Can Wireless Compete With Wired Access To The Home

A Review of Fixed Wireless Acess Technology And Economics

A Technical Paper prepared for SCTE•ISBE by

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Introduction

Consumer demand for home broadband access continues to be strong. Network operators are looking to grow their revenue by expanding services they offer. Home broadband offers that revenue growth opportunity.

1. Operators can expand home broadband services to unserved and underserved communities. Rural markets are one example of underserved communities.
2. For some network operators, even communities served by existing Internet service providers are attractive target for business expansion. These operators bring something new to the market, like higher data rate or lower cost or some other valuable feature.

When thinking about greenfield opportunities, operators must consider technology options available to them. Below we compare technology options for providing home broadband service.

Table 1 - Broadband access technology comparison

Technology	Unserved/Under-served (mostly rural markets)	Urban and suburban markets
DSL	It is expensive to build out DSL plant in rural areas since there is limitations on how far from central office can the plant be extended. Laying new copper is also an expensive proposition	DSL is less competitive with DOCSIS or fiber in more urban markets. For instance, maximum rates offered by VDSL2 could be greater than 100 Mbps with a range of around 500m from DSLAM node. G.fast promises higher data rates for shorter straight loops. For instance, 600 Mbps for 200m distance. Speed limitation start kicking for longer distances. There is no viable path for bit rate evolution beyond that.
DOCSIS HFC	May not be cost effective to expand cable plant into rural areas	DOCSIS 3.1 FD offers 10 Gbps shared downstream capacity. It is an attractive option but fiber and 5G offerings could disrupt DOCSIS also.
Fiber	Running new fiber to rural communities can get very expensive	Fiber is the leading medium for data transmission with virtually unlimited bandwidth. However, green field FTTH installations may not be economically viable. Similarly upgrading HFC or DSL plants to FTTH may only be feasible for selected communities
3GPP wireless (LTE/5G)	Since there is no need to run copper or fiber over long distances, 3GPP wireless constitutes an economic option to provide rural broadband service	New technologies like massive MIMO and availability of more spectrum in 5G mmWave bands enhance available capacity and range of a single cell site. This improves business feasibility of fixed wireless access FWA services. New operators can disrupt existing DOCSIS and fiber-based offerings. Established operators should study leveraging 3GPP wireless to defend and grow their business.
Proprietary wireless	Wireless is an attractive option for rural broadband. However, operators should consider issues when using proprietary wireless technologies. These technologies are not standards based, they may be limited to one vendor, have smaller ecosystem, an uncertain roadmap & lack of economies of scale. Compared to 3GPP, these technologies may not offer same level of quality.	Whether rural or urban, proprietary technologies face similar hurdles.

In this paper, we focus on 3GPP based FWA, as a promising technology for future home broadband access. We investigate the following in coming pages:

1. Can today's wireless technology support FWA.
2. Is there a viable business case for FWA as compared to alternatives (DOCSIS, FTTH).
3. Do any network operators have profitable FWA home broadband business.

Reasons for FWA Momentum

Several factors are coming together, boosting industry push for FWA:

1. Technology advances: Higher order modulation, massive MIMO, beamforming, carrier aggregation, multiple user MIMO are some of the features in LTE that are improving spectral efficiency of LTE. This has the dual effect of improving system capacity, but also cell edge bit rates – suitable for FWA. 5G adds further improvements to spectral efficiency by leaner air interface design.
2. Spectrum is the lifeline of wireless access. New spectrum has become available in mid band and higher bands. This spectrum offers wider channels and thus order of magnitude higher throughput than traditional cellular and PCS bands. LTE also allows use of unlicensed frequencies in 5 GHz band in conjunction with licensed bands to further uplift data rates.
3. As more and more network operators include FWA in their consumer offerings, a device and terminal ecosystem has developed. FWA offerings started in developing countries where high speed wireline infrastructure is lacking. That has helped to nurture the FWA ecosystem for everyone.
4. Governments realize the productivity gain and development effects of broadband connection availability to all citizens. Governments at many levels (federal, state, city) want to encourage deployment of high-speed home broadband in their jurisdictions. US federal government CAFII initiative is an example of subsidizing build out of rural broadband networks. CAFII program encourages network operators to ramp up broadband deployments in un/under served, mostly rural or exurban areas.

Fixed Wireless Access Network

FWA largely reuses MBB network architecture, with similar nodes as mobile broadband sans network features related to terminal mobility.

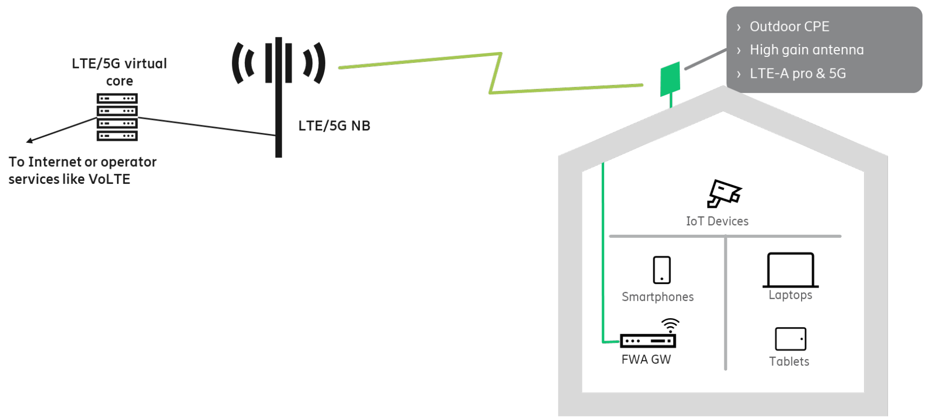


Figure 1 - Fixed Wireless Access network

LTE or 5G or dual LTE/5G CPE is installed on the rooftop of the home. This is typically a professional installation. Some operators offer indoor CPEs which are self-installed by the homeowner. Outdoor CPE has high gain antenna and LTE/5G modem to provide connection towards nearest LTE or 5G base station. Operators may provision an FWA GW inside home or integrate it with the outdoor CPE. FWA GW provides home broadband management functionality to the operator.

