Comparative Technical Analysis for 5G Fixed Wireless Access Rural Networks (2.6, 3.7 and 6.4 GHz)

A Technical Paper prepared for SCTE by

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1 Introduction

1.1 Executive Summary

CableLabs developed a simulations engine intended to estimate a set of Key Performance Indicators (KPIs), concerning the user experience for Fixed Wireless Access (FWA), when estimated across a cluster of cells. This simulations engine is further used to provide input data for the FWA economics performance analysis tool. The Economics Analysis Methodology is presented in a companion paper.

The Technical Performance Analysis discusses the impact of different limitations upon the cell coverage:

- The support of frequency reuse 1, when smart arrays are employed. More specifically how could the network load impact upon victim cell coverage, could be controlled by dynamically controlling the base station (BS) array vertical down-tilt angle.
- The interfering cell network load impact upon the victim cell user throughput (Tput), indicating a network load in the 50% range or less, may be optimal to avoid significant cell throughput degradation.
- BS antenna height (h_{BS}) of 30m and 60m were analyzed, pointing to: i) a higher network interference impact when the frequency is decreased; ii) a lower network interference impact for the outdoor-to-indoor (O2I) case vs. the outdoor scenario; and iii) a very low or close to the noise floor outdoor 6.4GHz network interference.
- The impact of fading and loss mechanisms upon outdoor and O2I propagation is further analyzed. The results show that the main contributor to outdoors increased path loss is the small-scale fading, as long as the O2I fading is kept in check (CPE positioned close to the outer wall closest to the victim BS).
- The uplink (UL) link Budget limitations, pointing to i) downlink (DL) and UL coverage are in the same range for h_{BS}=30m (3.7GHz) due the increased DL interference (MobEdge=2000m), ii) 2.6GHz coverage is slightly larger than the 3.7GHz, however the difference between the two is minimal due to the larger network interference impact on the 2.6GHz system, iii) the O2I UL coverage is more reduced vs. DL, due to reduced O2I DL interference and the reduced indoor CPE antenna gain vs. outdoor CPE gain,

The key results concerning cell coverage and user throughput are discussed from different angles:

- The outdoor coverage may extend beyond the serving cell edge, due to the highly directive outdoor CPE antennas.
- 2.6GHz line-of-sight (LOS) coverage is smaller than the 3.7GHz one (h_{BS} =30m and 60m), due to the higher network interference impact.
  - Non-LOS (NLOS) becomes the dominant propagation mechanism, since the network interference is greatly reduced in NLOS conditions. Overall, the 2.6GHz composite coverage is NLOS driven being higher than the similar 3.7GHz coverage.
- The network interference (h_{BS}=30m) is higher that corresponding to hBS=60m for the 2.6GHz, due to the smaller cell radius selected for this case (MobEdge =2000m).
- The outdoor 6.4GHz cell edge is limited by the lower BS effective isotropic radiated power (EIRP) of 36dBm.
- Providing NR in Unlicensed Spectrum (NR-U) services in unlicensed 6 GHz spectrum may require a densified network.

- The O2I cell edge is UL limited, due to the additional UL path losses, caused by the O2I loss, the indoor CPE being required to either i) have a higher conducted RF power and/or ii) use a directive antenna array with a higher gain vs. an omni antenna.
- For 3.7GHz, h_{BS}=60m, outdoor case, all scenarios exceeding a service availability>97% are impacted by an UL asymmetric link budget.
- As the probability of achieving a particular radio link thoughput (i.e. service availability) is increased to 99%, cell coverage is reduced.
- A FWA network planning targeting 95% service availability backed by 50% network load may be an optimal trade-off.

The paper is organized as follows:

- Section 2 introduces the analysis methodology and the simulations assumptions.
- Section 3 presents the main results.
- Section 3.1 discusses the limiting factors driving to a sub-optimal coverage.
- Section 3.2 summarizes the key results characterizing the user coverage and overall cell coverage, the coverage for FWA throughput thresholds.
- Section 4 summarizes the main findings of this analysis.

1.2 Wireless Spectrum Intended for Rural FWA Applications

FWA provides broadband service in areas where wired solutions are not prevalent or as a competitive alternative to wired broadband. One key performance factor is the optimization of wireless coverage for high throughput services. While earlier FWA implementations were hampered by spectrum and other technology implementations, 5G maximizes the potential FWA performance by employing channel bandwidths up to 100MHz (sub-7GHz) and up to 400MHz (24 – 52GHz spectra).

We identified the following spectra with channel bandwidth allocations in excess of 60MHz, which could be suitable for FWA in North America and Europe, following related spectrum auctions.

Table 1 – Bands Available at 2.6, 3.7 and 6.4 GHz for FWA Services

Frequency [MHz]	Band	Common Name	Max Channel BW [MHz] [4]	Market	Comments
2500 – 2696	n41	BRS	100	USA	
3550 – 3700	n48	CBRS	100	USA	
3450 – 3650 3650 – 3980	n77 Canada		100	Canada	
3300 – 4200	n77 global		100	Global	except USA and Canada
3450 – 3550 3700 – 3890	n77 USA	C-band	100	USA	
5925 – 7125	n96	6GHz	100 80	Regional USA, Canada	
5925 – 6425	n102		100 80	EU	

2 Analysis Tools and Assumptions

Throughput the paper we use the generic term BS for 5G BS (gNB).

2.1 Analysis Methodology

Our FWA coverage analysis is based on a simulation engine developed by CableLabs. This engine was designed to support an economics analysis based on the technical performance of a large-scale cluster of 5G of cells.

2.1.1 Simulations Engine Block Diagram

The simulations engine block diagram is presented (Figure 1). Within the simulation engine the System Level Simulator (SLS) module evaluates radio performance for unmodulated signals over a large number of iterations (Monte Carlo simulation). The SLS generates statistical results of aggregated interference across a cluster of 19 cells arranged in 2 rings surrounding the cell of interest. The 5G New Radio (NR) Link Level Simulator (LLS) simulates 3GPP compliant waveforms targeting the 5G NR performance in a simulated network environment including the network interference predicted by the SLS. The CPE/BS antenna pattern array block generates suitable BS and CPE antenna array patterns. The antenna arrays are critical for supporting frequency reuse (FR) 1 across the radio network by optimizing the link budget component.

The economics analysis block estimates the economic feasibility of the 5G FWA O2I and service delivery network under consideration, based on a set of technical KPIs. This paper focuses on the technical simulation consists of SLS, LLS and antenna characteristics. A companion SCTE Cable-Tec Expo 2022 paper presents the economics analysis.

The functionality of the component blocks is explained in sections 2.1.2 to 2.1.5.

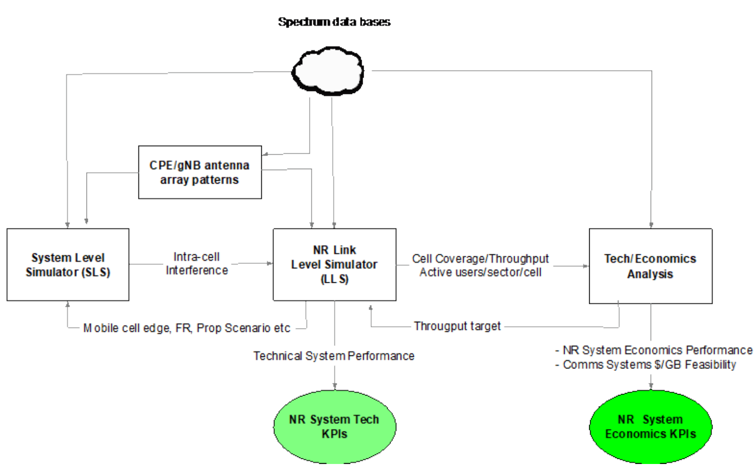


Figure 1. Block Diagram of the FWA NR Techno-Economics Performance Simulator.

2.1.2 CPE/BS Antenna Array Patterns

The CPE/BS antenna array patterns are critical for SLS and NR LLS to calculate the link budget in an interference rich environment, for both the victim path and interference paths in both DL/UL. The spectra used for this analysis are n41 (central frequency 2.6GHz), n77 (central frequency 3.7GHz) and n96 (central frequency 6.4GHz). For each of these bands, a number of antenna array parameters are estimated (Table 2, Table 3, Table 4). A selection of plots summarizing the performance of these arrays is presented in section 7.2.

An antenna array manufacturer may further optimize the electrical performance of the arrays described below. In this context, the performance of these array should be considered as readily achievable.

Table 2. CPE/BS arrays. Summary of the Main Configuration Parameters

	Array Type	Array of Subarrays	Subarray Size	Antenna Element Type	Vertical Electrical Tilt [º]	Estimated Mechanical Size L×W [mm]
CPE Indoor Antenna	UCA	4×1	1×4	Omni	0	
CPE Outdoor Antenna	URA	1×1	2×8×2	Cross-Dipole	0	400×150
BS	URA	4×1	4×4×2	Cross-Dipole	-15	

Table 3. Summary of the CPE Array Performance Parameters

	Max Gain [dBi]	Azimuth (Beam) HPBW [º]	Elevation HPBW [º]	Estimated Mechanical Size L×W [mm]
Indoor Antenna	8.2	360	10^0	58x58x158 (cylinder)
Outdoor Antenna 2.6GHz	16.0	16	53	
Outdoor Antenna 3.7GHz	17	16	52	400×150
Outdoor Antenna 6.4GHz	17.1	16	52	400×80

Table 4. Summary of the BS Array Performance Parameters

	Max Gain [dBi]	Azimuth (Beam) HPBW [º]	Elevation HPBW [º]	Estimated Array Mechanical Size L×W [mm]
2.6GHz	15.6	29	32	
3.7GHz	16.4	29	30	800×200
6.4GHz	16.5	29	28	480×120

2.1.3 System Level Simulator

The SLS is 3GPP compliant in terms of cell topology [1] and propagation models [2]. As shown in Figure 2, the SLS's topology consists of 19 sites, with the serving BS (#1) in the center and two rings of interfering BS (#2 – #19). The assumed cell Radii are presented in Table 5, where inter-site distance (ISD) is calculated as:

$$ISD = \sqrt{3} \times Radius \qquad \text{Equation 1}$$

For this analysis a three sectors per cell topology was assumed. All cells use a frequency reuse 1 (FR1). This topology allows each cell to employ the maximum channel bandwidth (BW), 100MHz for n41 and n77, 80MHz for n96, but triggering a significant intra-network interference for some scenarios. Adjacent channel interference is ignored since is much weaker than co-channel interference. The BS and victim CPE employ the antenna patterns presented in section 7.2. For this paper, we conducted a comparative analysis on multiple scenarios, exercising h_{BS}=30 and 60m, outdoor and O2I scenarios for 2.6, 3.7 and 6.4GHz frequencies. While the analysis summarizes results for both h_{BS}=60m and h_{BS}=30m, for the sake of brevity, the authors chose to minimize the amount of simulations plots concerning h_{BS}=30m.

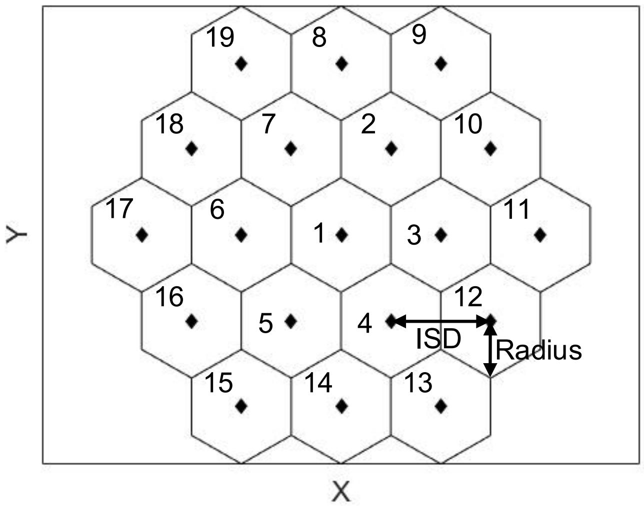


Figure 2. Example of the 19 Cells Topology Used by SLS.

