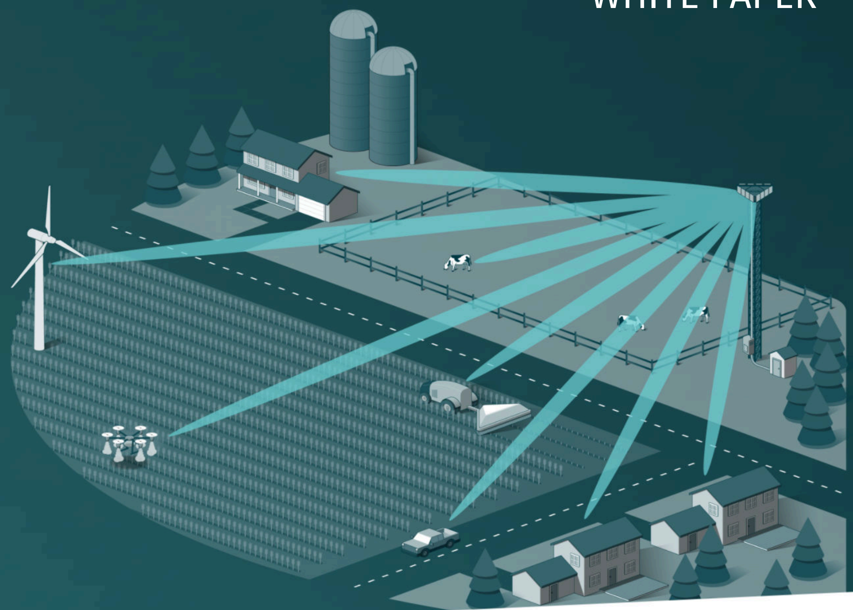
WHITE PAPER

Massive MIMO for Rural Broadband



SKYLARK WIRELESS®

FAR MORE THAN 5G

CONTENTS

ABSTRACT

The Skylark Wireless Faros® solution provides the best-in-class speed and coverage for rural broadband Internet access. With multi-gigabit speeds and over 1,000 mi² of coverage from a single tower, Faros transforms the economics of rural broadband to bridge the digital divide.

This White Paper provides results from a test pilot in central Texas, demonstrating over three times the spectral efficiency of competing TV White Space (TVWS) technologies, and ten times the coverage of traditional wireless deployments.

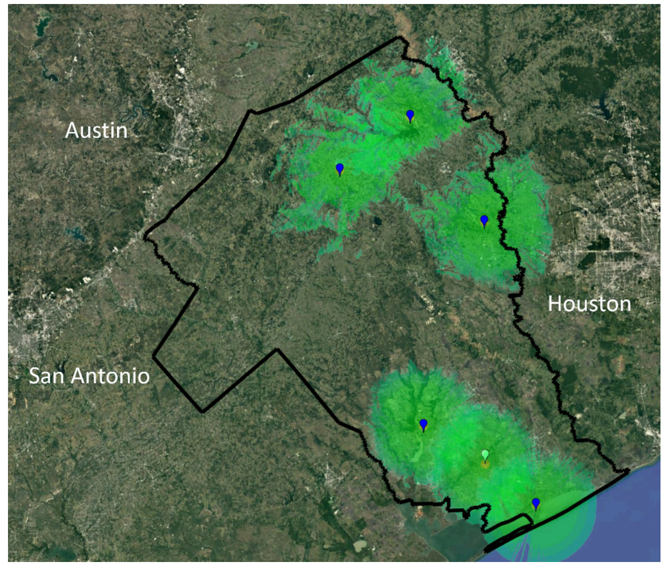


Figure 1: Six-tower coverage of Faros field trial in Texas.

INTRODUCTION

Over 40 million Americans and 3 billion people worldwide do not have broadband Internet access. The problem is simple: existing technologies cannot economically provide broadband to these under-served populations. As 5G wireless and gigabit connectivity are becoming pervasive in and around cities, rural areas have been left behind, often causing them to resort to expensive, slow, and intermittent satellite plans or no connectivity at all. *This growing disparity in connectivity is referred to as the digital divide, and it leaves billions without critical access to education, healthcare, commerce, entertainment, and telecommunication.*

The problem is that existing wireless technologies either provide long range or high speeds, but not both. As a result, Wireless Internet Service Providers (WISPs) are left providing incomplete coverage and sub-broadband speeds in many rural areas.