FWA network comprises of standard 3GPP architecture with an LTE/5G base station and core network. Operator can choose their own deployment strategies. Some considerations below:

1. Dedicated base station and frequencies for FWA or sharing base station and frequencies between FWA, MBB, IoT and other operator services
2. Dedicated core network for FWA or shared with other operator services
3. Physical or virtualized core and radio base station
4. Placement locations of radio and baseband processing of base station, as well as user and control plane components of core network
5. Type of transport between remote (base station) site and aggregation and data center sites.

FWA may require different architectural optimizations different from MBB. For instance, both user plane and control plane design of core network could be different for FWA subscribers. FWA service has fewer non-mobile supported users, thus lower control plane load and light-weight control plane nodes. On the other hand, data consumption is higher in the user plane. A more distributed user plane would be beneficial to improve network performance and reduce transmission costs. Similarly, centralizing baseband processing may not provide baseband pooling gains due to fixed nature of traffic. A centralized baseband pool may also increase fronthaul transmission costs.

Spectrum Options for FWA

Spectrum is the lifeblood of wireless communications. Not all spectrum is the same. Table below summarizes spectrum options commonly used for FWA.

Table 2 - Spectrum for FWA

Frequency	Benefits	Challenges	Availability
Mid band FDD (PCS, AWS etc.)	Widely available ecosystem Licensed Good propagation	Fully utilized in urban and suburban areas Narrower channel bandwidths	Now
2.5 GHz TDD	~200 MHz of licensed spectrum Best propagation amongst TDD spectrum US ecosystem available today Highest predictability due to licensed spectrum	Cost of acquiring spectrum Majority of spectrum in populated areas is owned	Now
3.5 GHz CBRS	150 MHz of spectrum Global LTE ecosystem Good balance between propagation, power and reuse Interference managed via SAS (Spectrum Access System)	Spectrum demand in urban and suburban areas	Late-2019 as defined by CBRS ecosystem certification timelines
5 GHz	555 MHz of spectrum	Propagation challenges - Maximum of 36 dBm EIRP. Prone to interference due to contention-based access method	Today
5.9 GHz-6.425 GHz	500 MHz of spectrum	Will likely follow unlicensed framework established for 5 GHz	Estimated 2022
24 GHz – 39 GHz	Channels of 100 MHz possible Carrier agg of 400 MHz or more	Significant challenges - propagation	Starting mid-2019
57 GHz – 71 GHz	14 GHz of spectrum Suitable for point-to-point	Significant challenges - propagation and atmospheric absorption	Partially Today; Partially in 2022

Operators providing MBB services could use any of the spectrum above for FWA depending on utilization of their spectrum resources. Greenfield operators could start off with CBRS spectrum in combination with 5 GHz band and perhaps also upcoming mmWave high bands.

Carrier aggregation of LTE/5G bands becomes a critical feature for FWA services:

1. There may not be enough spectrum in one band

2. Spectrum may not be contiguous
3. Combining high bands with lower bands improves cell edge rates
4. Higher peak and average rates can be offered

Starting Up and Evolving FWA Network

As network traffic grows and as operator offer higher rate broadband services, there will be a need to enhance and upgrade the FWA network. Operator with existing cellular assets could follow a network strategy as below.

1. Use existing MBB cell-site infrastructure for FWA sites, by just adding carriers or slices for FWA. This enables cost effective start up for FWA services

2. Install outdoor CPEs on rooftops of homes or on sides of buildings. Outdoor CPE enable better coverage, longer range and higher system capacity

3. For many existing operators, legacy bands are fully occupied by MBB DL traffic. There may still be capacity left over, specifically in the UL portion of FDD bands that could be given to FWA traffic

4. Operators could upgrade legacy FDD bands to 4T/4R configurations or even FDD massive MIMO to squeeze more network capacity out of legacy FDD bands

5. Operators could add TDD band in 2.5 or 3.5 GHz (with massive MIMO radios). TDD bands are well suited to FWA. Spectrum costs tend to be lower and TDD profiles could match asymmetric downlink heavy nature of home broadband traffic

6. Operators can add mmWave 5G sites in high traffic demand areas on poles to offload FWA traffic from larger macro type sites. mmWave 5G could also be used to provide very high throughput (~ 1 Gbps) service to selected neighborhoods

7. To evolve networks further and to take advantage of 5G's better spectral efficiency and operational ease, operators could upgrade 4G bands to 5G. Since operators need to support both 4G and 5G terminals, there will be a need to operate 5G network together with 4G using schemes like real time spectrum sharing. Real time spectrum sharing allocates spectrum proportionally to 5G and 4G users, as per real time usage demand, without the need to partition spectrum statically and reducing data rates for legacy 4G users

8. Operators could introduce virtualized RAN running on COTS hardware and centralize deployment and management of pieces of FWA RAN functionality

Greenfield FWA operators that do not have existing spectrum assets could start with step 5 above. Greenfield operators would need to consider their migration strategies to 5G as well. 5G migration that could be accomplished with software upgrade to 4G eNBs and 4G CPEs provide a more compelling option. Even greenfield operators must consider implications of providing 5G and 4G services on the same spectrum, as their user base migrates over time from 4G to 5G.

3GPP Data Rate Evolution

Following picture shows data rate evolution of 3GPP technologies. In LTE, this evolution is accomplished primarily by adding carrier aggregation and spatially multiplexed layers, using 4x4 MIMO and higher order modulation like 256 QAM. Carrier aggregation allows operators to bond together narrower spectrum from several frequency bands into one larger logical channel. This increases data rate to the user. 4x4 MIMO enables transmission of up to 4 layers of spatially multiplexed streams, using the same air interface time and frequency resources. Compared to single stream, 4x4 MIMO could quadruple effective data rate. Higher order modulation attempts to send more bits of information on a single OFDM symbol, thus enhancing end user bit rate.

