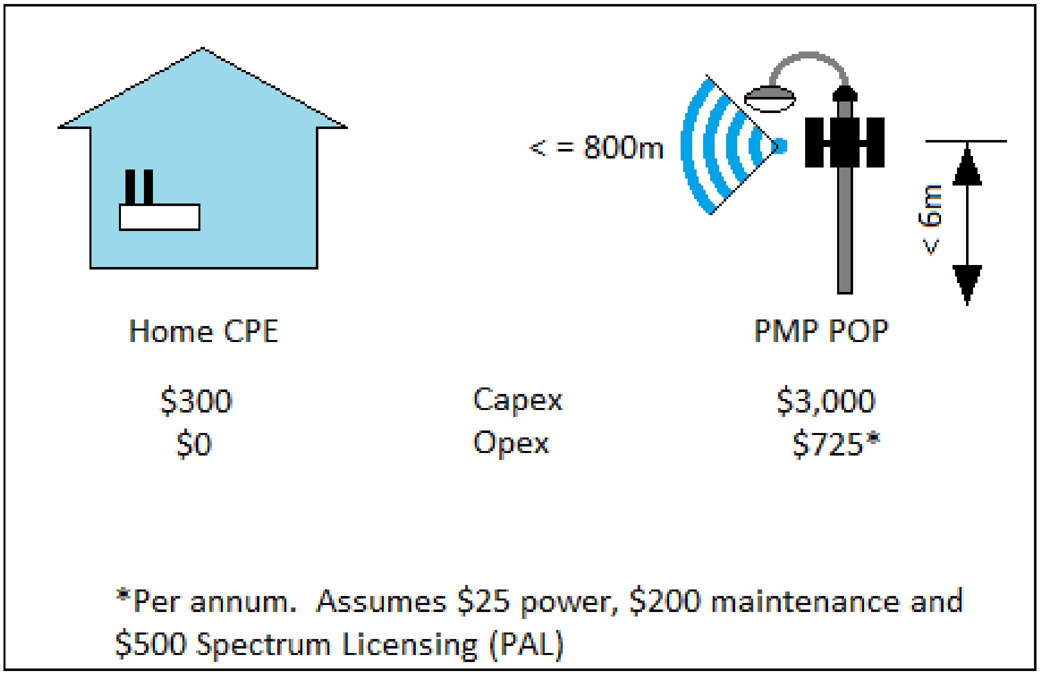


Figure 33 – NLOS/nLOS Sub-6 GHz Infrastructure Costs

Note that the POP CAPEX presumes $2K in mast costs (hugely variable and depends upon availability of repurposed, available parasitic mounting space), $500 for POP/Small Cell hardware and another $500 in network connection costs. It is important to note that the POP costs may be amortized over the client population targeted by the service group (i.e., if the wireless service group population is 50 clients, the $3,725 annual cost is ~ $75/client).

2.3 Millimeter Wave costs

LOS wireless infrastructure carries a higher financial ante than NLOS due to higher complexity both on the CPE and BS sides. Additionally, where self-installation is a reasonable consideration for NLOS with its in-home CPE, the fact that LOS systems require an ORU (outdoor receiver unit) and potential placement optimization of this unit, implies that some budgetary citation for installation labor applies (a $100 bookmark was placed for this). The balance of the $650 client side costs was assigned to $300 for the ORU, $200 for the internal HN router, and $50 for the interconnecting cabling and grounding aspects.

On the POP CAPEX front, the monopole was tagged with a $20K cost, the Small Cell and antenna together cost $2K, and network infrastructure connectivity was set at $500. The summary looks as follows in Figure 34.