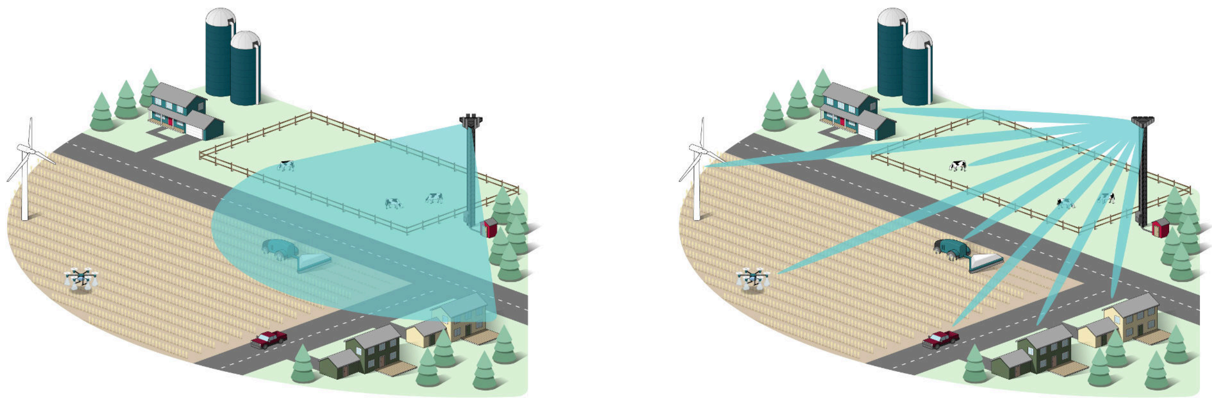
The key to bridging this digital divide is a new 5G wireless technology called *Massive MIMO*, which transforms the economics of serving these low-density population areas. With the ability to cover over 1,000 mi² from a single tower, Skylark's Faros[†] solution can provide high-speed Internet service to people and businesses it was infeasible to serve with existing technologies.

Skylark Wireless has deployed field trials of its Faros Massive MIMO solution with 6 towers in south-east central Texas in cooperation with a local Mobile Network Operator (MNO). This White Paper focuses on the performance of a single sector in our Texas pilot, which demonstrates over 14 $^{bps}/_{Hz}$ to 4 clients at a range of 7.7 to 17.1 km. Furthermore, we show reliable connections at 17 km non-line-of-sight (NLoS) and 30 km line-of-sight (LOS). The deployment supports both Television White Space (TVWS) between 470—698 MHz and the adjacent licensed 700 MHz spectrum.

These are preliminary results in the field with a reduced number of spatial streams, as we have shown over 30 $^{bps}/_{Hz}$ at close range and expect to support over 50 $^{bps}/_{Hz}$ in the field upon product release. With a full 3-sector deployment and 40 MHz of bandwidth, a single Faros base station can provide up to 6 Gbps aggregate throughput and coverage to over a 1,000 mi², serving thousands of homes, farms, IoT devices, and businesses.[‡] This revolutionizes the economics of serving rural areas, bridging the digital divide in rural areas where traditional technologies have failed.

[†] Faros means "Lighthouse" in Greek; the Skylark Faros system sweeps beacons for extended range, similar to how a lighthouse operates.

[‡] 40 MHz x 50 $^{bps}/_{Hz}$ x 3 sectors = 6 Gbps



Existing Technologies

Massive MIMO

Figure 2: Most existing technologies spread energy across the entire coverage sector, only serving one user at a time and creating large amounts of interference (*left*). Massive MIMO forms dozens of narrow beams multiplying the range and capacity of the system (*right*).

FAROS MASSIVE MIMO

Massive MIMO is an emerging 5G radio technology that uses coherent arrays of digital radios to beamform to many users at the same time *on the same channel* by leveraging wireless spatial separation. As shown in Figure 2, compared to 4G and other 5G technologies, this provides greater distance with beamforming gain, greater network capacity with multi-user beamforming, and greater robustness with spatial diversity. Whereas 4G and other 5G systems serve multiple users by switching between them in frequency and time, a Massive MIMO system adds a third dimension to switch between users on different *spatial streams*.