5G NR introduces leaner air interface and wider carriers in mid (2.5-6 GHz range) and higher (> 6 GHz range) bands. Data rate enhancement support is available both in base station and UE equipment.

To provide an attractive FWA service, operators should aim to start off higher on the data rate ladder and strive to climb even higher with the right network infrastructure and terminal/CPE solution.

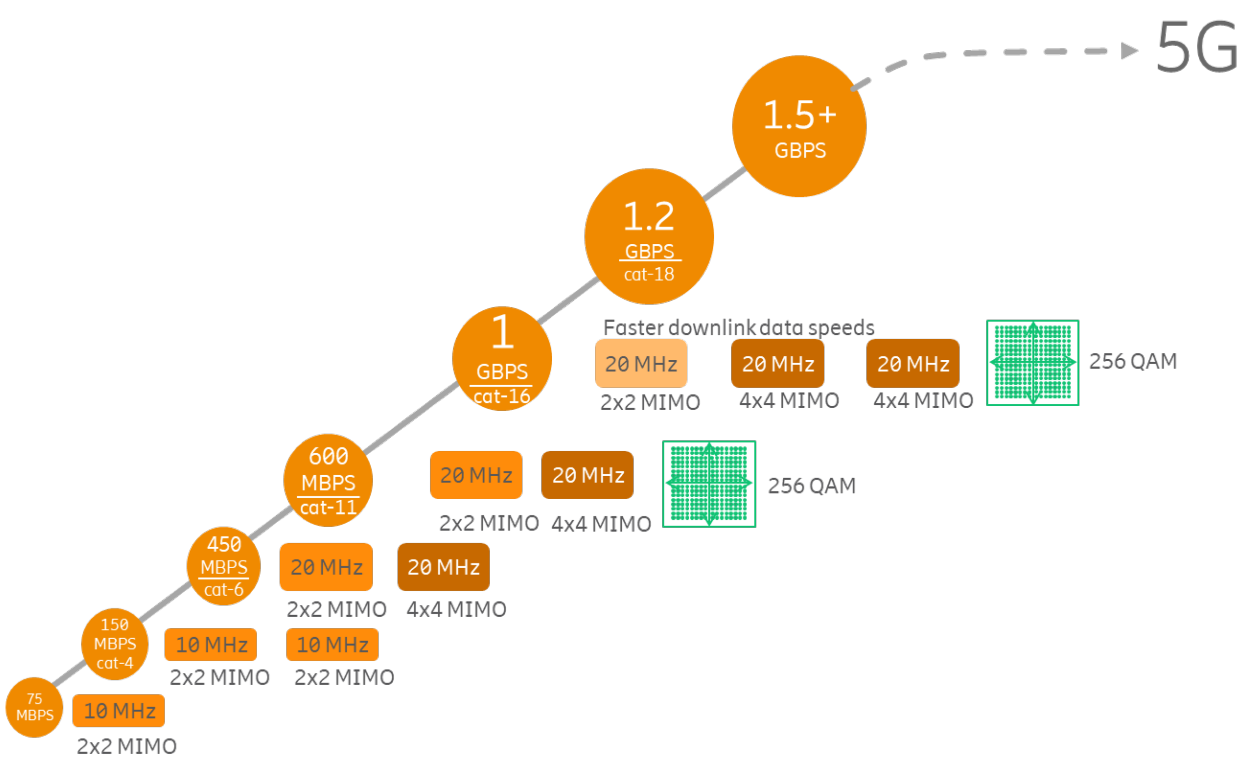
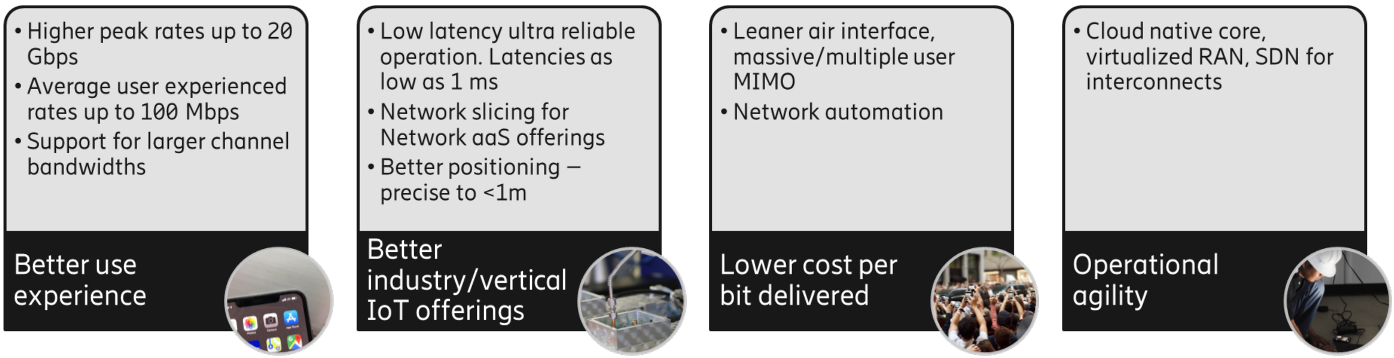


Figure 2 - LTE throughput ladder

FWA with 5G

Picture below summarizes key benefits of 5G NR.



FWA operator can utilize each one of these aspects of 5G to their benefit.