The related cell radius and ISD are presented in Table 5**.**

Table 5. Assumed cell radius (MobEdge) and ISD for h_{BS} =30m and 60m

h_{BS} [m]	Cell radius (MobEdge) [m]	ISD [m]
30	2000	3464
60	4000	6928

SLS is a Monte Carlo simulation technique that runs a large number of iterations (e.g., 100,000 for each scenario analyzed) to output statistical results. For each iteration, a random CPE location is generated inside the serving cell. Distance, relative azimuth and elevation angles between the CPE and each of the 19 BS sites are calculated to estimate path loss, antenna gain, shadowing loss, small-scale fading, and O2I wall penetration loss for both the serving link and interference links. The distributions of these parameters are generated by the Monte Carlo simulation, based on which the service availability (e.g., 95% or 99%) is derived.

Network load is another variable given that not all radio resource blocks are fully allocated for all BSs at all times. For example, if the network load is set to 25%, each of the interfering cells and the victim cell have a 25% probability to transmit in each SLS iteration. All bands under consideration are time division duplex (TDD) bands. We assume TDD sync is enforced among BS s to avoid DL-to-UL and UL-to-DL interference. In this paper, we focus only on the aggressor-to-victim DL-DL interference from the aggressor BS to the victim CPE. Another internal study (not discussed here) indicated that UE to UE and UE to BS interference are negligible, even when TDD aligned.

The cell scenarios modeled in this paper are based on 3GPP channel models [2] as defined by the rural macro (RMa) environment. A random LOS probability is assigned for each SLS iteration, then the path loss, shadowing and fading are calculated for this probability of LOS or NLOS conditions. A Ricean *K*-

factor of 12 dB is used to generate small-scale fading in the LOS condition and small-scale fading Rayleigh distribution in NLOS conditions. The O2I wall loss is also based on the 3GPP model [2] following a Gaussian distribution for a residential home (wood outer wall, regular glass windows, with a glass/wall ratio of 0.3) centered on a mean value of 9.3 dB and standard deviation of 4.4 dB [2].

The calculation of interfereence power level and aggregated interference is presented in [12]. The aggregated network interference is further used by the NR LLS to estimate the signal-to-interference-plus-noise ratio (SINR) for the target victim CPE. Shadowing (large-scale fading), small-scale fading, and O2I loss variables for the signal link are also provided to the NR LLS to quantify service availability.

2.1.4 Link Level Simulator

The NR LLS is a Matlab-based simulator, developed in compliance with relevant recommendations from the 3GPP [2], [3], [4], [5], 6], [7], ITU [8], [9], [10] and TIA [11] targeting the behavior of a 5G waveform when subject to a target propagation environment and for a given geography, propagation model and system interference impact.

The LLS outputs the following technical performance KPIs.

- Dynamic DL/UL SINR, predicting the DL/UL link budget asymmetry per path length unit.
- User throughput versus path length for LOS, NLOS and composite propagation.
- DL user spectral efficiency (SE) versus path length as a function of NR Rel-16 link adaptation.
- DL received signal level (RSL) versus path length.
- BS array EIRP vs. path length and vertical tilt angle.
- Victim fade margin and system interference impact (based on the SLS inputs).
- 50, 100, 300 Mbps (configurable) and mobile cell edge coverage service availability.
- Coverage and user throughput vs. BS array vertical tilt angle.
- Coverage and user throughput vs. network load.
- Network interference power vs. BS EIRP or BS array tilt angle or network load etc.

2.1.4.1 LLS Methodology

The analysis methodology employs the following steps.

The PathLoss is calculated based on:

$$PathLoss(f, path, BS, CPE, environment) = PropagationLoss + prctile\{Shadowing + AtmosphericConditions, Outage\} \qquad \text{Equation 2}$$

where:

PropagationLoss is a function of (distance, frequency), including BS Height, CPE height, CPE Outdoor/O2I scenario and clutter;

prctile function calculates the additional link fade margin for the target availability

Shadowing outdoor large-scale fading modeled by a Gaussian distribution (sigma scenario, mean path loss) and

AtmosphericConditions additional path loss caused by rain fading, water vapor fading and gaseous fading. For a path length <5 km below 10 GHz, the impact of atmospheric conditions upon the PathLoss may be negligible. More details about the environmental factors methodology upon the PathLoss could be found in [12].

The link SINR is calculated based on:

$$SINR = RSL - prctile\{LargeScaleFading + SmallScaleFading + ShadowingO2I + Interference(NetworkLoad) - WallLoss(sigmaO2I, MeanLoss)\} - NF + 10 \times log10(OS) \qquad \text{Equation 3}$$

where

NF CPE noise figure (it includes the CPE modulation implementation losses);

OS Oversampling ratio (CPE PHY). Though the oversampling is effective on improving the SINR for noise-limited environments, it may have a limited capability on interference limited ones.

SmallScaleFading Modeled as the Rayleigh distribution for NLOS (Rice distribution with low *K* factor available is optional);

ShadowingO2I Modeled by a normal distribution {meanWallLoss, sigmaO2I}; Mean(WallLoss) is the mean outer wall penetration loss (O2I only), as a function of wall material, glass to wall area ratio, and glass material.

Interference(Outage, NetLoad) Network interference plus noise floor as a function of link outage probability and network load. The (System) Interference is calculated by the SLS for given outage, MobileCellEdge, and CPE/ BS antenna geometries.

The CodingRate function calculates the LDPC coding rate and the QAM modulation order as a function of SINR, based on the QAM256 modulation and coding scheme (MCS) table.

$$[MCScoding, MCSqam] = CodingRate(SINR) \qquad \text{Equation 4}$$

where

MCSqam QAM order for the target distance, subject to link adaptation,

MCScoding MCS coding rate for the target distance, subject to link adaptation.

Spectral Efficiency is defined as:

$$SpectralEfficiency = MCSqam \times MCScoding \qquad \text{Equation 5}$$

The User Throughput (*UserTput*) is calculated as follows:

$$UserTput(distance) = MCScoding \times MCSqam \times PRB \times (TDD\_DL\_sym\text{-}DMRS\text{-}ControlSym) \times MIMO \times Slots \times Subframes \times Frames \qquad \text{Equation 6}$$

where

MCSCoding Emulates the link adaptation as a function of the SINR degradation by calculating the LDPC user coding rate,

MCSqam Emulates the link adaptation as a function of the SINR degradation by calculating the QAM modulation order,

PRB The number of Physical Resource Blocks per slot,

TDD_DL_sym Chosen as 12 symbols/slot (TDD ratio 12:1:1), maximizing the DL output,

DMRS Selected as 1 symbol/slot,

ControlSym The number of control symbols per slot,

MIMO DL MIMO rank. MIMO performance in O2I propagation environments may be subject to degraded performance under severe multipath conditions due to the large amplitude imbalance between the different Rx air layers reaching the antenna receiver.

Slots 2^{μ}, where μ=numerology order: SCS= $\mu\times$15kHz, where μ=1, 2, 3, 4 (NR Rel 15-17)

Subframes Number of subframes/frame:10/frame

Frames Number of frames per second (10/s).

The overall BS User Throughput (*DLUserTput*) is based on:

$$DLUserTput = UserTput \times Beams \times Sectors \quad \text{Equation 7}$$

where

UserTput User throughput data (it excludes the control and signaling data)

Beams beams/sector and

Sectors sectors/cell.

All the above steps are repeated three times to calculate above parameters for LOS, NLOS and composite (LOS/NLOS) for UMi, UMa, or RMa scenarios (only the RMa scenario considered for this analysis). The above functions are calculated for every meter of the path length, supporting high accuracy plots.

2.1.5 Economics Performance Simulator

This paper focuses on the technical performance parameters of mid-band spectrum. A companion strategy brief looks at the potential competitive implications of FWA services, based on main KPI of the Technical Performance Analysis (e.g., household (CPE) distribution per coverage as a function of path length to the BS). The analysis estimates how much capacity can be created by cell area under a range of assumptions. Using data from CableLabs' quarterly bandwidth usage report, the analysis forecasts future peak broadband demand per average household, factors household density for the areas of interest and estimates what percentage of FWA subscribers can be supported from a market penetration perspective.

2.2 Assumptions

There is a large set of assumptions backing the Key Performance Results, presented in this paper. All simulations results presented in this paper are based on this set of assumptions. These assumptions are grouped in the following categories:

- System and cell simulations assumptions (see Table 16)
- BS and CPE simulations assumptions (see Table 17)
- Atmospheric/environment conditions assumptions (see Table 18)
- CPE/ BS arrays summary of the main configuration parameters (see Table 2)
- Summary of the CPE array performance parameters (see Table 3)
- Summary of the BS array performance parameters (see Table 4)

Samples of BS and CPE arrays performance plots (3.7GHz) are presented in Figure 15 and Figure 16.

3 Key Results

The key performance parameters (coverage, throughput) are impacted by a series of other parameters. The following sub-sections analyze the impact of these parameters upon coverage and user/cell throughput. All throughput values presented hereby, represent user throughput only, the signaling and control data being de-embedded.

3.1 Sensitivity Analysis for Key Inputs

We analyze different cell coverage limitations, due to different factors.

Table 6. Cell Coverage Limitations

Sub-section	Parameter	Frequency (GHz)	BS antenna tilt	Network load	h_{BS} (m)	Cell radius (m)	O2I	Service availability
3.1.1	BS antenna tilt	3.7	0º vs. -15º vs. -21º	50%	60	4000	Outdoor CPE	95%
3.1.2	Network load	3.7	-15º	25% vs. 50% vs. 75%	60	4000	Outdoor CPE	95%
3.1.3	BS antenna height	2.6, 3.7 and 6.4	-15º	50%	30 vs. 60	2000/ 4000	Indoor/ outdoor CPE	95%
3.1.4	Fading and O2I Loss	3.7	-15º	50%	30/60	2000/ 4000	Indoor CPE	95% and 99%
3.1.5	DL/UL	3.7	-15º	50%	30/60	2000/ 4000	Indoor/ outdoor CPE	95%

3.1.1 BS Antenna Down Tilt

BS antenna array's performance is critical for controlling the radiated interference across the neighboring cells. Dependent on BS array performance, the network operator may enable or not frequency reuse 1. Frequency reuse is the number of times the same RF channel (frequency) is reused throughout the network. The most efficient spectrum utilization occurs when the same frequency is reused across the entire network, frequency reuse 1 being the most efficient one.

These simulations highlight the impact of vertical tilt upon frequency reuse 1 in a 5G network. We chose 3 vertical tilts: 0º (along the horizon), -15º (-3dBi along the horizon) and -21º (equivalent to -6dBi in the H direction), for a 3.7GHz 4×4×2 sub-array, grouped in 4×1 subarrays (2×2 subarray configuration).

Figure 3 is based on BS antenna array's ability to steer the beams vertically by electrical means, rather than mechanical ones (e.g., LTE case).

For the particular scenario simulated, the effective radiated power vs. the horizon is max EIRP (Vtilt=0º), -2.5dB (Vtilt=-15º) and -5 dB (Vtilt=-21º). This EIRP reduction is further compounded, during the simulations process with the path loss, system interference and different fading mechanisms for the propagation scenarios under consideration. Unlike a mechanically controlled vertical tilt, such an antenna array could accommodate dynamic tilt factors, dependent on the network load, potentially alleviating the impact of interference.