Each of the “beams” shown in the right of Figure 2 represents an independent spatial stream, which is an additional data stream overlaid on the same radio channel that provides additional capacity. For example, a Massive MIMO system with 16 spatial streams would be able to to provide 16 times the spectral efficiency and capacity of an equivalent single-antenna (SISO) system under ideal radio propagation conditions.

Though highly dependent on the environment, the installation configuration, and the frequency of operation, prototype non-commercial Massive MIMO systems have demonstrated unprecedented spectral efficiency of over 100 bits per second per Hertz (bps/Hz), compared to 4G LTE-A and 5G NR at a maximum of 5 bps/Hz and 6 bps/Hz, respectively, with a single radio.[†] Skylark's first-generation Faros platform is expected to operate at an average of 50 bps/Hz in the field, making it the most efficient way to utilize expensive and scarce radio spectrum below 6 GHz. When leveraging TVWS and licensed 700 MHz spectrum, Faros has the range and throughput to replace over 10 traditional WISP towers with more consistent NLoS coverage, as shown in Figure 3.

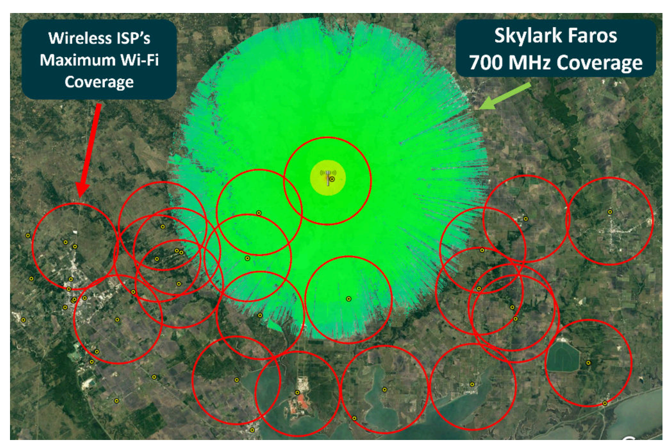


Figure 3: Coverage comparison between Faros and traditional technologies used by WISPs. Faros can provide over ten times the coverage of existing solutions.

[†] Spectral efficiency is a measure of how much capacity the wireless system can achieve for a given amount of spectrum. For example, one TV channel is 6 MHz, so a spectral efficiency of 50 bps/Hz would provide 6 MHz $\times$ 50 $bps/Hz = 300$ Mbps.

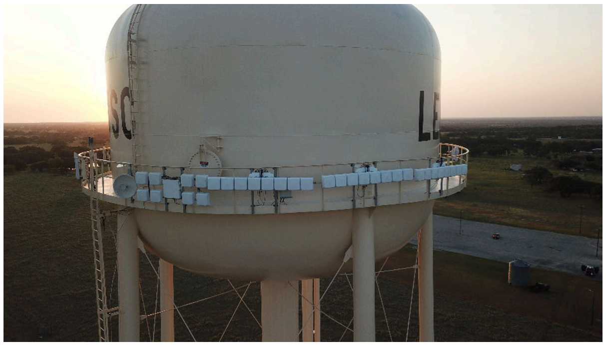


Figure 4: Faros 64 radio TVWS and 700 MHz Massive MIMO base station deployed in central Texas.

Figure 5: Faros CPE 17 km from base station.

Existing MIMO Technologies

While some 4G and 5G solutions support phased-array beamforming, MIMO, low-order multi-user MIMO (MU-MIMO), or some hybrid thereof, it is important to distinguish between these technologies and true Massive MIMO, provided by Skylark's Faros solution.

Phased array beamforming uses a single radio connected to an array of antennas to steer a *single* analog beam towards the intended user; while this increases range and signal strength to the user, it does not have the ability to multiply the capacity of the spectrum with more than one spatial stream. Moreover, its ability to form beams is limited: it can only form one beam, which is suboptimal when there are multiple paths to the intended client, and it suffers from coverage gaps caused by array blinding. In contrast, fully digital beamforming, which is employed by MU-MIMO and Massive MIMO, sense the environment and form beams on every path to the client, ensuring maximum coverage and performance.

mmWave is a 5G technology that leverages high-band spectrum that is 28+ GHz combined with phased array beamforming. It is not very spectrally efficient, but instead uses large chunks of spectrum, more than 500 MHz, to achieve multi-gigabit performance. However, this high frequency spectrum has limited propagation, and thus is typically restricted to well under 1 km range and line-of-sight (LOS) conditions. mmWave is currently being deployed in dense urban settings to provide the last 10-100 m broadband connection to the home, but requires a density of towers for ubiquitous coverage that is not practical in rural areas.