1. 5G offers much higher peak and average data rates, allowing FWA operators to offer faster speeds.
2. Converged operators, offering MBB and FWA services, can use 5G's enhanced QoS and network slicing mechanisms to better use common RAN, transport and core infrastructure and provide guaranteed FWA SLAs to their subscribers – reducing their network costs
3. 5G leaner air interface and inherent support for massive MIMO/multiple user MIMO allows operators to transmit more data using limited spectrum, reducing cost per bit delivered. Additionally, mmWave bands with higher channel bandwidths could also allow lower cost per bit of FWA data
4. Cloud native core RAN and transport virtualization, software defined networking and use of COTS hardware enables agile operations and cost-effective networks

Improving 5G mmWave Reach

mmWave spectrum offers large channel bandwidths and large amount of spectrum. This enables peak data rates up to 20 Gbps. However, propagation of mmWave spectrum is challenging and range is smaller – less than 1 km. FWA deployment of mmWave can improve on some of the propagation limitations as below:

1. 5G mmWave antenna arrays can be miniaturized, so large number of antennas can be built in mmWave radios. The antenna arrays allow use of massive MIMO and beamforming. In 5G mmWave, beamforming is used to mostly improve coverage by focusing the RF energy in the direction of intended receiver.
2. Outdoor CPEs become even more critical for 5G mmWave to avoid building penetration losses and to provide line of sight from 5G base station radio to 5G UE.
3. Dual connect operation further enhances coverage, which is typically UL limited. In NR NSA operation, UL from anchor LTE carrier in lower frequency bands could be used to improve cell range. In NR SA operation, a mid band NR carrier can be aggregated with mmWave NR carrier, further improving the effective range of NR cell. This is shown in picture below.

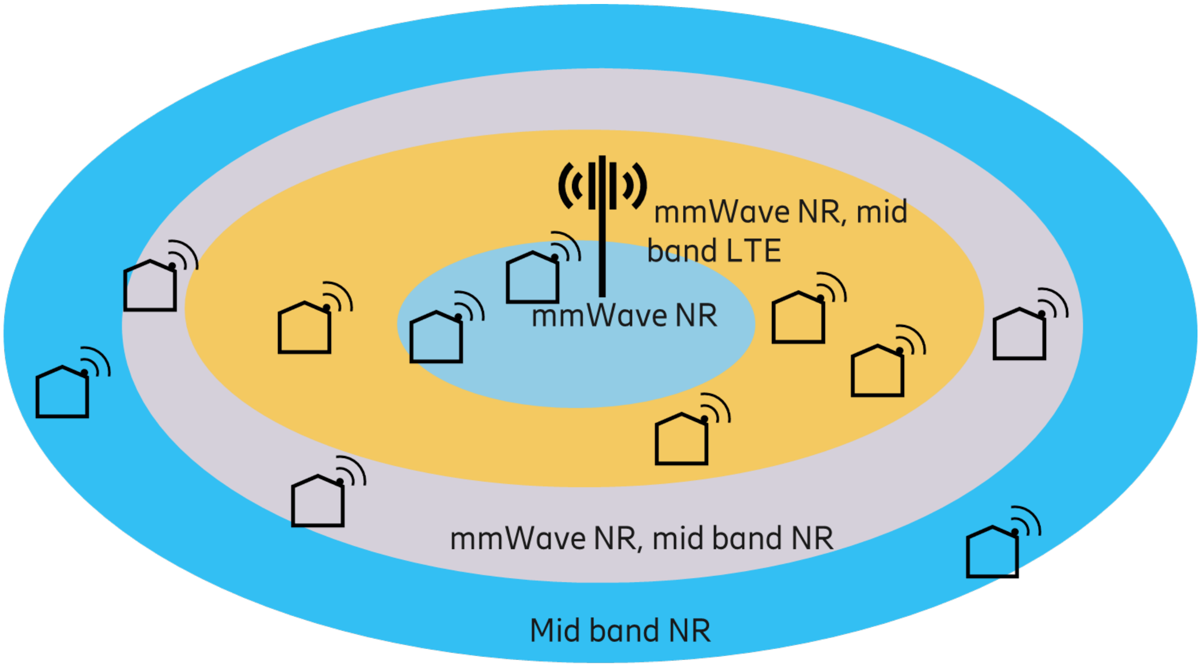


Figure 3 - Combining mid band with mmWave band

CBRS for FWA

CBRS band in 3.5 GHz spectrum could be a good option for FWA services because:

1. Relatively larger amount of spectrum is available. 150 MHz total allocated for all users. 70 MHz would be dedicated to PAL operation in a licensed mode of operation, while 80 MHz would be available for GAA unlicensed operation. GAA interference and coexistence is managed by SAS. Even though GA is unlicensed, GAA operation is expected to be more predictable because of spectrum coordination functionality provided by SAS.
2. CBRS supports TDD operation, which is well suited to FWA.
3. CBRS provides a good compromise between coverage and capacity. The nature of the spectrum allows practical implementation of massive MIMO radios in this band. Using massive MIMO radios and multiple user MIMO, capacity enhancement - even over narrower frequency bands – is possible.
4. Strong FWA ecosystem is developing in CBRS band.
5. CBRS implementations are beginning with LTE. We expect migration to 5G in CBRS from 2020.

Massive MIMO for FWA

Traditional cell sites broadcast signal from LTE sector in all directions covered by that sector. In some places, there would be users that can take advantage of the signal. But most likely, there would be many places where there are no users and the signal broadcasted spatially over wider area would be wasted. Moreover, this wide beam pattern from base station antenna causes inter-cell interference in neighboring cells. The result, from the point of view of a UE, is that total signal levels are lower, and the interference is relatively higher, resulting in a low baseline SINR. Lower SINR implies lower throughput.

Figure 4 - Coverage under broadcast beam

Massive MIMO aims to solve this problem by employing beamforming. Large number of antennas are used in the base station radio to form narrower beams at the UE location. Because RF power is focused into narrow beams, desired signal level to the UE increases. Additionally, since the cell site is not broadcasting in the coverage area of the sector for traffic channel – it only transmits narrow beams, intercell interference to adjacent cells is reduced. Consequently, SINR experienced by UE improves and so does the throughput. Beamforming tracks channel conditions and strives to maintain optimum beam structure in the cell.

For FWA service, massive MIMO beamforming is useful in enhancing SINR and improving throughputs to the CPE. However, beamforming by itself only provides marginal improvements. Even though we have a higher sector capacity X in the cell, it is still shared between CPEs served by the cell. If there are 16 CPEs served by the cell at one instance in time, each CPE would get X/16 th of the throughput. These CPEs are being scheduled in separate resource blocks as indicated by different colors of beams in the picture below, thus sector capacity is split among the CPEs.