The related impact upon the system interference (assuming all BS antennas are tilted by the same angle) and the cell user throughput/coverage are presented in Figure 4. The impact of horizontal beam steering upon the network interference is not discussed in this paper.

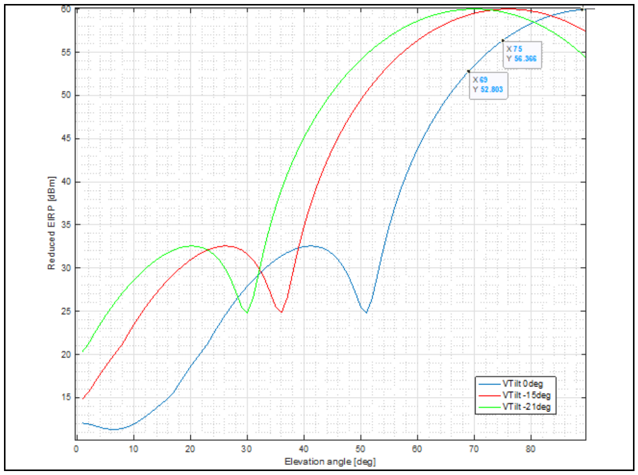
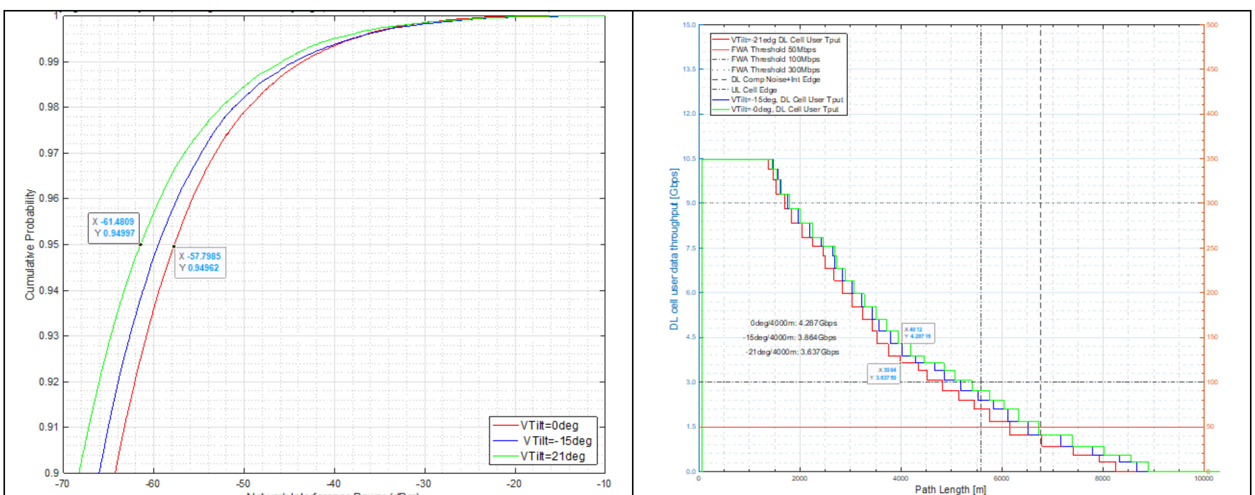


Figure 3. BS Antenna Tilt Impact upon EIRP Distribution vs. Elevation Angle (Reference Boresight Horizontal Direction), 3.7GHz (h_{BS}=60m).

The related DL SINR degradation, for Path Length=2000m and 4000m (Cell Mobile Edge), network load is presented in Figure 4.



a. CDF of System interference. b. Comparative user throughput.

Figure 4 Vtilt impact upon system interference and the related user throughput degradation as a function of Elevation Vtilt=0º/-15º/-21º (h_{BS}=60m, outdoor scenario, NetLoad=50%, 95% Service Availability, 3.7GHz).

Table 7. Vtilt Impact upon Network Interference and DL Cell Throughput, referenced to the horizontal direction, (3.7GHz, Mobile Cell Edge=4000m, NetLoad=50%, 95% Service Availability)

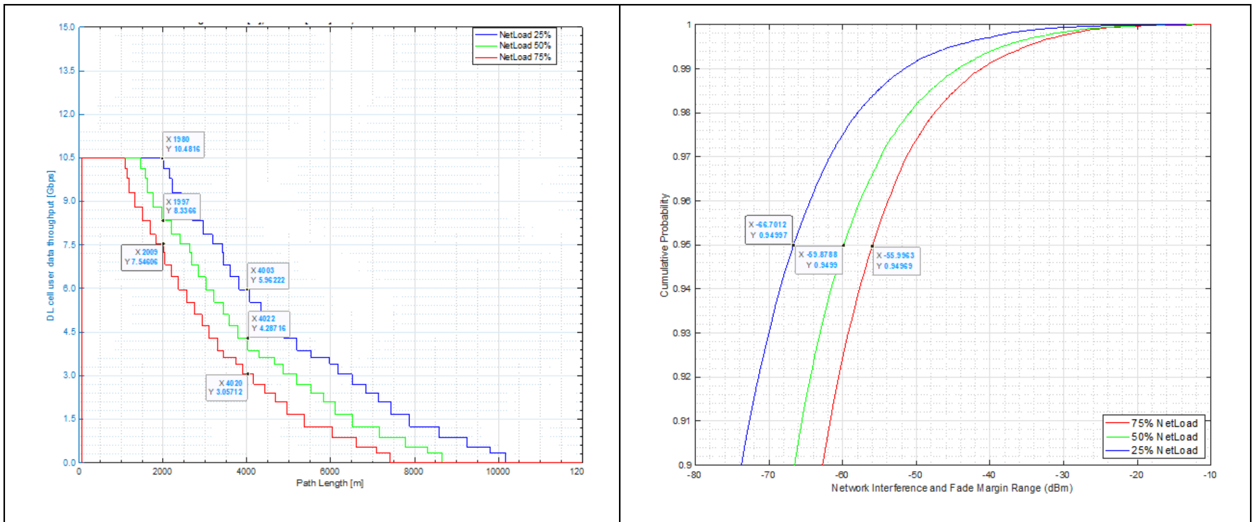
Vtilt Variation		Network Interference Variation		DL Cell Throughput Variation	
Vtilt	Gain Variation [dB]	Interference Power [dBm]	Degradation [dB]	Tput [Gbps]	Degradation [%]
0	-6	-57.8	3.7	4.3	0
-15º	-3	-59.5	2	4.3	0
-21º	0	-61.5	0	3.6	15.2

Observations:

- Due to the higher directivity of the outdoor CPE array, one beam's coverage could extend into the adjacent cell, though exceeding the target MobEdge (e.g., 4000m for the modeled case).
- No significant cell throughput degradation on the MobEdge (4000m, h_{BS}=60m), when the BS array is tilted from 0^0 down to -15^0.
- The effective user throughput degradation when the BS array is tilted down to -21º from 0º, is 0.63% (24 users per cell) or 15.2% for the entire cell.
- Frequency Reuse 1 could be effectively implemented.
- The DL SINR gets improved by ~2dB when the BS antenna tilt gets tilted by 21º. A sharper vertical beam would reduce even more the network interference power radiated towards a victim cell, thus improving the victim user's SINR and related throughput. As a consequence, a larger subarray vertical size should be used in order to optimize even more FR1 coverage (e.g., 4 subarrays each subarray being 8×4×2 antenna elements, amounting to a 16×8×2 array).
- If the BS antenna's tilt is controlled dynamically, as a function of the network load, the system interference and subsequently the cell coverage and user throughput could be optimized.

3.1.2 Network Load

The impact of network load upon the cell performance in terms of cell (user data) throughput is analyzed, while holding BS Vtilt constant (-15º). We compare the cell throughput and the CDF of the network interference for NetLoad=25%, 50% and 75%, see Figure 5. The quantitative results are summarized in Table 8.



a. Comparative DL cell (user data) throughput

b. Comparative network interference impact

Figure 5. Comparative network interference impact upon (a) DL User Data Throughput and (b) Network Interference (expressed as CDF), impact for 25%, 50% and 75% network load (Outdoor scenario, 95% Service Availability , h_{BS}=60m, 3.7GHz)

Table 8. NetLoad impact upon overall cell radius (user data only), for h_{BS}=30m (MobEdge=2000m) and h_{BS}=60m (MobEdge=4000m).

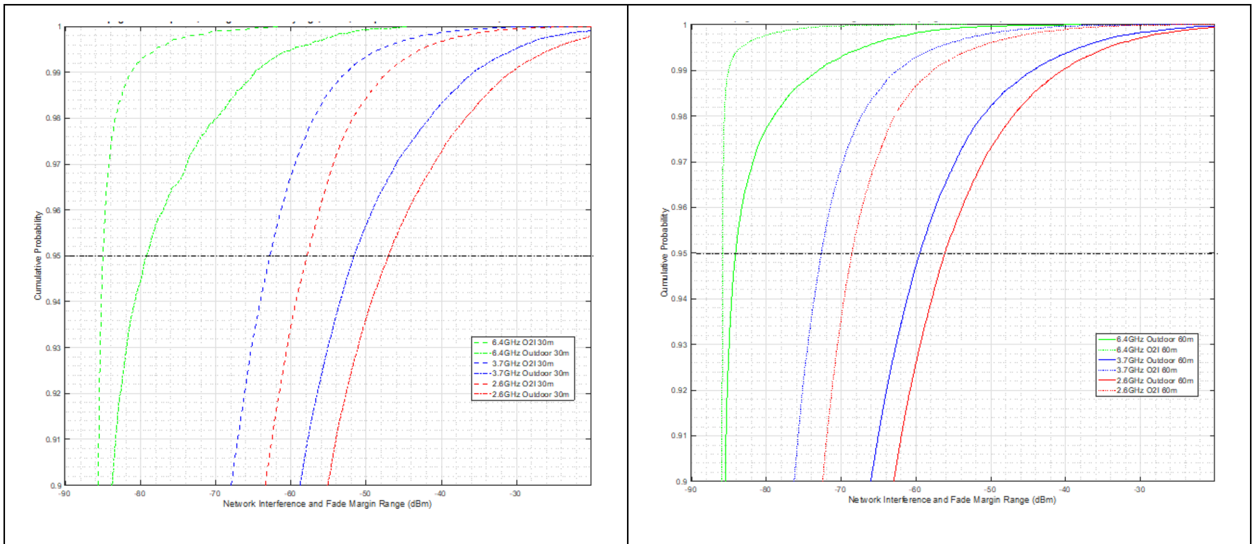
	Cell Radius=2000m		Cell Radius=4000m (DL edge)	
NetLoad	Cell Tput [Mbps]	Variation	Cell Tput [Mbps]	Variation
25%	10481	0%	5962	0%
50%	8336	-21.5%	4278	-28.3%
75%	7540	-28.1%	3057	-48.8%

Observations:

- Cell throughput gets degraded by 48.8% (h_{BS}=60m, MobEdge=4000m) and by 28.1% (h_{BS}=30m, MobEdge=2000m), when NetLoad is increased from 25% up to 75% on the cell radius.
- The higher is the netload, the lower is the cell coverage and user/cell throughput.
- The coverage and throughput degradation caused by the increased network load highlights the significance of steering 5G antenna arrays, dynamically updating Vtilt as a function of network load, across a cluster of cells accordingly.

3.1.3 BS Antenna Height

The network interference impact caused by low and high BS antenna heights (h_{BS}=30m and h_{BS}=60m), outdoor and O2I scenarios, for the 3 frequencies of interest (2.6, 3.7 and 6.4GHz) is analyzed. Summary results are presented in Figure 6. The quantitative results are summarized in Table 9.



a. h_{BS}=30m

b. h_{BS}=60m

Figure 6. Comparative network interference impact for outdoor and O2I scenarios (network load 50%, 95% service availability, Vtilt=-15^0, 2.6, 3.7 and 6.4GHz), h_{BS}=30m and 60m.