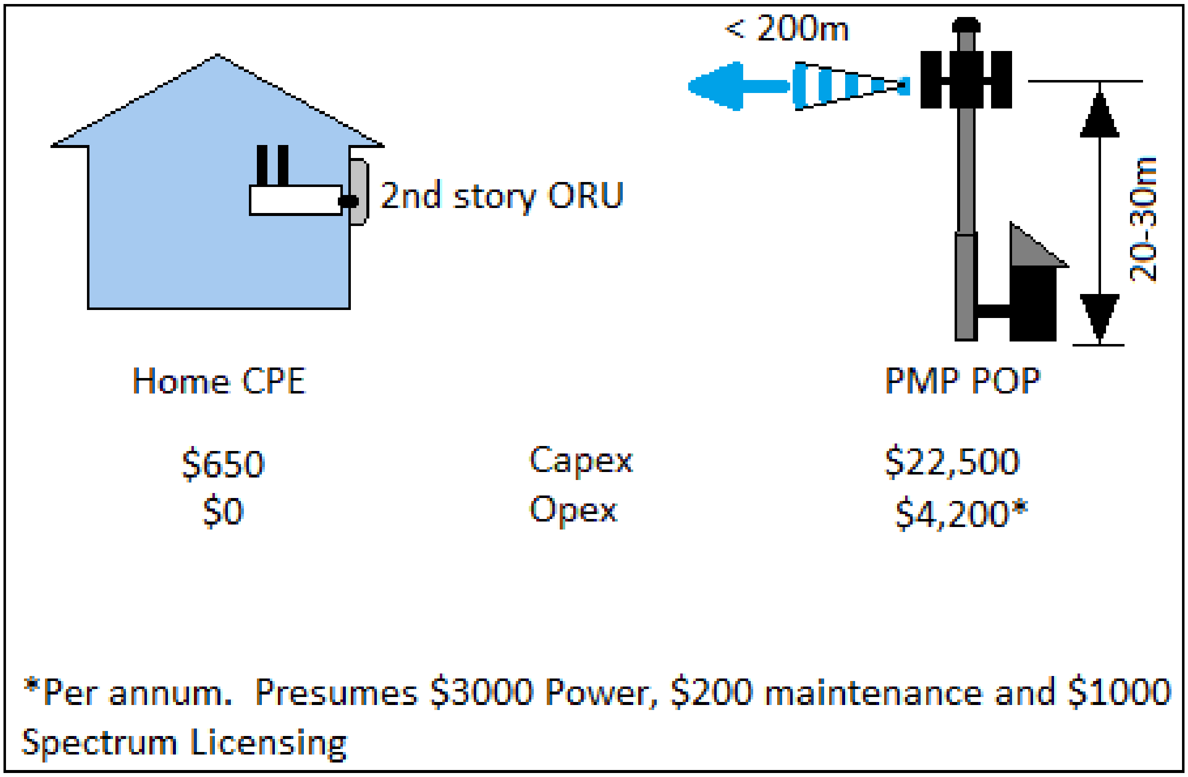


Figure 34 – LOS Infrastructure Costs

As with the NLOS case, amortization of the BS mast, antenna, and electronics may be performed over the client population. The critical differential here is that the service radius for LOS is only ~ 200 meters (which may imply only a couple of dozen clients, or less — and the initial investment is an order of magnitude higher).

3 Intangible Allowances

3.1 Aesthetics

Outdoor wireless AP placement has the potential to be extremely antagonistic from the aesthetic perspective. LOS considerations which must account for potential interference from foliage and interdicting land masses mandate an almost guaranteed level of intrusive environmental presence. Where nLOS APs can be situated in lower-height, disguised locations (and advantage themselves of parasitic placement on street furniture like streetlamps or signage in cases where up to 2nd story height is possible), LOS terminals, for both physical aperture and radiated power considerations, typically are placed well above ground level (to heights of 80 feet and beyond) and intrude on the landscape's skyline. In groomed communities subject to HOA governance on utility visual signature, there are tangible costs associated with potential litigation to obtain the necessary accommodations and intangible costs in public opinion regarding what many communities view as a blight on property values'

In these regards, there is no question that in-ground network connectivity trumps wireless approaches.