Massive MIMO improves capacity but also coverage.

1. SINR improvement over cell edge implies cell edge could be pushed farther from the site, increasing cell range.
2. There is an indirect effect. On many occasions, DL rates are impacted by lack of UL coverage, since UL channel suffering from poor radio conditions may not be able to handle TCP flow control. TCP ACKs/NACKs may not be received from UL channel for DL data transmissions. Large number of base station RX antennas improves UL link budget, extending UL coverage, improving TCP flow control and indirectly helping DL.

5G massive MIMO beamforming adds beamforming to UE in addition to LTE eNB. This could result in further improvement in throughput.

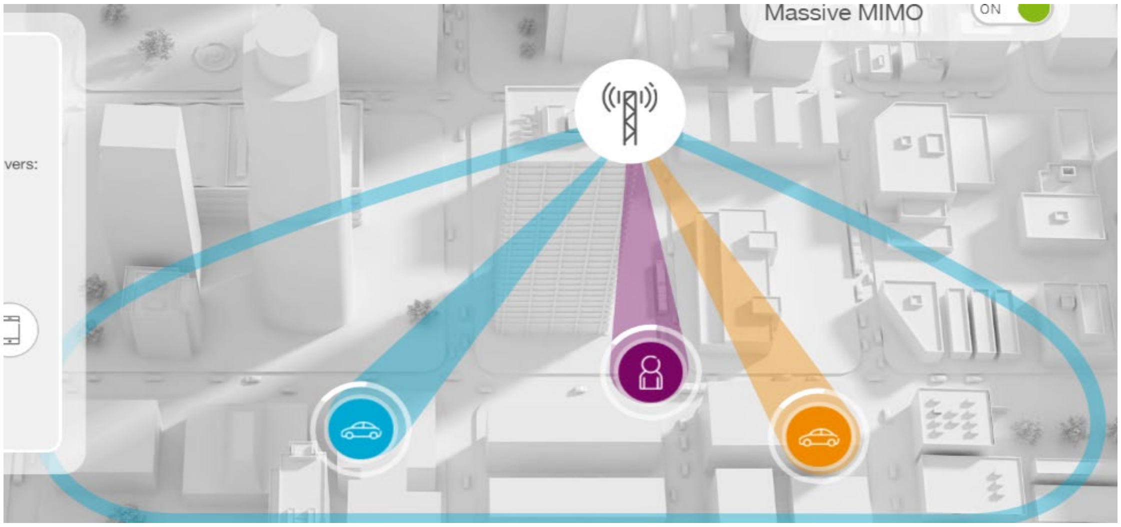


Figure 5 - Beamforming with SU-MIMO

If the CPEs are orthogonal, so that beams transmitted to the CPEs do not interfere (i.e., overlap spatially), we could allocate the same resource blocks all over again to each CPE. This is shown by the same color of beam in the picture below and is called multiple user MIMO. If the sector capacity is X and there are 16 (full-buffer) users simultaneously receiving data in the cell, each user can be assigned as much as full capacity X. There are two benefits of multiple user MIMO.

1. System capacity is enhanced. In the example above, baseline sector capacity was X with just beamforming. After adding multiple user MIMO, sector capacity becomes 16X (since each of the sixteen users is receiving data with throughput X). This is order of magnitude improvement in system capacity, compared to when a single stream was sent to the UE.
2. User throughput improves also. Depending of the SINR experienced by user, their throughput would vary. But since we are allocating potentially all RBs to each user, individual user throughput would improve. For the example above, we assume all users are in good radio conditions, each user's throughput could be as high as X, which is a 16-time improvement.

We can think of multiple user MIMO creating 16 virtual sectors inside one physical sector in this example.

One consideration for multiple user MIMO is that users need to be orthogonal or spatially separated far enough, such that beams don't overlap. A more intelligent scheduling algorithm would aim to increase UE orthogonality by exploiting not only spatial but also temporal selection of transmissions.

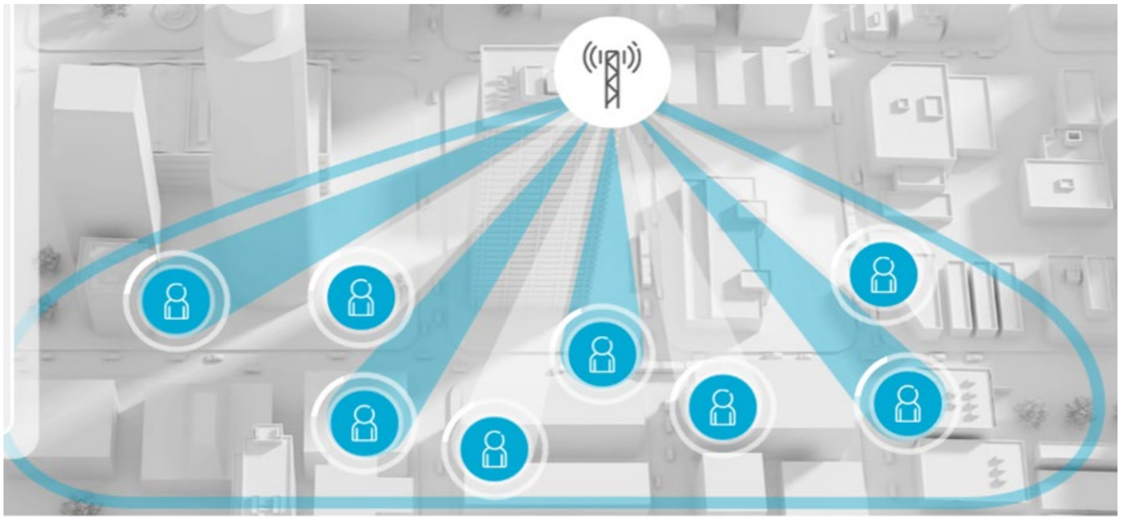


Figure 6 - Beamforming with MU-MIMO

Since home broadband offers very high data buckets, capacity enhancement of LTE/5G network is always an important consideration. This is true for high subscriber density urban and suburban areas, but also for low density rural areas. In rural areas, improvements in coverage from massive MIMO beamforming may also be of interest. See picture below from field measurements conducted by Ericsson. Here we are comparing DL throughput for 4T4R system with 64T64R systems with massive MIMO. We can see that massive MIMO systems have better range.