Table 9. Comparative BS antenna impact upon network interference power impact upon victim cell (2.6, 3.7 and 6.4 GHz).

	h_{BS}=30m		h_{BS}=60m		Degradation	
Central Frequency	Outdoor	O2I	Outdoor	O2I	Outdoor	O2I
2.6 GHz (ChBW=100MHz)	-47.2	-58	-56.3	-68.6	9.1	10.6
3.7 GHz (ChBW=100MHz)	-51.8	-62.9	-60	-72.8	8.3	9.9
6.4 GHz (ChBW=80MHz)	-79.5	-85	-84.2	-85.8	4.7	0.8

Observations:

- Mobile Cell Edge of 2000m is chosen for h_{BS}=30m , which triggers a higher network interference impact upon the victim cell than h_{BS}=60m (MobEdge 4000m). DL SINR is degraded as follows, when remote head (RH) height is reduced from h_{BS}=60m down to h_{BS}=30m:
    - Outdoor scenario: 9dB (2.6GHz), 8.3dB (3.7GHz) and 4.7dB (6.4GHz).
    - O2I scenario: 10.6dB (2.6GHz), 9.9 (3.7GHz) and 0.8dB (6.4GHz).
- The 2.6GHz system is subject to the highest network interference, among all considered scenarios, due to the lowest propagation losses vs. 3.7 and 6.4GHz cases.
- The outdoor 6.4 GHz system operates as a quasi interference free system, due to the lower EIRP density: 27dBm/10MHz vs. 50dBm/10MHz (2.6 and 3.7GHz).
- The network interference for the O2I case is lower than for the outdoor one, due to the additional O2I propagation fading impact.

3.1.4 Small-Scale, Large-Scale Fading and O2I Loss

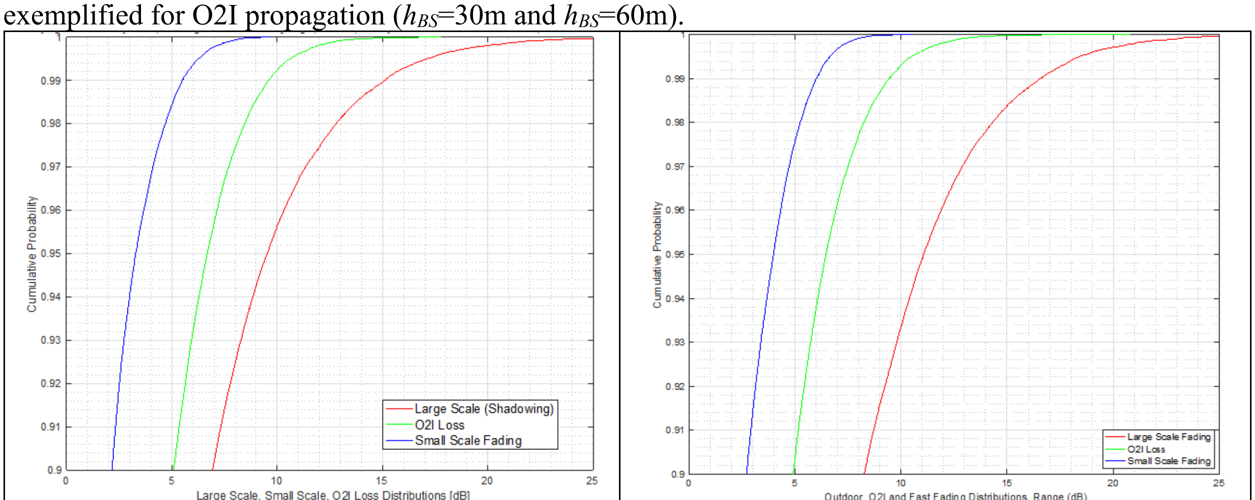
The O2I propagation is subject to 3 different types of fading mechanisms:

- Large-scale fading, also known as shadowing

        - The propagation delay is larger than the coherence time of the channel, hence the resulting received amplitude and phase are quasi constant. This type of fading is mainly caused by obstruction of the main path (e.g., shadowing, path loss).
- Small-scale fading
        - This is due to the multipath components in the propagation channel. The multipath arrived at the receiver can be constructive or destructive depending on the phase of each multipath, which cause the signal strength variation.
    - The small-scale Fading was modeled by a Rice distribution (K=12 dB) for LOS conditions and by a Rayleigh distribution for NLOS conditions.
- O2I loss is a Gaussian distribution centered on the mean value of the outer wall. It was assumed that the indoor CPE is positioned 1m behind the closest outer wall to the serving BS. The O2I fading does not apply for the outdoor scenario.

It should be noted that the Doppler spread fading, affecting mobile communications, doesn't impact FWA propagation.

All these three fading/loss mechanisms are modeled by three different distributions, which are summed up statistically, following 100,000 random victim CPE locations. The cumulative loss is further calculated by applying CDF function for the target service availability. The three distributions presented above are exemplified for O2I propagation (h_{BS}=30m and h_{BS}=60m).



a. h_{BS}=30m b. h_{BS}=60m

Figure 7. CDFs of Large-Scale, Small-Scale and O2I fading, for an O2I Propagation Scenario (h_{BS}=30m and h_{BS}=60m)

The following table summarizes the quantitative analysis. The channel is more likely in LOS condition with the smaller cell radius with 30m BS height. Thus, the large-scale and small-scale fading at 30m h_{BS} are relative smaller than that at 60m h_{BS}.

Table 10. The Link Budget Penalty Caused by Different Types of Fading Encountered by O2I Propagation (h_{BS}=30m and 60m)

	h_{BS}=30m			h_{BS}=60m		
Service Availability	Large-scale fading (Shadowing)	Small-scale Fading	O2I loss (dB)	Large-scale fading (Shadowing)	Small-scale Fading	O2I loss (dB)
95%	9.4	3.3	6.7	11.0	6.4	6.4

99%	15.3	5.5	9.6	14.3	5.2	9.4

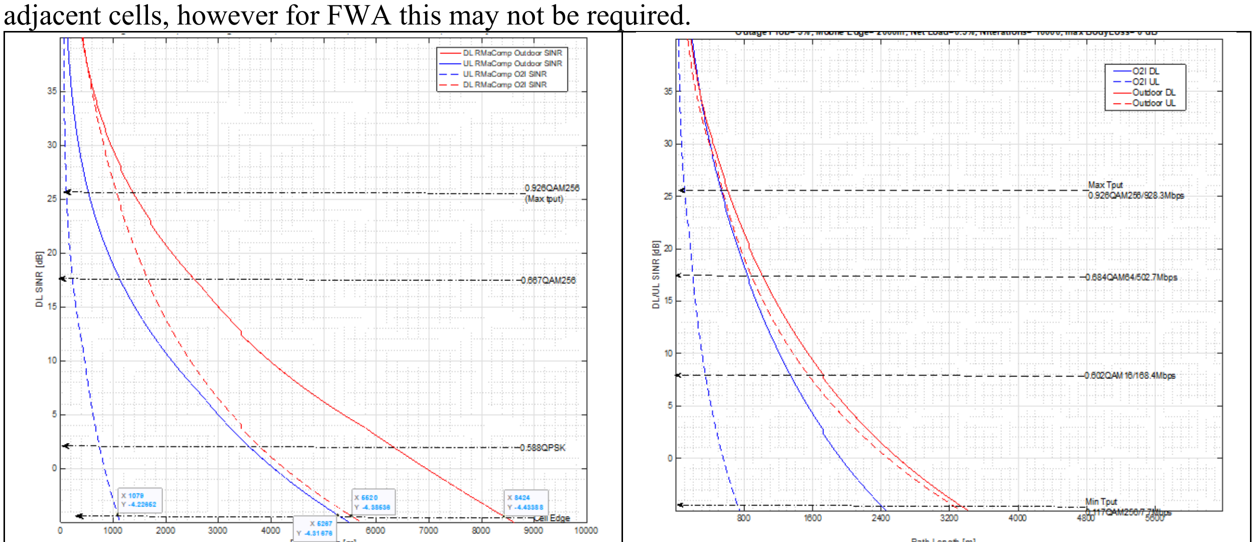
Observations:

- Large Scale (shadowing component) fading has the strongest impact among the three mechanisms analyzed, due to the NLOS propagation (Rayleigh type fading).
- The higher is the desired service availability, the higher is the composite fading impact upon the link budget.
- The O2I Loss could become the driving factor of the composite fading if the CPE is placed deep inside the house (vs. the outer wall facing the BS) and/or other construction materials used for the outer wall.
- FWA could use a lower target service availability (e.g., 95%):
    - Even for a higher service availability, the user experience impact may not be noticeable, as long as the user may not use the highest achievable allocated user data rate.

3.1.5 DL SINR and UL SNR

UL link budget is another coverage limiting factor. Usually the CPE/UE has a lower EIRP than the BS, driving to an asymmetrical link budget. This could cause coverage limitations, limited by the UL lowest MCS connection. In this section we examine the UL SNR impact upon the Cell Edge (MobEdge).

Firstly, we compare DL SINR and UL SNR for outdoor and O2I scenarios (3.7GHz, h_{BS}=60m), as presented in Figure 8. The max throughput is achieved for SINR=25.5dB (0.925 coding rate and QAM256), while the minimum throughput (cell edge conditions) is achieved for SINR=-4.5dB (0.117 coding rate and QPSK). It should be noted that the network planners may use a higher min MCS, for cell edge calculations, allowing cell overlapping in order to support seamless mobile handover between adjacent cells, however for FWA this may not be required.



a. h_{BS}=60m	b. h_{BS}=30m

Figure 8. Comparative DL and UL SNR for Outdoor and O2I Scenarios (3.7GHz), h_{BS}=60m vs. h_{BS}=30m

The coverage reduction (referenced to cell edge) is summarized in the following table. The cell coverage reduction is calculated against the respective MobEdge (for h_{BS}=60m and h_{BS}=30m).

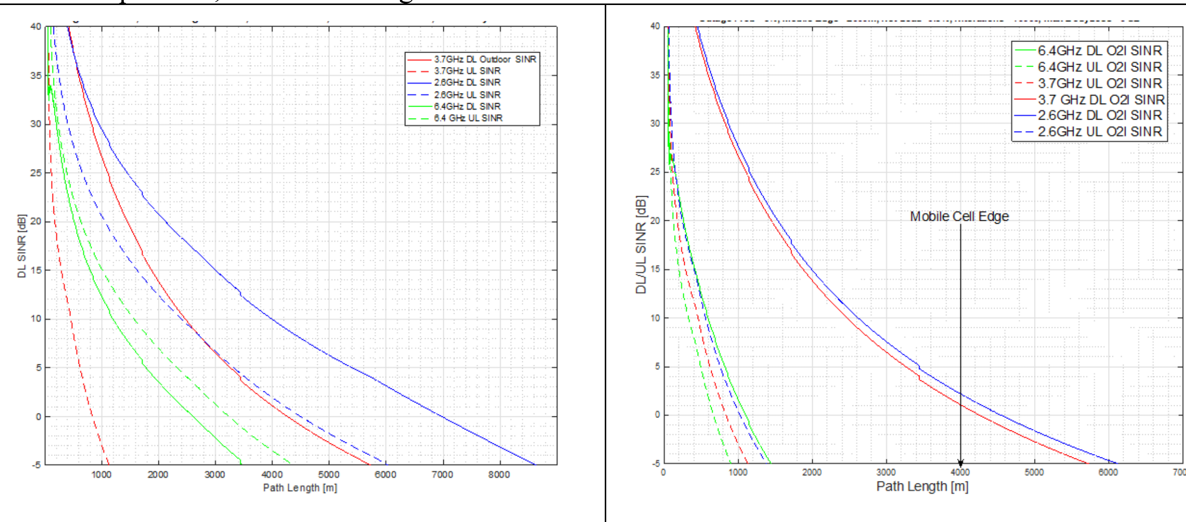
Table 11. Coverage and coverage reduction due to asymmetrical link budget (3.7GHz, h_{BS}=60m, 95% service availability, NetLoad=50%)

	h_{BS}=30m (MobEdge=2000m)			h_{BS}=60m (MobEdge=4000m)		
	Min(DL SINR)	Min(UL SNR)	Coverage reduction (%)	Min(DL SINR)	Min(UL SNR)	Coverage reduction (%)
Outdoor	3559m	3268m	16%	8424m	4316m	0%
O2I	2400m	720m	91%	5520m	1079m	92.8%

Observations:

- DL coverage is larger than the UL one for 3.7GHz, low and high RH height scenarios.
- Outdoor DL and UL coverage are in the same range for h_{BS}=30m (3.7GHz) due the increased DL interference (MobEdge=2000m).
- The O2I UL coverage is more reduced vs. DL, due to reduced O2I DL interference and the reduced indoor CPE antenna gain vs. outdoor CPE gain.