3.2 nLOS (3.5 GHz CBRS) Congestion

As the 3.5 GHz band offers an experimentation-friendly 3-tier licensing arrangement which actively promotes low-cost application testing via the General Authorized Access (GAA) entry level, it might behoove cable operators exploiting the band — despite the temptation to surf a GAA tier on accessibility -- to adopt a Priority Access License (PAL), such that explicit bandwidth requirements for geographic areas may be protected from a competing service co-option. And while the GAA tier advertises access to a marginally larger spectrum than PAL (80 MHz versus 70 MHz), there are no air time guarantees relative to other GAA pretenders in the geographic tract such that a QoE can be inferred. The short story then is that, to avoid situations where competing service leverage of the 3.5 GHz CBRS band promotes the accommodation of other services, MSOs' intended use of the band for a geographic area warrants investment in the protection of PAL licenses. (License auctions are expected beginning in 2018).

Conclusions

The implications of providing a future-proofed wireless bitrate capability to all subscribers beyond the reach of wireline in a cable system requires the analysis of wireless delivery options which include LOS, nLOS and NLOS systems — each of which comprises a mixed bag of capability and compromise. The broader bandwidth of millimeter LOS delivery, with its promise of massive MIMO antenna structures on both base station and client endpoints, unfortunately burdens itself with compromises involving client-side signal recovery costs, short signal throw, aesthetic challenges and perhaps too-easily non-deterministic link quality. nLOS and NLOS sub-6 GHz systems can be made to overcome these challenges. However, the available bandwidth puts considerable pressure on massive MIMO and signal processing upgrades on the base station side to create the scalar benefits which effectively multiply spectral efficiency to levels necessary to anticipate user bitrate consumption a mere 4-5 years in the future. The relentless bitrate consumption growth defined in Cloonan's Curve suggest that, ultimately, the facility of sub-6 GHz NLOS will be associated with a redundancy role for more LOS-based delivery — or perhaps in an ad hoc augmentation role for temporal housing arrangements.

There is also an argument which might bear examination (despite the hefty cost of the required redundant infrastructure) which proposes that a hybrid fiber-coax-wireless (HFCW) scheme might be a useful offloading solution in mixed-use cases where separating a few heavy consumers via differential delivery PHY wireless might buy service phase-in time for major upgrades to the legacy wireline business. One could also bind delivery on a flexible basis across both wireless and wireline PHYs and orchestrate a closed-loop, QoE-deterministic multipath delivery scheme which senses delivery impairment per PHY and adjusts link exploits accordingly.

As cable operators move Fiber Deeper going to an all passive coax network, the ability to deliver multiple Gbps of capacity to a single home, seems an easier path than building out a FWA millimeter wave architecture. However, given that 5G POP/Small Cells require wired backhaul, the potential for the MSO to leverage its network for mobile 5G seems to be a more complimentary investment. In discussions with MSOs, who are also MNOs, they struggle now to see a FWA solution to deep residential deployments. They see some potential to use their network to potentially lead out to target MDUs served predominantly by their competitors, and often see value in pulling Fiber. However, they do see the value of adding 5G and CBRS POPS to their HFC and growing Fiber Networks for outside mobility applications.

For MNOs, those that don't own wired broadband networks, the use of FWA is an opportunity to cherry pick areas for a Fixed Wireless overbuild. We have seen some Wireless ISPs already offer millimeter wave broadband delivery services targeting dense areas with only one incumbent, areas where consumers are deprived of choice of broadband provider. The investment scale which nourishes those shared wireless technical advances applicable to both unlicensed and dynamically licensed space for MSOs (cable, telco, and MNO alike) means that applications of FWA will emerge as we move to mobility on 5G systems. The economics and the size of the optimum cell is still under debate. What is also clear is that the easier direction for FWA is dense MDU environments is targeting a single wireless connection to the outside and using other solutions internally, like Ethernet and Wi-Fi. The Residential 5G deployments will only emerge driven by the rise of mobile 5G devices which will happen in 2021 at scale and will then see the 5G small cell deploy in ever decreasingly small cell sizes.