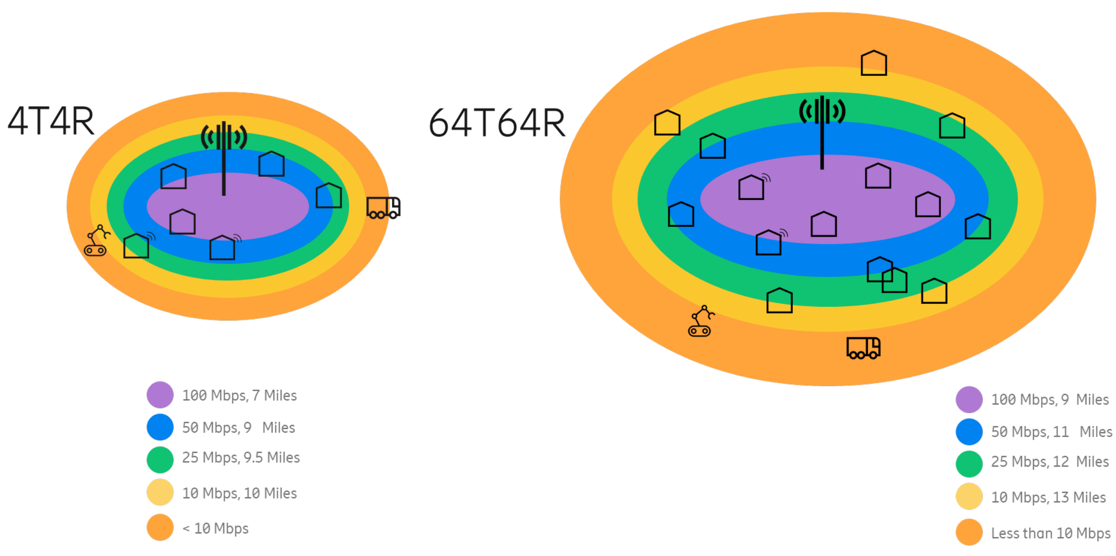


Figure 7 - Comparison of 4T4R and 64T64R user throughput and coverage

Summary of Technical Section

We summarize our discussion of FWA technology below.

1. 3GPP LTE and 5G provide compelling option for FWA services both for existing and new operators.
2. LTE and 5G FWA solutions are applicable to rural, as well as suburban and urban markets.
3. Operators can start off with LTE and then climb the throughput ladder to more system capacity and higher end user rates.
4. Especially for new operators, CBRS provides an attractive way to start up FWA service offerings
5. 5G mmWave spectrum could be useful add on to mid band FWA. 5G mmWave based FWA could also be used in urban areas on its own.
6. Massive MIMO and multiple user MIMO are key techniques to increase system capacity and FWA user throughput.

We conclude that we have the technologies and spectrum today to enable FWA services both for new and existing network operators. In later section of this paper, we show actual FWA field experiences.

FWA Business Considerations

FWA can help operators with their business challenges:

1. Existing operators that have legacy wireline networks like DSL may find it costly to maintain and to upgrade. Operators that want to expand footprint or upgrade existing capabilities could do that with wireless.
2. The yardstick from broadband has moved since subscribers consume more data and expect faster speeds. Wireless technologies can allow operators to enable fiber like capabilities.
3. In some cases, wireless could be cheaper option than deploying fiber.
4. Expanding wireline plants can be time consuming esp. when it comes to the last mile. Wireless can help operators shorten cycle time and reduce customer churn.
5. Wireless networks are multi-service. Once established for FWA, operators can use them to generate new revenue from services like MBB roaming or IoT connectivity.

FWA economics

Below we look at factors effecting economics of FWA.

<u>Cost of spectrum</u>. Licensed spectrum could be expensive. For example, operators spent upwards of 40 BUSD for AWS3 spectrum licenses. Since spectrum is expensive, it is important to squeeze maximum utility from it. One strategy is to use inexpensive unlicensed or lightly licensed spectrum for FWA such as CBRS and 5 GHz spectrum. Another strategy is to use mmWave bands for capacity. mmWave band offer large amount of spectrum for relatively lower costs.

<u>Cost of network equipment</u>. Since spectrum is scarce and expensive, operators should look at acquiring high performance base station equipment with advanced feature and functionality for FWA like massive MIMO, 5G etc. Similarly, base station sites could be expensive to procure, construct and maintain. A high-performance base station solution that maximizes coverage could also lower the overall costs of deploying and maintaining an FWA network. In previous sections, we saw system capacity improvements

from massive MIMO. Assuming a massive MIMO base station could provide 4x capacity improvement, that will translate into building 4x less sites and spending about 4x less on acquiring spectrum.

Network equipment also includes the LTE or 5G core network and any transmission and aggregation equipment in the operator transport network.

Cost of Site Acquisition and Construction could be significant and even higher than cost of network equipment on the site. Existing operators could leverage their MBB sites to lower site related costs. New FWA operators could also aim to reduce site related costs by deploying high performance base station equipment and by introducing automation in their deployment processes.

Site OPEX comprises of rent payments, backhaul costs, electricity bills and general maintenance costs. Site rent and backhaul comprise the major portion of OPEX costs. TCO for self-owned backhaul would be better than leased line OPEX over the long run. One factor to evaluate here is building of own microwave backhaul.