We run the same analysis, comparing the cell coverage due to the UL link budget asymmetry, for different frequencies, as shown in Figure 9.



a. Outdoor scenario

b. O2I Scenario

Figure 9. Comparative DL and UL SNR Degradation 2.6GHz vs. 3.7GHz vs. 6.4GHz, for Outdoor and O2I Scenarios (95% service availability, h_{BS}=60m).

Observations:

- The outdoor 2.6GHz coverage (both DL and UL) is slightly larger than the 3.7GHz.
- The DL interference limits the cell coverage for 6.4GHz (outdoor case), due to the close DL/UL EIRP difference (6dB) and increased UL coverage.
- The O2I coverage is severely limited by the UL coverage (poor UL link budget due to the additional O2I Loss).

3.2 Cell Coverage

The user data throughput is limited by the factors presented in section 3.1 and determined by the assumptions employed for this analysis:

- Subcarrier spacing=30kHz for all three frequencies
- 2000 slots/frame
- 4 beams/sector
- 3 sectors/cell
- 2 users/beam
- MIMO 2×2

The relationship between total user throughput and user throughput:

$$CellThroughput = BeamsSector * Sector/Cell * User/Beam * UserThropughput. \qquad Equation\ 8$$

where BeamsSector $* \frac{\text{Sector}}{\text{Cell}} * \frac{\text{User}}{\text{Beam}} = 24$. The DL comparative cell and user throughput for 2.6, 3.7 and 6.4GHz with 60m h_{BS} are analyzed.

3.2.1 Cell and User (Data) Throughput

The cell and user throughput plots are presented in Figure 10 (outdoor/O2I h_{BS}=60m). All throughput values represent user data (control and signaling data have been de-embedded).

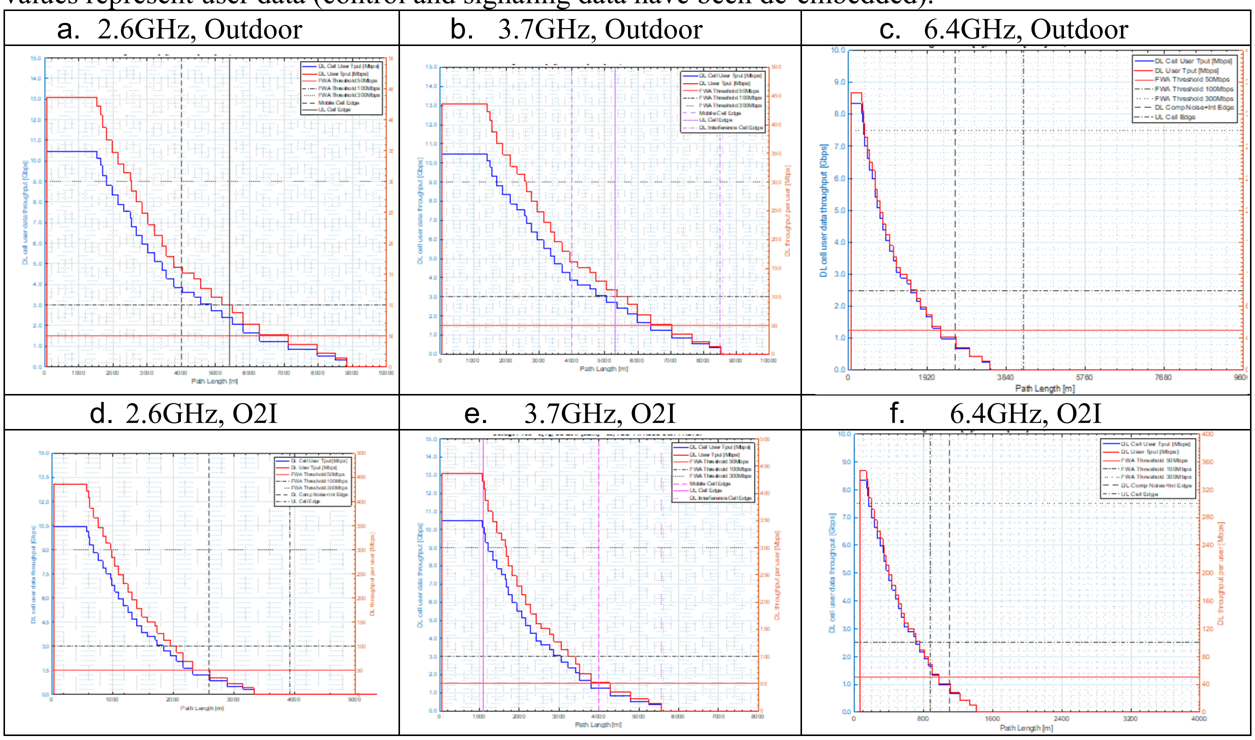


Figure 10. Comparative Cell (User Data) and Throughput per User (User Data Only), 2.6, 3.7 and 6.4 GHz, for h_{BS}=60m Outdoor and O2I Scenarios[1]

It should be noted:

- DL cell edge accounts for the DL system interference
- The throughput jagged plots are generated by the link adaptation algorithm (QAM-256 MCS table).
- The UL System interference is minimal due to the lower CPE EIRP and lower CPE antenna height (increased obstruction probability).

[1] Network Load 50%, 95% service availability, VTilt=-15^{0}

Similar plot shapes are obtained for all scenarios under consideration (30 and 60m, outdoor and O2I, 2.6, 3.7 and 6.4GHz). For the sake of brevity, we present the summarized data in Table 12 and Table 13, the limiting cell edge being highlighted. We analyze the limitations imposed on the cell edge by the following factors:

- DL cell edge, propagation and different fading and loss mechanisms limitations.
- Mobile cell edge (MobEdge) defined initially by the network planner (e.g., 2000m for h_{BS}=30m).
- UL cell edge limited by the asymmetrical link budget (DL driven).

There are 3 different cell edges. The relationship between them:

$$RealCellEdge = min(DLCellEdge, MobEdge, ULCellEdge) \qquad \text{Equation 9}$$

Table 12. Cell Coverage h_{BS}=30m (95% Service Availability, NetLoad=50%, Vtilt=-15º)

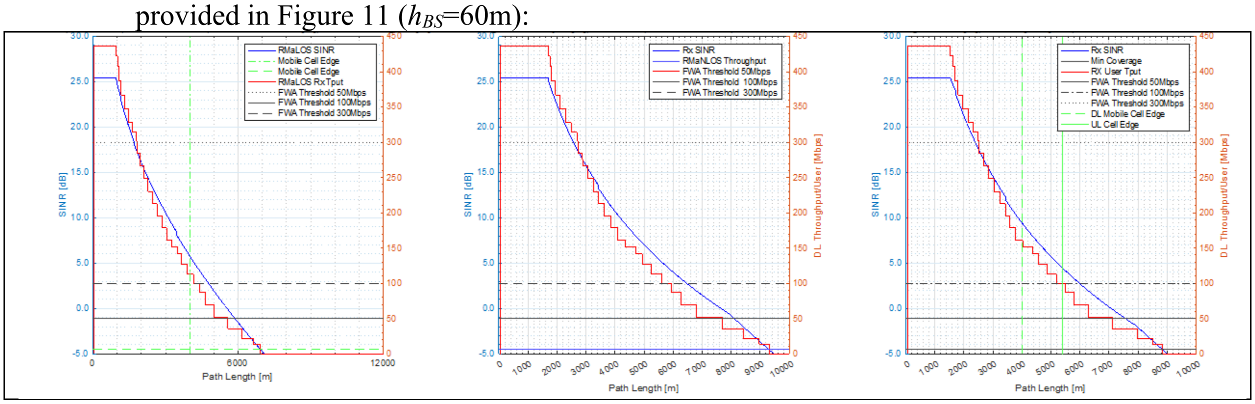
	Outdoor				O2I			
Frequency [GHz]	DL Edge	MobCellEdge	UL Edge	Real Edge	DL Edge	MobCellEdge	UL Edge	Real Edge
2.6	3276	2000	3917	2000	2125	2000	1198	1198
3.7	3331	2000	3244	2000	2402	2000	723	723
6.4	1694	2000	2832	1694	1048	2000	560	560

Table 13. Cell Coverage h_{BS}=60m (95% Service Availability, NetLoad=50%, Vtilt=-15º)

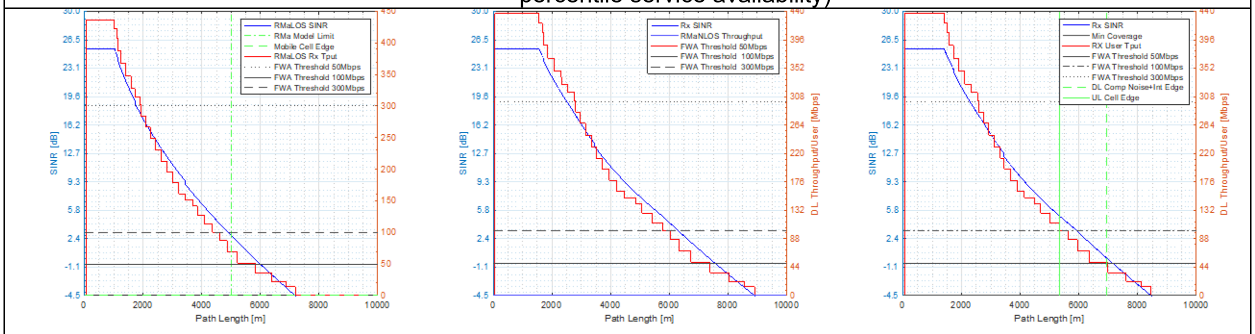
	Outdoor				O2I			
Frequency [GHz]	DL Edge	MobEdge	UL Edge	Real Edge	DL Edge	MobEdge	UL Edge	Real Edge
2.6	8846	4000	6398	4000	6002	4000	1344	1344
3.7	8461	4000	5339	4000	5572	4000	1097	1097
6.4	3436	4000	4249	3436	1395	4000	847	847

Observations:

- DL outdoor coverage is limited by the mobile cell edge (2.6 and 3.7GHz).
    - The network planner may allow a larger MobEdge than initially predicted
- DL outdoor 6.4GHz coverage is limited by the limited DL EIRP (36dBm)
- The O2I coverage is limited by UL cell edge, for all frequencies
    - The O2I coverage may require a higher CPE EIRP.
- While it may be expected to see a larger coverage for the 2.7GHz vs. the 3.7GHz case, the lower frequency advantage is partly offset by:
    - The higher interference impacting both the signal and network interference, but since SINR=SNR-I, the SINR impact may not be straightforward. A graphical explanation is provided in Figure 11 (h_{BS}=60m):



a. 2.6GHz RMa LOS, NLOS and Composite SINR and User Throughput (h_{BS}=60m, Vtilt=-15deg, 95th percentile service availability)



b. 3.7GHz Rma LOS, NLOS and Composite SINR and User Throughput (h_{BS}=60m, Vtilt=-15deg)