MIMO techniques use multiple radios at both the base station and client to improve signal strength and, in some implementations, send multiple spatial streams to the same client. While MIMO does significantly improve coverage and can double the spectral efficiency of the system, it is sub-optimal in that it does not leverage the spatial diversity of serving multiple clients simultaneously. Thus, MIMO can rarely serve more than two spatial streams efficiently and is limited in its ability to improve the range and capacity of the system.

MU-MIMO employs multiple radios at the base station to serve multiple clients simultaneously through fully digital beamforming. The number of clients, or spatial streams, that can be served simultaneously is limited by the number of radios on the base station. Notably, as each radio provides more transmit power, spatial diversity, and beamforming gain, the range and coverage consistency also improves with each additional radio. MU-MIMO provides the best spectral efficiency and coverage compared to existing wireless technologies. However, the overhead of measuring the environment, tracking users, and calculating the beams is significant, and thus existing 4G and even cutting-edge 5G solutions are limited to 8 spatial streams. Unfortunately, this overhead is substantial enough that most systems only support up to 4 spatial streams, and even those that support more rarely use more than 4.

Massive MIMO is MU-MIMO scaled up to 32+ base station radios capable of providing 16+ spatial streams. To implement Massive MIMO efficiently requires a com-

Figure 6: Faros compact weatherproof CPE (20 x 12 x 6 cm).

Figure 7: Faros CBRS (*left*) and BRS (*right*) 64 radio Massive MIMO base stations.

plete re-thinking of the base station hardware, wireless protocols, clients, and digital signal processing. Otherwise, the cost and overhead of Massive MIMO negate the potential gains from having more radios on the system.

Skylark's Faros system implements true Massive MIMO in a system that can scale to hundreds of radios with no overhead bottlenecks.

Deployment Considerations

While Massive MIMO is the most spectrally efficient wireless technology with the best coverage, it does have some important differences and considerations compared to traditional technologies: *1)* peak performance is dependent on client locations, and *2)* aggregate base station performance is always greater than client performance.

Massive MIMO achieves its superior performance by sending multiple spatial streams to multiple users simultaneously. However, if every user being served is extremely close to each other (or at the same angle to the base station in line-of-sight environments), then the number of spatial streams that can be optimally created will be limited to just a few, thus reducing the peak capacity of the base station. To achieve its full potential, clients should be distributed throughout the coverage area or in multiple clusters. Notably, in high multipath environments such as within buildings or in urban environments, this is typically not a constraint.

Unlike traditional technologies, the clients and base station have *different* peak throughputs. This is because the base station serves multiple clients simultaneously, and thus its aggregate throughput is always greater than an individual client. Since the performance of individual clients is generally determined by the amount of spectrum available, this is an important consideration when provisioning networks.

For example, a 30 MHz channel may support reliable 100/20 Mbps (downlink/uplink) broadband service to an individual client. A traditional system would divide this capacity across clients, with no one client actually achieving 100/20 Mbps in a busy network. In contrast, a Massive MIMO base station forms spatial streams to dozens of clients simultaneously and would achieve aggregate sector throughput in excess of 1 Gbps, with many clients achieving 100/20 Mbps service, simultaneously.

Other Technologies

Some rural areas may have access to wireline solutions, including DSL and Fiber, or, as a last-resort fall back to satellite connectivity. WISPs have traditionally used fixed wireless technologies based on Wi-Fi (IEEE 802.11).