Cost of CPE. Operators would deploy 100x more CPEs than the number of base stations. For this reason, FWA business cases tend to be sensitive to the cost of CPEs. So, there is a need to drive down the cost of CPE. However, the specs of the CPE could impact network performance and system capacity. A lower spec inexpensive CPE may be detrimental to system capacity – forcing operator to spend more on spectrum and network infrastructure. Outdoor CPEs with high power and high gain antenna enhance network performance and system capacity. However, outdoor CPE may require costly professional installation. Indoor CPEs could be self-installed by the subscriber. On the other hand, self-install prevents operators from guaranteeing performance. Moreover, indoor CPEs may appear as cell edge user to the network, consuming larger share of air interface resources, deteriorating system performance. Operators need to weigh all the cost and performance tradeoffs before crystalizing their CPE strategy.

Technology choice could be critical for the overall business case. A technology that requires frequent upgrades could be costly and may incur disruptions to service. Along this line, effortless upgradability of LTE to 5G (via software without hardware rips) could be beneficial. Since migration of users would not happen overnight, operators should also consider coexistence of LTE and 5G users in the best possible way. Here real time spectrum sharing between LTE and 5G users becomes critical. Without it, operator may be forced to procure new spectrum for 5G.

Subscriber density impact the business case for FWA. A higher subscriber density is preferable to generate higher revenues per cell site and offset operator's network CAPEX and OPEX expenses.

Similarly, a higher market share will allow operator to generate more revenue per site. An FWA business case resting on smaller market share or lower subscriber density could be challenging.

Traffic growth projections factor into the business case in terms cost of future network expansion. This is tied to data speed offerings, since faster speeds may require FWA network densification or more spectrum etc. More traffic and higher data speeds could require more sites, more spectrum or more infrastructure equipment.

Business Case Example

It is possible to realize a viable business case for FWA – i.e., an FWA solution with positive cash flow and cost structure better than alternate solutions. Below we show a sample business case for rural and suburban FWA. In this scenario, operator could achieve less than $300 per home passed with a positive cash flow in 3.5 years.

Budgetary Value*

- Suburban and Rural:
  - $<300 Cost per Home Passed
  - 600 homes/sq. mile – Suburban
  - 10 homes/sq. mile - Rural
  - Cash flow positive <3.5 years

Performance

- 10, 25, 50, and 100 Mbps service
- Network supports 2 Mbps Busy Hour Throughput per HHC with a 28% YoY growth
- Aligned with market take rates, pricing, and targeted network design metrics

Time to Revenue

- Network deployment can begin when 3.5GHz spectrum usage is enabled by FCC’s SAS/ESC certification
- Network deployment using 2.5 GHz licensed spectrum possible today

* Subscriber growth assumed 10% to 33% in 5 years, 3.5 GHz CBRS spectrum; assumes 60 MHz spectrum

Business case metrics used:

Cost per home passed: This is the cost of building FWA coverage for the number of homes in the service area. This cost does not include customer premises costs.

Cost per home connected: This is the cost of providing connectivity to a customer, including networks and customer premises equipment costs.

Time to revenue: Month or year to cash flow positive

Return on investment

FWA business models

Operators have been trying different business models for FWA. Below, we list a few:

1. Rural high speed FWA. NBN in Australia provides broadband service to rural subscribers. Offering includes 1000 GB bucket with data speed as high as 100 Mbps. To achieve coverage and performance, NBN uses 60 to 100 MHz of licensed TDD spectrum. NBN provides service to otherwise un/underserved communities.
2. 5G FWA. Verizon has launched an FWA service over mmWave 5G variant for $50-70 per month with no contract. The 5G type FWA service is being deployed in targeted urban and suburban areas and it is meant to compete with existing cable, fiber and other home broadband offerings.

3. Converged MBB and FWA service. Here operator can offer a service to connect a WiFi router, MiFi devices, tablets etc. via the same network. Data consumption from all devices is pooled into a single bucket. Some of the supported devices are mobile and can roam outside of home. This offering has features of both mobile broadband and fixed broadband.
4. Rural FWA and IoT network: A rural operator provides FWA service and using the same network can offer up low power wide area or massive IoT for smart farms.
5. Rural FWA and MBB roaming: A rural operator deploys FWA LTE network. With network slicing, any residual capacity in the network could be used to accommodate roaming MBB subscribers.

FWA Field Experiences

In this section, we look at field trial results from FWA. We highlight performance potential of new technologies like massive MIMO and NR.

In the first instance, we show results from a rural FWA trial using CBRS spectrum. The cell site is configured as 4T4R and we are using two 20 MHz LTE carriers. Outdoor CPEs are used in this set up. Since, this configuration is closer to standard LTE, we can use this as baseline for comparisons.

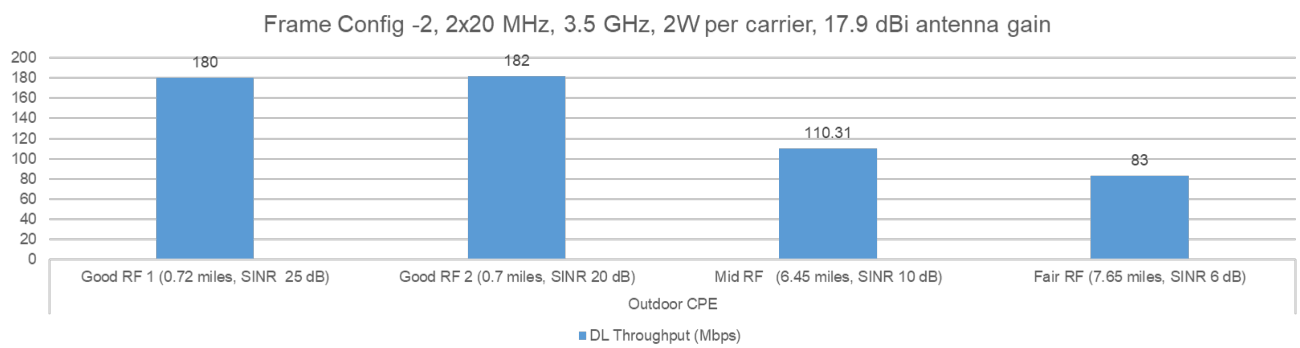


Figure 8 - Downlink thoughput under different RF conditions

Peak throughput of 180 Mbps in the DL was seen at 0.7 miles from the site. An average home would experience 110 Mbps. One measurement was taken at around 7 miles from the site with 110 Mbps speed in the DL.