Figure 11. Comparative LOS, NLOS and Composite SINR and Tput, 2.6 3.7GHz[2]

We define

RealCellEdge=min{DLInterferenceEdge, ULEdge, MobCellEdge} *Equation 2*

Observations (h_{BS}=60m, h_{BS}=30m[3])

- 2.6GHz LOS coverage is smaller than the 3.7GHz one (both h_{BS}=30m and 60m), due to the higher network interference impact.
- NLOS becomes the dominant propagation mechanism because of the network interference is greatly reduced in NLOS conditions, 2.6GHz gets a larger RMa NLOS and RMa composite coverage. Overall, the 2.6GHz overall composite coverage is higher than the 3.7GHz one.
- The network interference (h_{BS}=30m) is higher for the 2.6GHz, due to the selected MobEdge (2000m).
- The outdoor 6.4GHz RealCellEdge is limited by the lower BS EIRP (36dBm).
  - The unlicensed 6GHz spectrum regulatory regulations restricts max(EIRP)=36dBm.
- Providing NR-U services in unlicensed 6 GHz spectrum may require a densified network.
- The O2I cell edge is UL limited, due to the additional UL path losses, incurred due to the O2I loss. Under these assumptions, the indoor CPE is required either:
  i) have a higher conducted RF power and/or
  ii) use a directive antenna array with a higher gain vs. an omni antenna.

However, it should be noted that increasing the indoor CPE EIRP may also increase the indoor multipath, which may require a different analysis.

3.2.2 50, 100 and 300Mbps Coverage

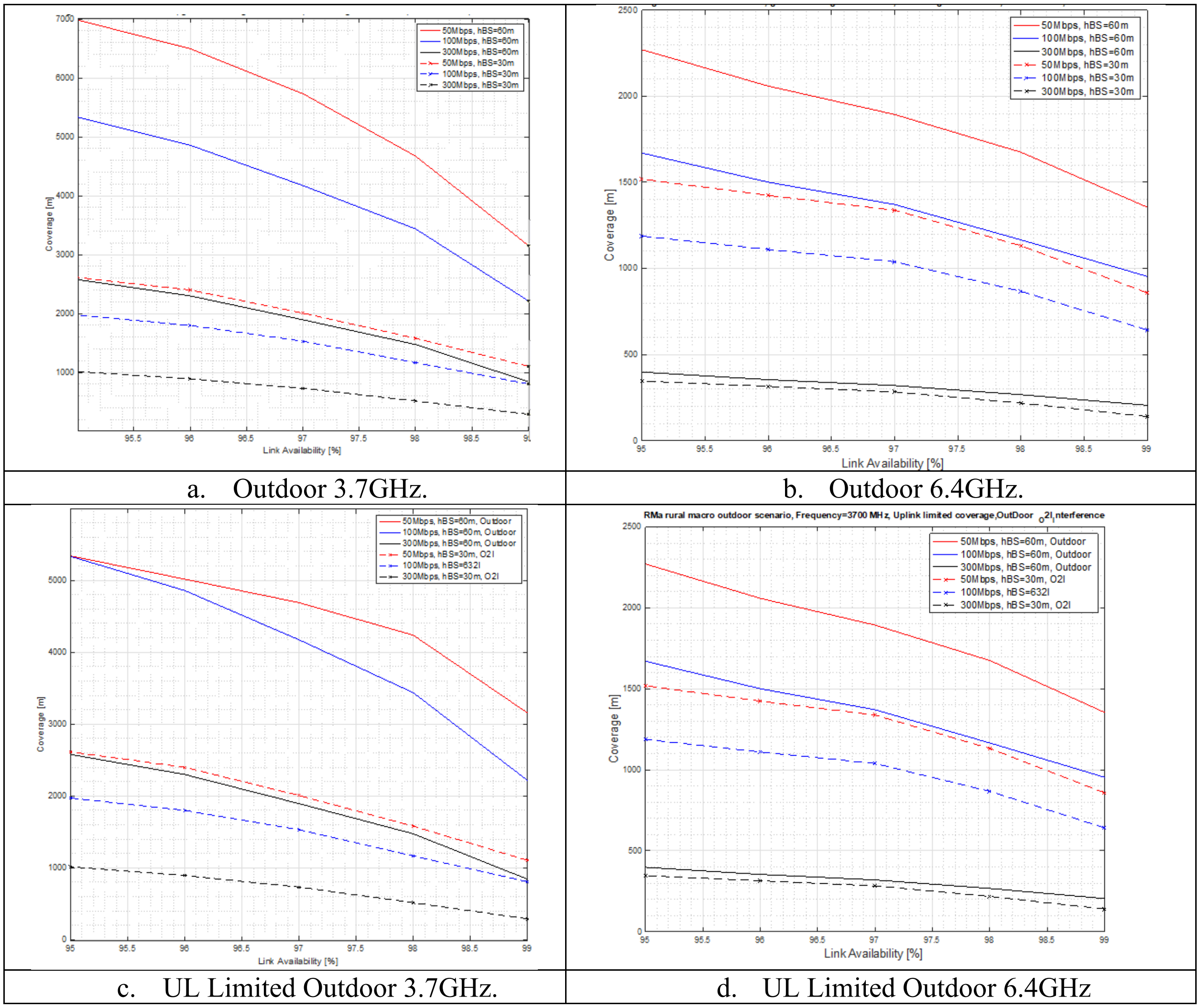
We considered the 50, 100 and 300Mbps as three different traffic tiers for FWA services. We modeled the related coverage for these tiers, for 3.7 and 6.4GHz, outdoor and O2I scenarios. We also model the impact of different service availability rates upon coverage. The outdoor 3.7 and 6.4GHz coverage vs. service availability is plotted with and without UL limitation (Figure 12), for both h_{BS}=30m and 60m.

Observations:

[2] 95% service availability, 50% network load, 60 m h_{BS}.
[3] Related plots available.

- Providing a higher target user rate availability (e.g., 99%) for outdoor 3.7GHz (same applies to 2.6GHz) a progressive coverage reduction may occur. The higher the target the service availability, the higher are the propagation losses and the shorter is the coverage.
- The higher the target user throughput (e.g., 300Mbps), the smaller is the related coverage.

The coverage reduction between 95% and 99% service availability is summarized in Table 14.



a. Outdoor 3.7GHz. b. Outdoor 6.4GHz.

c. UL Limited Outdoor 3.7GHz. d. UL Limited Outdoor 6.4GHz

Figure 12. Outdoor (30 and 60m), 3.7GHz, 50, 100 and 300Mbps Coverage

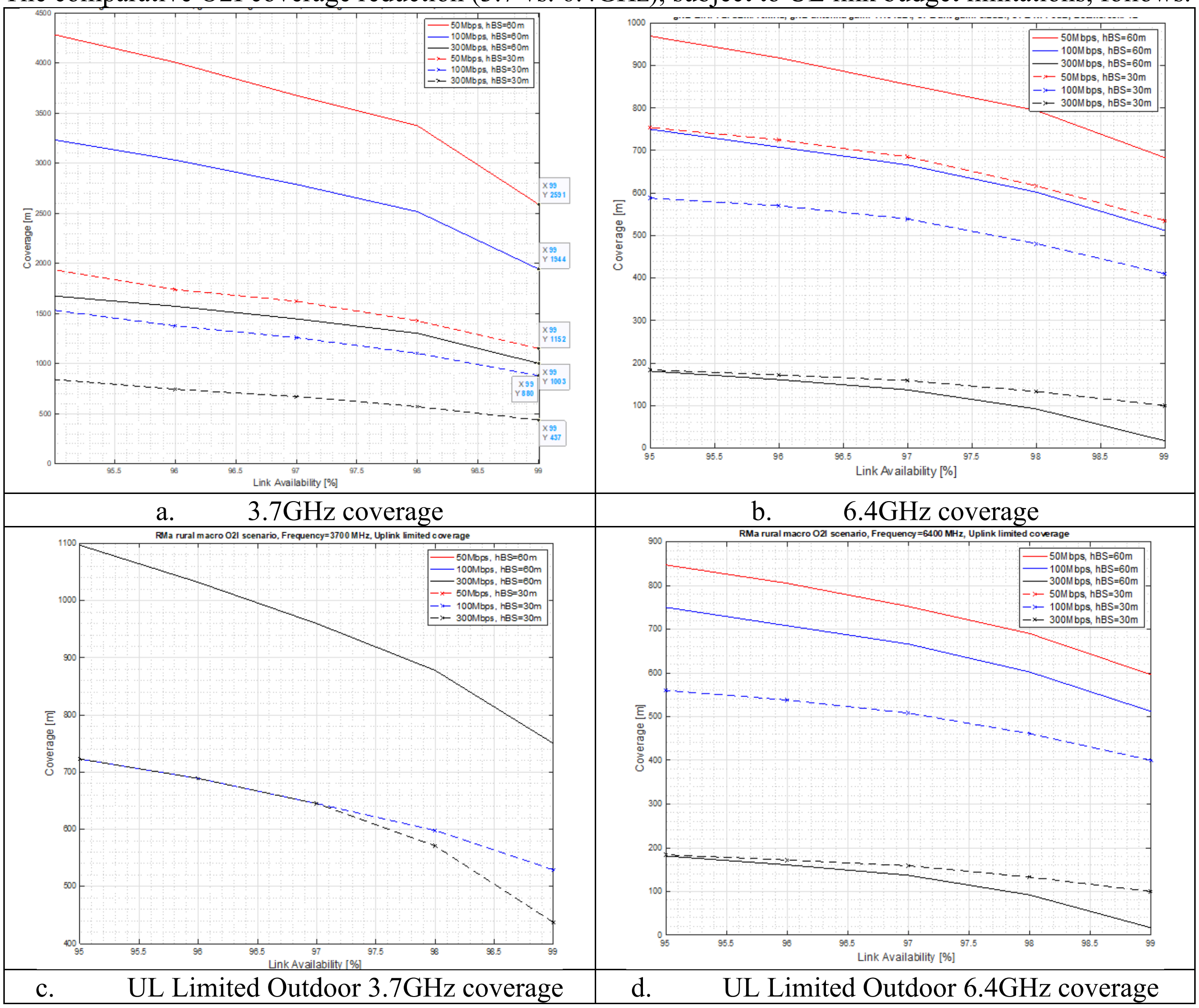
Table 14. Coverage Reduction (50, 100 and 300Mbps), for Outdoor 3.7GHz

	h_{BS}=60m			h_{BS}=30m		
	50 Mbps	100 Mbps	300 Mbps	50 Mbps	100 Mbps	300 Mbps
95%	6984	5334	2577	2613	1972	1015
99%	3156	2216	806	1104	802	290
Coverage Reduction	80.6%	82.7%	90.2%	68.6%	83.4%	91.8%

Table 15. Coverage Reduction (50, 100 and 300Mbps), for O2I (3.7GHz)

	h_{BS}=60m			h_{BS}=30m		
	50 Mbps	100 Mbps	300 Mbps	50 Mbps	100 Mbps	300 Mbps
95%	4285	3235	1676	1937	1533	843
99%	2591	1944	1003	1152	880	437
Coverage reduction	63.4%	63.8%	64.1%	64.6%	67%	73.1%

The comparative O2I coverage reduction (3.7 vs. 6.4GHz), subject to UL link budget limitations, follows.