Typically, the only wireline solution available in rural areas is DSL, which usually has speeds below 1 Mbps but can reach up to 5 Mbps when near the telephone exchange. This is well below the requirement of 25 Mbps for broadband service and will not even reliably provide HD video streaming. Installing new wireline, including fiber, costs $10,000s per mile and is not economically

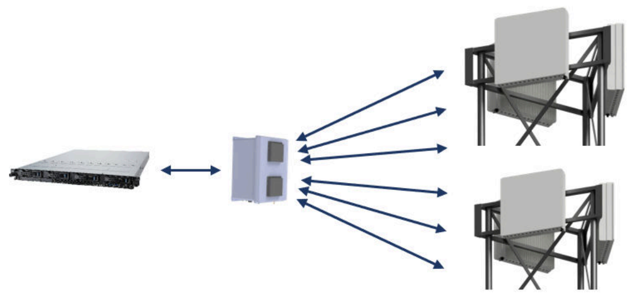


Figure 8: Faros enables scalable Massive MIMO with multiple Radio Units (RUs) connected to a Distributed Unit (DU) hub that synchronizes them for coherent MIMO operation, controlled by a Centralized Unit (CU) for network orchestration.

Figure 9: Temporary client used for range testing.

viable in rural areas unless it is heavily subsidized or part of new development, such as when it is installed along with power or other infrastructure.

The primary challenges for satellite communications are latency, capacity density, and cost. While satellites *can* provide HD or even 4K streaming video, the latency is constrained by the speed of light, which requires over 500 ms round trip time for geostationary (GEO) satellites. This means loading even simple web pages takes multiple or even tens of seconds, and telecommunication and gaming are impossible. Low Earth Orbit (LEO) satellites have the potential to decrease the latency of satellite-based service, however they still do not provide the capacity density required to profitably serve rural, suburban, and urban populations and require thousands of satellites with high costs and less than 5-year lifespan. As a result, satellite plans have traditionally been expensive and have capped data usage; thus satellite remains the option of last resort for most users.

BRIDGING THE DIGITAL DIVIDE

Existing technologies simply cannot economically serve many rural areas. While a few kilometers of fiber or a single cell tower can pass[†] hundreds or thousands of users in an urban or suburban environment, in rural areas this same capital investment may only serve dozens of users, or less. By providing an order of magnitude more coverage and performance, Faros Massive MIMO reduces the capital and operating expenses required to deliver broadband service, making regions with low-density populations not only reachable, but also profitable for the network operator.

[†]In telecommunications the term "pass" refers to premises covered, but not necessarily connected. For example, in wireline solutions this would mean the cable or fiber passes the premise, but is not run in to the building. In wireless, it means that the premise is covered, but the antenna and equipment to connect to the network are not installed.

Skylark Faros Solution

Skylark Wireless's Faros Massive MIMO solutions provide both unprecedented range and capacity, resulting in an order of magnitude better performance and lower cost in wireless deployments. Skylark's patented multi-user beamforming techniques significantly extend the range of base stations, provide more uniform coverage, and multiply the capacity of available spectrum. This allows each tower to serve more users over a larger area, drastically reducing the cost per square mile of coverage and significantly improving user experience.

While Faros operates in any spectrum between 50 MHz and 6 GHz, it is the only platform suited to serve rural areas using lower UHF frequencies that have long-range NLoS propagation, such as the TVWS and 700 MHz bands. Notably, the frequency determines the size of antennas, enabling much smaller base stations with integrated antennas at higher frequencies, such as BRS (2.495—2.69 GHz) and CBRS (3.55—3.7 GHz) , shown in Figure 7.

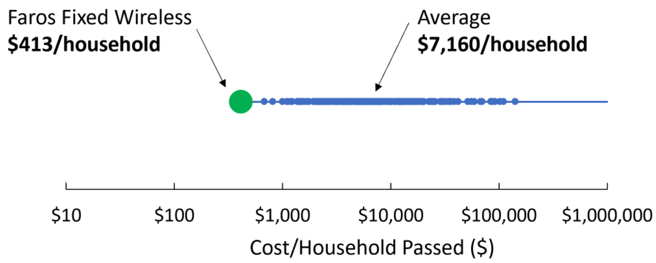


Figure 10: Comparison of capital expenditure per household passed of Faros vs. existing technologies, based on 2019-2020 USDA ReConnect projects. Faros is over 17 times less expensive compared to traditional solutions for proving rural broadband coverage.