Each 20 MHz channel offered average sector capacity of 50 Mbps. Assuming busy hour demand of 2 Mbps per home, each sector would be able to support 50 homes. The number of homes supported by each sector could be increased by adding more CBRS spectrum (more than 2x20 MHz).

In the next instance, we show how massive MIMO can improve system capacity and individual CPE throughput. We note that CPE placement is ideal, i.e., CPEs are in line of sight and under good RF conditions. They are also spatially separated to minimize inter-beam interference and allow the possibility of achieving good multiple user MIMO gains.

Figure 9 - Setting for multiple user MIMO testing in ideal radio conditions

These tests use a single 20 MHz LTE carrier with 64 QAM modulation in mid band TDD spectrum. 16 CPEs are configured to transmit simultaneously. System is set up to use up to 16 layers in both DL UL. Total system throughput of ~740 Mbps was observed in the DL.

Table 3 - Results of throughput testing with 16 layer MU-MIMO in good radio conditions

	UE1	UE2	UE3	UE4	UE5	UE6	UE7	UE8
DL Tput(Mbps)	47.16	46.93	46.52	46.72	46.1	46.32	46.31	45.32
UL Tput(Mbps)	8.72	8.91	8.78	8.92	8.89	8.9	8.89	8.92
	UE9	UE10	UE11	UE12	UE13	UE14	UE15	UE16
DL Tput(Mbps)	45.98	45.83	45.64	45.9	47.3	47.13	45.98	46.9
UL Tput(Mbps)	8.9	8.87	8.93	8.86	8.9	8.88	8.92	8.93

In the next field trial, our objective is to compare performance of massive MIMO and multiple user MIMO against traditional LTE in 2T2R, 2x2 single user MIMO. UE placement is more realistic: with 2 CPEs in good radio conditions, 4 in medium radio conditions and 2 in poor coverage. Massive MIMO system is configured only for 64 QAM and 8 layers. 2x2 MIMO system is configured for LTE transmission mode 3 and 256 QAM. We use a single 20 MHz TDD LTE carrier in single band and our spectrum band is in the mid bands.

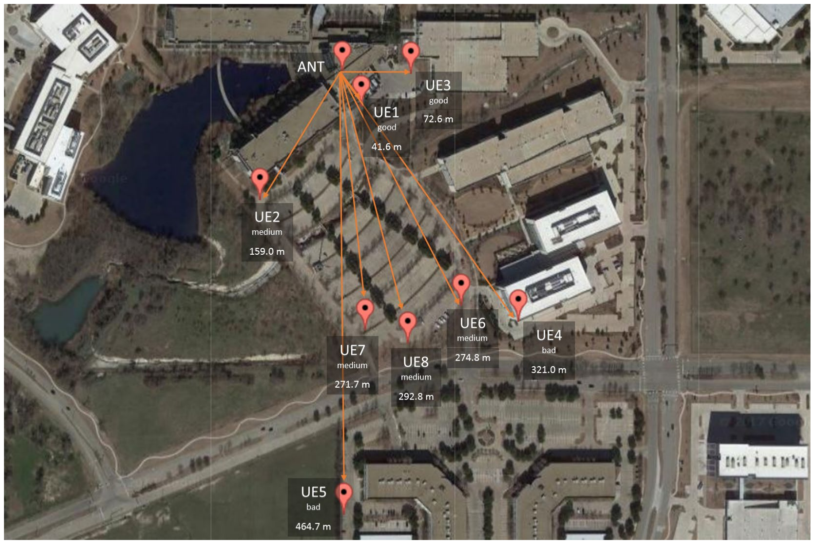


Figure 10 - Setting for MU-MIMO field testing in varying radio conditions

Results show a total system throughput of 178 Mbps for massive/MU-MIMO MIMO system vs. 84 Mbps 2x2 SU MIMO system. This is a 2x improvement in system capacity, as well as considerable improvement in individual UE throughput. With 16 layers, we could expect a 4x improvement in system throughput. Enabling 256 QAM for massive MIMO system would result in higher system capacity gains.

Note: System capacity gains from massive MIMO are tied to layer utilization. Users in over-lapping beams cannot be MU-MIMO users, limiting gains in more practical situations.

Table 4 - Results of 8 layer MU-MIMO testing in varying radio conditions

	MU-MIMO DL Throughput	SU MIMO DL Throughput
	Mbps	Mbps
UE1	43.83	16.93
UE2	11.78	9.25
UE3	44.73	15.30
UE4	4.69	4.92
UE5	17.19	7.03
UE6	22.65	9.19
UE7	17.80	13.24
UE8	15.13	8.76
SUM	*177.78*	*84.63*

Good RF conditions
Medium RF conditions
Poor RF conditions

Finally, we show coverage and range of a massive MIMO system in rural area. We use single 20 MHz carrier in mid band with outdoor CPEs. We also use MU-MIMO. High single user throughput performance is achieved at more than 10 km away from the cell site. Total system capacity of 200 Mbps was achieved for 8 MIMO layers.

Figure 11 - FWA with beamforming and MU-MIMO in rural area

Conclusions

In this article, we have shown:

1. FWA technology components are in place.
2. There is a viable business case for FWA.
3. Operators have been experimenting with different business models.
4. Deployments that began with rural FWA are moving into suburban and urban areas. Several operators in the US and globally have already been operating profitable FWA business.

FWA has the potential to disrupt existing broadband business. SCTE members could leverage FWA to further build out their own home broadband offerings.

Abbreviations

AP	access point
bps	bits per second
FEC	forward error correction
HFC	hybrid fiber-coax
HD	high definition
Hz	Hertz
ISBE	International Society of Broadband Experts
SCTE	Society of Cable Telecommunications Engineers

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