a. 3.7GHz coverage

b. 6.4GHz coverage

c. UL Limited Outdoor 3.7GHz coverage

d. UL Limited Outdoor 6.4GHz coverage

Figure 13. Comparative O2I (h_{BS}=30 and 60m) Coverage, for 3.7 and 6.4GHz, When Subject to UL Coverage Limitations

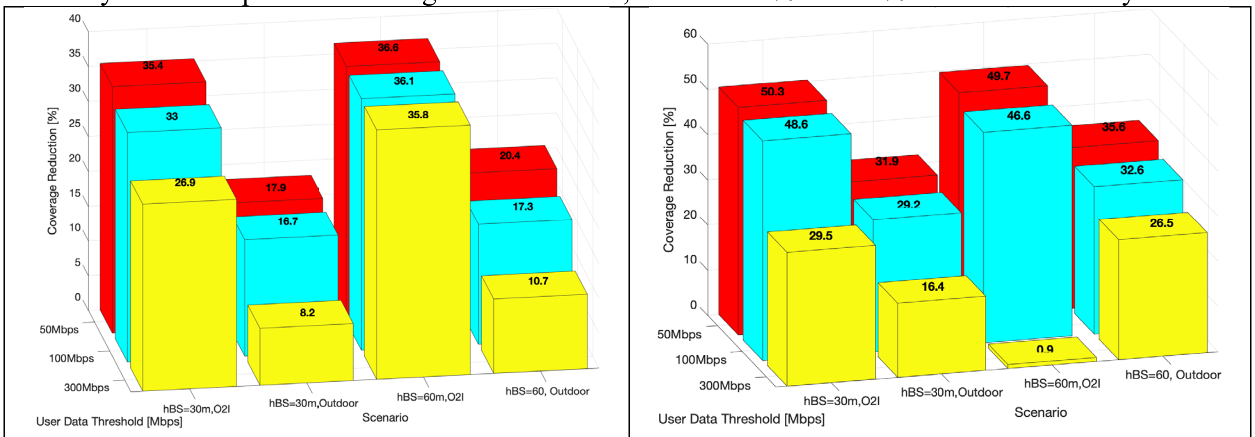
Observations:

- The O2I 3.7GHz coverage is severely UL limited, due the O2I loss.
- The O2I 6.4 GHz (h_{BS}=60m and 30m) 50Mbps related coverage is UL limited, due the UL link budget impairment caused by the O2I fading.
- The UL indoor CPE may require a higher EIRP.

The cell coverage reduction between 95% and 99% service availability is calculated:

$$CoverageReduction\ [\%] = (CellRadius(99\%)/CellRadius(95\%))\hat{}2\%100 \qquad \textit{Equation 10}$$

We analyze the comparative coverage reduction KPI, between 99% and 95% service availability.



a. 3.7GHz	b. 6.4GHz

Figure 14. Coverage reduction between target 99% and 95% Service Availability, for 3.7GHz and 6.4GHz.

Observations:

- A severe coverage reduction occurs, when the service availability is increased from 95% up to 99%, for the outdoor, h_{BS}=60m and 30m scenarios.
  - The outdoor propagation is impacted by large-scale and small-scale fading, resulting into a better coverage for service availability=95% and by a sharper reduction for 99%.
- The O2I propagation is impacted by three fading mechanisms (large-scale, small-scale fading and O2I loss), hence a relatively lower coverage (vs. outdoor coverage) for service availability=95%, and a milder reduction for 99%.
- For the 6.4GHz, O2I, h_{BS}=60m, 300Mbps case, the target service availability is practically non-existent (cell radius=17m), hence a severe coverage reduction degradation.

All of the above considerations highlight the challenges associated with high target service availability (e.g., 99%).

- However, due to the flexible 5G link adaptation algorithm, the user may not perceive the impact, since the user may not run consistently high data applications, close to the data threshold allocated for that user (e.g., most of the households may run applications demanding 30-60Mbps, while being subscribed for a 100Mbps plan).
- A FWA network planning targeting service availability=95% backed by NetLoad=50% may be a realistic target.

4 Conclusions

A variety of FWA scenarios was analyzed based on CableLabs' system simulations engine. The models used a comprehensive set of assumptions, presented in the Appendix. The simulations targeted a comparative technical performance of rural FWA networks, operating in 2.6, 3.7 and 6.4GHz, when operating with tall towers (h_{BS}=60m) and medium size towers (h_{BS}=30m).

4.1 The Impact of Coverage Limiting Factors

A. The impact analysis of different limiting factors upon coverage indicates:

1. Vertical tilt of the BS antenna array, while supporting a Frequency Reuse 1 topology (3.7GHz)
   - Due to the higher directivity of the outdoor CPE array, A beam's coverage could extend into the adjacent cell, exceeding the target MobEdge (e.g., 4000m for the modeled case).
   - The effective user throughput degradation when the BS array is tilted down to -21deg (-6dB EIPR reduction vs. Horizontal Tilt alignment) from 0deg may not be significant (0.63% per user) but the network interference gets decreased by 3.7dB.
   - Frequency Reuse 1 could be effectively implemented.
   - A sharper vertical beam would reduce even more the Network Interference power radiated towards a victim cell, improving the victim user's SINR and related throughput. As a consequence, a larger subarray vertical size could be used in order to optimize even more FR1 coverage (e.g., 4 subarrays each subarray being 8×4×2 antenna elements).
   - If the BS antenna's tilt is controlled dynamically, as a function of the network load, the system interference, the cell coverage and user throughput could be further optimized.

2. Comparative Network Load impact upon user throughput and network coverage:
   - The higher is the network load, the lower is the cell coverage and user/cell throughput.
   - The coverage and throughput degradation caused by the increased network load highlights the significance of controlling 5G antenna arrays, dynamically updating Vtilt as a function of network load, across a cluster of cells.

3. BS Array height impact upon network interference.
   - The DL SINR is degraded, when RH height is reduced from h_{BS}=60m (MobEdge=-4000m) down to h_{BS}=30m (MobEdge=2000m):
     - Outdoor scenario: 9dB (2.6GHz), 8.3dB (3.7GHz) and 4.7dB (6.4GHz)
     - O2I scenario: 10.6dB (2.6GHz), 9.9 (3.7GHz) and 0.8dB (6.4GHz)
   - The 2.6GHz system is subject to the highest network interference, among all considered scenarios, due to the lowest propagation losses vs. higher frequencies.
   - The outdoor 6.4 GHz system operates as a quasi-interference free system, due to the lower EIRP density: 27dBm/10MHz vs. 50dBm/10MHz (2.6 and 3.7GHz)
   - The network interference is lower for the O2I case vs. outdoor, due to the O2I propagation.

4. Small-scale, large-scale and O2I fading mechanisms' impact
   - Large Scale (shadowing component) fading has the strongest impact among the three mechanisms analyzed, due to the NLOS propagation (Rayleigh type fading).
   - The higher is the desired service availability, the higher is the composite fading impact upon the link budget.
   - The O2I Loss could become the driving factor of the composite fading if the CPE is placed deep inside the house (vs. the outer wall facing the BS) and/or other construction materials used for the outer wall.
   -
   - FWA could use a lower target service availability (e.g., 95%):
     - Even for a higher service availability, the user experience impact may not be noticeable (e.g., throughput), as long as the user may not use the highest achievable allocated user speed.

5. DL and UL SNR impact
- DL coverage is larger than the UL one for low and high RH height scenarios (3.7GHz).
- DL and UL coverage are in the same range for h_{BS}=30m (3.7GHz) due the increased DL Interference (MobEdge=2000m)
- The Outdoor 2.6GHz coverage is slightly larger than the 3.7GHz.
- The DL interference limits the cell coverage for 6.4GHz (outdoor case), due to the close DL/UL EIRP difference (6dB/10MHz) and increased UL coverage.
- The O2I coverage is severely limited by the UL coverage (poor UL link budget due to the additional O2I Loss).

B. Cell and User coverage analysis

1. Cell and user throughput
   - Outdoor 6.4GHz DL coverage is limited by DL EIRP (36dBm)

DL outdoor coverage is limited by the mobile cell edge (2.6 and 3.7GHz). In return, this supports a larger MobEdge.

- 2.6GHz LOS coverage is smaller than the 3.7GHz one (h_{BS}=30m and 60m), due to the higher network interference impact.
    - NLOS becomes the dominant propagation mechanism; since the network interference is greatly reduced in NLOS conditions, 2.6GHz gets a larger Rma NLOS and Rma composite coverage. Overall, the 2.6GHz overall composite coverage is NLOS driven being higher than the similar 3.7GHz coverage.
- The network interference (h_{BS}=30m) is higher for the 2.6GHz, due to MobEdge (2000m).
- The outdoor 6.4GHz RealCellEdge is limited by the lower BS EIRP (36dBm).
- Providing NR-U services in unlicensed 6 GHz spectrum may require a densified network.
- The O2I cell edge is UL limited, due to the additional UL path losses, caused by the O2I loss. Under these assumptions, the indoor CPE is required either:
    i) have a higher conducted RF power and/or
    ii) use a directive antenna array with a higher gain vs. an omni antenna.

2. 50, 100 and 300Mbps coverage
   - All service availability <99% (h_{BS}=60m, Outdoor, 3.7GHz) scenarios are impacted by the UL asymmetric link budget.
   - The outdoor 6.4GHz case is subject to no impact by the UL link budget limitation, due to the lower DL EIRP (36dBm/80MHz).
   - The higher the service availability target, the shorter is the coverage due to the higher path loss.

   - The O2I 3.7GHz coverage is severely UL limited, due the O2I loss.
   - The O2I 6.4 GHz (h_{BS}=60m and 30m) 50Mbps related coverage is UL limited, due the UL link budget impairment caused by the O2I fading.
3. Service Availability
   - Coverage is severely reduced, when service availability is increased to 99% (outdoor, h_{BS}=60m and 30m).
       - The outdoor propagation is impacted by large scale and small-scale fading, resulting into a better coverage for service availability=95% and by a sharper reduction for 99%.
   - The O2I propagation is impacted by O2I loss, hence a relatively lower coverage compared with the outdoor case.
   - For the 6.4GHz, O2I, h_{BS}=60m, 300Mbps case, the target service availability is practically non-existent (cell radius=17m), hence a severe coverage reduction degradation.

- The user may not perceive the impact of high user data rate reduction, unless the user runs consistently high data applications (e.g., most of the households may run applications demanding 30-60Mbps, while being subscribed for a 100Mbps plan).
- A FWA network planning targeting service availability=95% backed by NetLoad=50% may be a realistic target.