Faros is uniquely *scalable*, allowing base stations to grow from two to hundreds of radios, with a corresponding increase in range and capacity, as demonstrated in the results below. This is accomplished with a modular architecture using a Faros Distributed Unit (DU) hub to connect and synchronize multiple remote Faros Radio Units (RUs), as shown in Figure 8. Multiple DUs may be aggregated at a centralized location, or Faros Centralized Unit (CU), which performs traffic scheduling and network orchestration. This flexibility allows network operators to seamlessly provision and scale their networks according to their needs and evolving user demands.

Faros is an end-to-end solution, providing both the base station, Figures 4, 7, and 8, and low-cost customer premise equipment (CPE), Figures 5, 6, and 9. Moreover, Faros is a software defined radio (SDR) system; its entire baseband processing is implemented in software and firmware, enabling unprecedented flexibility and field-upgradeability.

Economics of the Divide

Faros significantly reduces the cost to deploy broadband in rural areas, making it economically viable in areas that were previously infeasible to serve, and increasing profitability in areas that are being served inadequately with existing technologies. As shown in Figure 3, one Faros tower can cover over 10× the area of traditional wireless towers. Coverage alone, however, is not enough; the tower must have enough capacity to provide broadband speeds to the users. Traditionally, more bandwidth is required to provide this additional capacity, however the sub-6 GHz spectrum required for this range and NLoS propagation is scarce and expensive, with typically narrow channel bandwidth. Thus the drastic improvement in spectral efficiency provided by Faros is critical for enabling broadband speeds in rural areas economically.

As a result, areas currently served by ten or more traditional WISP towers can be replaced by a single Faros tower, drastically reducing capital and operating costs. More importantly, areas that were previously infeasible to serve, e.g., since it would take dozens of traditional towers to serve hundreds of users due to terrain or population density, can now be economically served using a single Faros tower.

Based on an analysis of 243 greenfield USDA ReConnect projects from 2019 to 2020, Skylark's Faros solution is over 17 times less capital intensive than traditional solutions for providing rural broadband coverage, as shown in Figure 10.

FIELD-TRIAL PERFORMANCE

Skylark's Faros solution provides over 30 bps/Hz at close range, 14 bps/Hz at approximately 10 km in this field demonstration, and reliable connections at over 30 km. To field-test the performance of the Faros prototype system with all overhead accounted for, Skylark deployed six towers in Texas, shown in Figure 1.

This White Paper focuses on the performance from one sector on a tower just outside of Giddings, Texas, shown in Figure 4. The deployed hardware supports both TVWS and licensed 700 MHz spectrum; these trials use the lower 700 MHz band, specifically 4.5 MHz of bandwidth centered at 707 MHz. Since the 700 MHz band is immediately above the TVWS band, these results are also representative of TVWS performance, with TVWS perhaps having even slightly better propagation due to its lower frequency. The base station is deployed at 36 m above ground level at an elevation of 150 m, and these results use 28 radios. Each radio supports up to 30 dBm output power and is connected to a 7.5 dBi dual-polarized panel antenna. Seven permanently deployed clients are distributed with ranges between 7.7 to 17.1 km in the sector, as shown in Figure 12 and detailed in Table 1, with additional temporary client locations up to 30 km away. Each client, shown in Figures 5, 6, and 9, supports up to two spatial streams, with dual-polarization, and we report preliminary results for up to eight spatial streams at long-range and sixteen at close range. Notably, Faros currently supports up to thirty-two spatial streams; thus we expect significant improvements as more clients are deployed.

Client	Height	Elevation	Distance	Antenna
A	22 m	146 m	8.5 km	7.5 dBi Panel
B	9.1 m	162 m	10.0 km	7.5 dBi Panel
C	18 m	159 m	12.9 km	7.5 dBi Panel
D	4.6 m	148 m	8.1 km	9 dBi Yagi
E	18 m	132 m	7.7 km	7.5 dBi Panel
F	7.6 m	124 m	10.3 km	9 dBi Yagi
G	8 m	140 m	17.1 km	14 dBi Yagi

Table 1: Permanently installed client parameters. The base station is deployed at 36 m above ground at an elevation of 150 m.