And lastly, there is still a lot of activity around trying to leverage sub 6 GHz frequencies into the 5G requirements space. 3GPP have added support in New Radio to support sub 6 GHz and even sub 1 GHz to create the overlay capability for millimeter non-determinism to fall back on other transmission frequencies and to allow NB-IOT to run on lower sub GHz frequencies. Additionally, applying Element Arrays to work with sub 6 GHz frequencies offers up potential for paired antenna and spatial streams to reuse spectrum and use spectrum at higher bits/Hz.

We have come a long way in the drive to 5G — but as the saying goes — there is still a long way to go.

Abbreviations

AP	access point
bps	bits per second
BS	Base station
CAGR	Compound annual growth rate
CAPEX	Capital Expenditures
CBRS	Citizens Broadband Radio Service
CBSD	Citizens Broadband Radio Service Device
FEC	forward error correction
FTTH	Fiber-to-the-home
FWA	Fixed Wireless Access
Gbps	Gigabits per second
GHz	Gigahertz
HFC	hybrid fiber-coax
HD	high definition
Hz	hertz
LOS	Line-of-sight
nLOS	Near-line-of-sight
NLOS	Non-line-of-sight
OBE	Overcome by events
OPEX	Operating Expenditures
ORU	Outdoor Receiver Unit
QoE	Quality-of-Experience
P2P	Peer-to-peer
PMP	Point-to-Multipoint
POP	Point of Presence

PTP	Point-to-Point
SCTE	Society of Cable Telecommunications Engineers
SG	Service Group
SINR	Signal-to-Ingress and Noise-Ratio
TCO	Total Cost of Ownership
WLL	Wireless Local Loop

Bibliography & References

5G Channel Model for bands up to 100 GHz (2.3 October 2016), 5GCMSIG White Paper

5G NR mmWave, Ozge Koyman, Qualcomm Research

CBRS: New Shared Spectrum Enables Flexible Indoor and Outdoor Mobile Solutions and New Business Models, Kyung Mun, CBRS White Paper, CBRS Alliance, March 2017

Cell Towers and Aesthetics: Blight on the Neighborhood or Sign of the Times?, Paul J. Weinberg, Zoning and Planning Law Report

FCC 15-47, REPORT AND ORDER AND SECOND FURTHER NOTICE OF PROPOSED RULEMAKING, April 21, 2015 (*3.5 GHz CBRS band creation)*

FTTH Deployment Assessment, Cartesian (formerly CSMG), 2009 (used by permission)

Future Directions for Fiber Deep HFC Deployments, John Ulm and Zoran Maricevic, SCTE/ISBE Expo '16

LuMaMi – A flexible testbed for massive MIMO, Joao Vieira, Steffen Malkowsky, Karl Nieman, Zachary Miers, Nikhil Kundargi, Liang Liu, Ian Wong, Viktor Owall, Ove Edfors, Fredrik Tufvesson, Lund University

Making 5G NR a Reality, Qualcomm Technologies, Inc, Sept 2016

Massive MIMO for Next Generation Wireless Systems, Erik G. Larsson, ISY, Linköping University, Sweden, Ove Edfors, Lund University, Sweden, Fredrik Tufvesson, Lund University, Sweden, Thomas L. Marzetta, Bell Labs, Alcatel-Lucent, USA, arXiv: 1304.6690v3 [cs.IT] 12 Jan 2014

Massive MIMO: Ten Myths and One Critical Question, Emil Bj¨ornson, Erik G. Larsson, and Thomas L. Marzetta, arXiv:1503.06854v2 [cs.IT] 18 Aug 2015

Millimeter Wave System Performance Characterization for 5G Data Access, Shirish Nagaraj, Lea Castel, Tommaso Balercia, Bishwarup Mondal, Jong-Kae Fwu, Communications and Devices Group, Intel

Shared Spectrum Market Opportunity for Cable MSOs, Mark Lowenstein, Mobile Ecosystem, April 2017