5 Abbreviations

3GPP	3rd Generation Partnership Project
BRS	Broadband Radio service
BS	Base Station
BW	Bandwidth
CBRS	Citizens Broadband Radio
CPE	Customer Premises Equipment
CDF	Cumulative Distribution Function
DL	Downlink
DMRS	Demodulation Reference Signal
EIRP	Effective Isotropic Radiated Power
FBR	Front-to-Back Ratio
FR1	Frequency Reuse 1
FWA	Fixed Wireless Access
gNB	5G base station
hBS	Height of the gNB antenna (remote head)
HPBW	Half Power Beamwidth
ISD	Inter Site Distance
KPI	Key Performance Indicator
LDPC	Low Density Parity Coding
LLS	Link Level Simulator
LOS	Line-of-sight
MCS	Modulation and coding scheme
MHz	MegaHertz
MobEdge	Network planner cell edge target
NLOS	Non-LOS
NR	New Radio
O2I	Outdoor to Indoor
PRB	Physical Resource Block
RH	Remote Head
SCS	Sub Carrier Spacing
SCTE	Society of Cable Telecommunications Engineers
SINR	Signal to Noise and Interference Ratio
SNR	Signal to Noise Ratio
SLL	Side Lobe Level (main side lobe level vs. main lobe boresight)
SLS	System Level Simulator
TDD	Time Division Duplexing
Tput	Throughput
UCA	Uniform Circular Array
UL	Uplink
URA	Uniform Rectangular Array

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11. TIA-10, Interference Criteria for Microwave Systems, Telecommunications Industry Association, May 2019
12. Dorin Viorel, Ruoyu Sun, Sanjay Patel, "5G FWA Technical Performance Analysis for Mid-Band Small Cell Networks," White Paper, CableLabs, Sept. 2021. [Link]

7 Appendix

7.1 Simulations Assumptions

Table 16. System And Cell Simulations Assumptions

SYSTEM	VALUE	CELL	VALUE
System interference	Per SLS feed	**Service Availability (%)**	95
Cluster of cells PLOS	As defined by [20]	**Sector/Cell**	3
Network traffic load (%)	25/50/75	**Beam/Sector**	4
O2I propagation scenario	O2I residential (TR38.901)	**Carrier aggregation**	1
Channel model	3GPP TR38.901	**Cell edge SINR (AWGN driven) (dB)**	-4.54
Number of SLS iterations	100,000	**MIMO**	2×2
Max body loss (dB)	0	**Air layer (MIMO) EIRP reduction MIMO x2 [dB]**	-3
NLOS small-scale fading	Rayleigh	**O2I path length (behind outer wall) (m)**	1
LOS small-scale fading	Rice, K=12 dB	**O2I wall material**	Wood
O2I large-scale fading	N{mean 9.35, sigma 4.4}	**Glass/outer wall ratio**	0.3
RF Waveform polarization angle	Cross-Polarized	**Central frequency (MHz)**	2596/3700/6400
NR band	n41, n77, n96	**Link Adaptation**	Enabled
Mobile cell edge (m)	2000 (h_{BS}=30m); 4000 (h_{BS}=60m)	**Modulation implementation loss**	3
ISD [m]	3640 (h_{BS}=30m) 6920 (h_{BS}=60m)		
Frequency Reuse	1		
Interference model	DL		

Table 17. BS AND CPE Array Simulations

BASE STATION	VALUE	CPE	VALUE
Antenna array		**Indoor Antenna array**	
Subarray	4x4x2	**Outdoor Antenna array**	URA 2x8x2
DL MIMO rank	2x2	**Outdoor antenna element**	Cross-Dipole
Antenna element	Cross-Dipole	**Indoor CPE height [m]**	2
SubArray structure	4x4x2	**Outdoor CPE height [m]**	4
Antenna height above clutter (m)	30 or 60	**Outdoor array boresight Gain (3.7GHz)**	16.4
Antenna array Tilt [º]	-15	**Outdoor Azimuth HPBW [deg]**	16.4
Subarray boresight gain 3.7GHz [dBi]	17.0	**Indoor antenna gain (3.7GHz)**	8.2

Table 18 PHY/RF Assumptions

BS	Value	CPE	VALUE
rmsEIRP/10MHz [dBm]	50	rmsEIRP (dBm)	30
Active users/beam	2	Noise figure (dB)	6
Sub Carrier Spacing [kHz]	30	PHY Oversampling ratio	X4
Slots/Subframe	2	DMRS symbols	1
Subframes/Frame	10	User symbols	1
TDD ratio	11:2:1		
DL Control (PCCh+DMRS) syms	2		

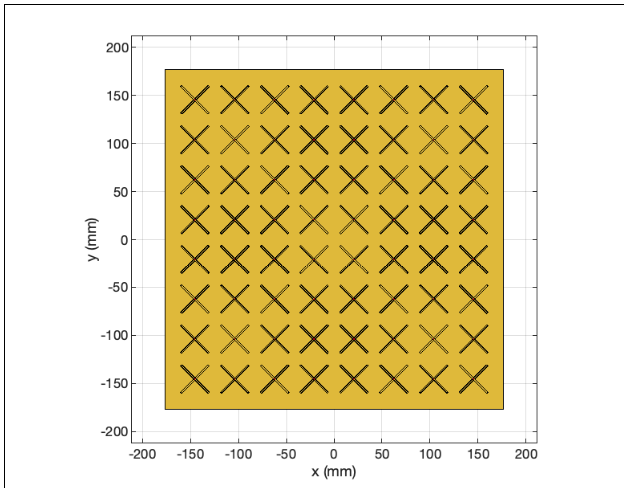
Table 19. Atmospheric/Environment Conditions Assumptions

ENVIRONMENT			
ITU rain region	Disabled	Average House Height [m]	8
Slanted path profiles	Disabled	Average Street Width [m]	20
Crane rain region	B2		
Atmospheric pressure	Sea level		

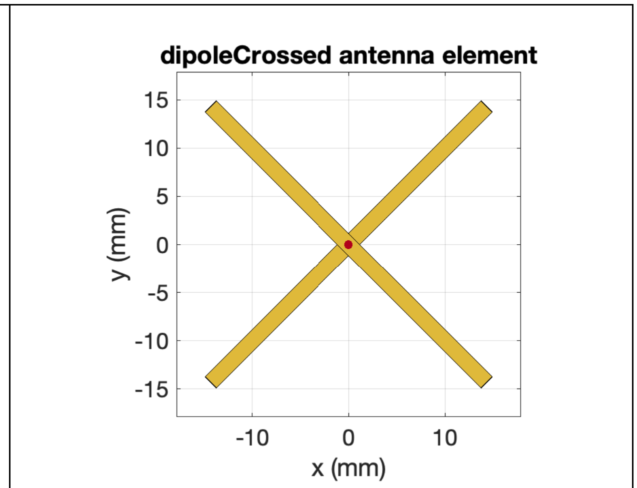
BS /CPE array assumptions could be found in section 2.1.2.

7.2 BS and CPE Antenna Array Performance Plots

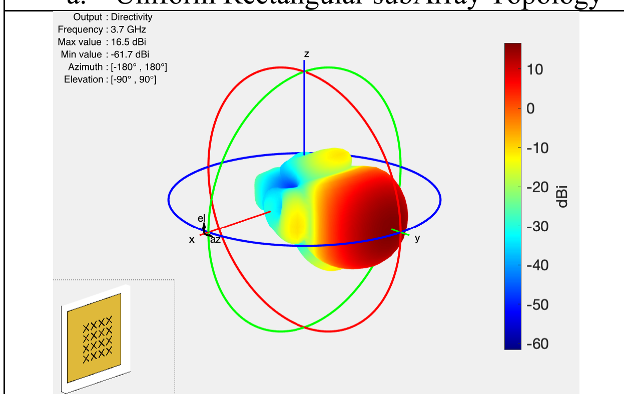
7.2.1 BS Array



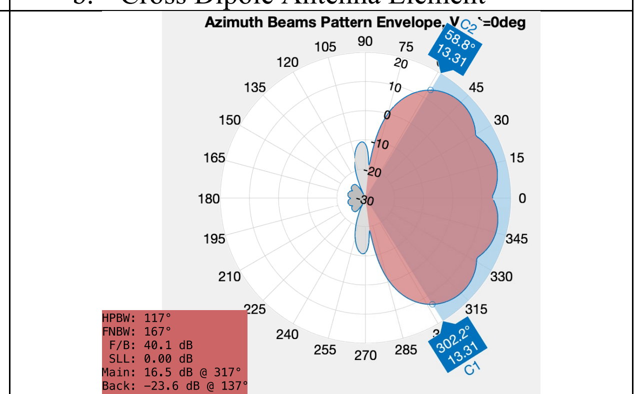
a. Uniform Rectangular subArray Topology



b. Cross Dipole Antenna Element



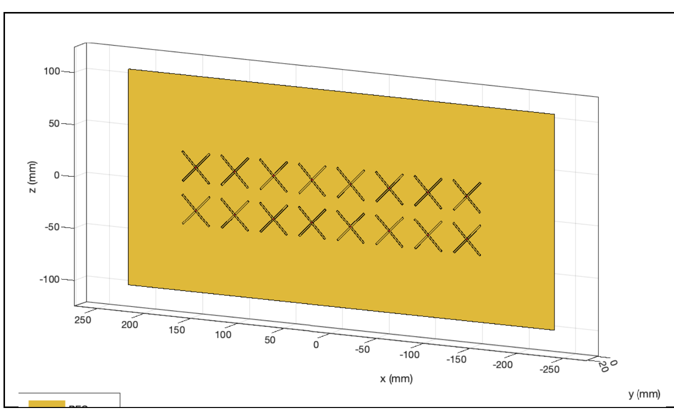
c. 3D Radiation Pattern of a 4x4x2 Subarray

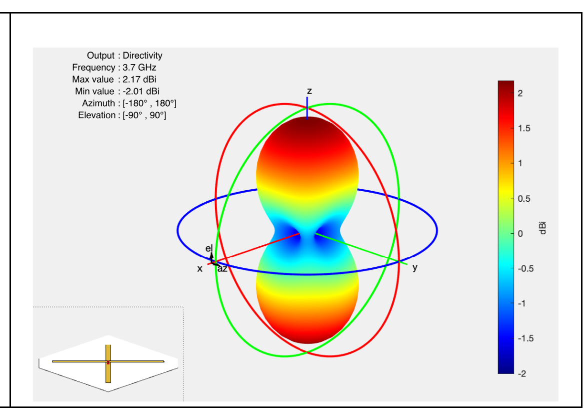


d. Multi-beam Azimuth Pattern

Figure 15. Sample of BS array parameters (3.7GHz). (a) Array geometry [2 2] subarrays, (b) Cross-Dipole antenna element geometry, (c) 3D radiation of a subarray (4x4x2) and (d) multi-beam azimuth radiation pattern.

7.2.2 CPE Array





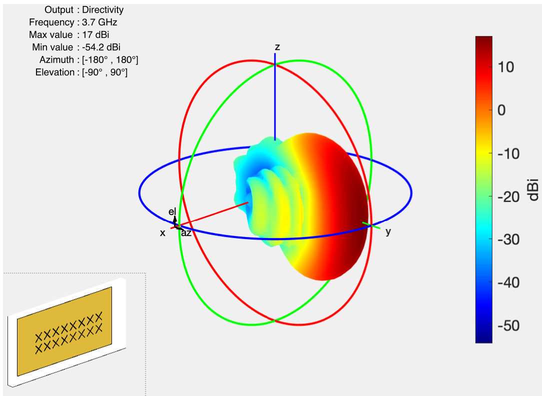
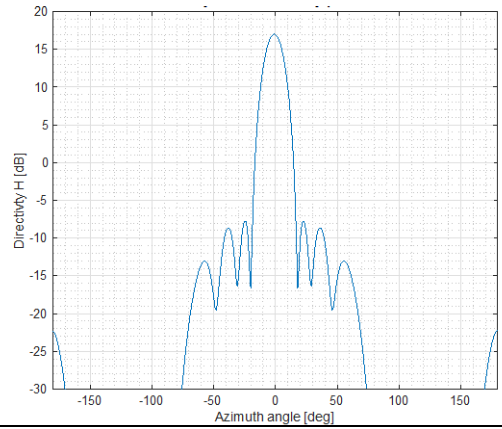
<table>
<tr><td>a. Outdoor CPE array geometry.</td><td>b. 3D pattern (cross-dipole element)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>c. 3D radiation pattern (CPE outdoor array).</td><td>d. Azimuth radiation pattern.</td></tr>
</table>

Figure 16. Sample of Outdoor CPE Array Parameters (3.7GHz). (a) Array Geometry, (b) 3D Pattern of the Cross-Dipole Antenna Element, (c) 3D Radiation Pattern of the CPE Array and (d) Azimuth Radiation Pattern (Rectangular Coordinates).