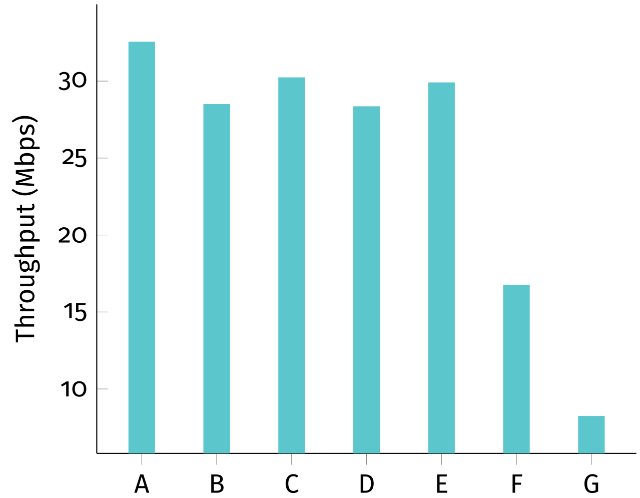


Figure 11: Single-user throughput of permanently installed clients with 4.5 MHz of spectrum. Clients F and G have lower performance because they are very long-range NLoS.

Spatial Stream Performance

One of the primary advantages of Faros Massive MIMO is its ability to multiply the capacity of spectrum with support for dozens of spatial streams. Figure 13 shows the performance of Faros as the number of spatial streams increases. Even at 10 km, we see that each additional spatial stream multiplies the spectral efficiency. These preliminary results only demonstrate up to 8 spatial streams at long range, and up to 16 streams at close range. However, Faros supports up to 32 spatial streams,

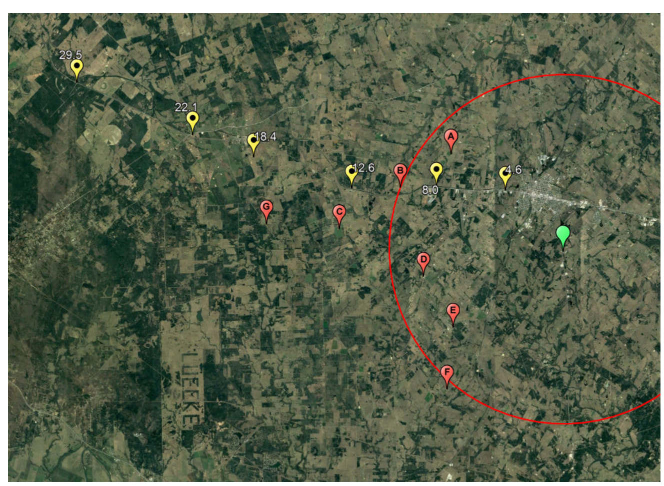


Figure 12: Locations of base station (green), permanent clients (red), and temporary range-test clients (yellow, labeled with range in km) in central Texas. The red line is 10 km radius from base station.

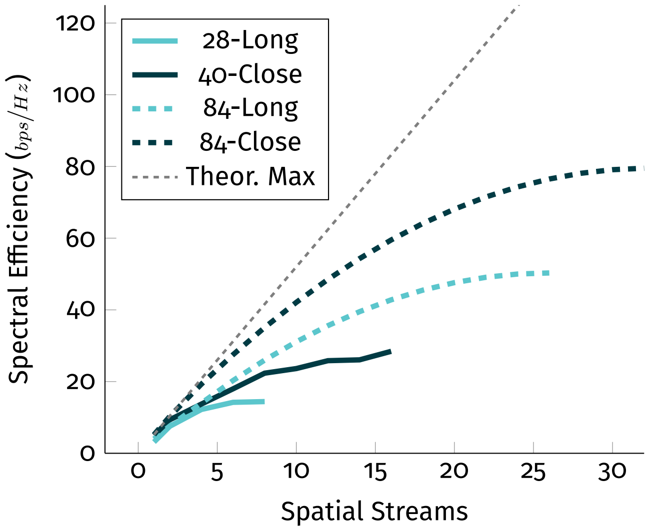


Figure 13: Spectral efficiency vs. number of spatial streams. Legend entries denote the number of base station radios and range, where long range is approximately 10 km. Dashed lines indicate projections. "Theor. Max" is the theoretical maximum system spectral efficiency under perfect propagation conditions. Lines stop when more spatial streams do not improve capacity.

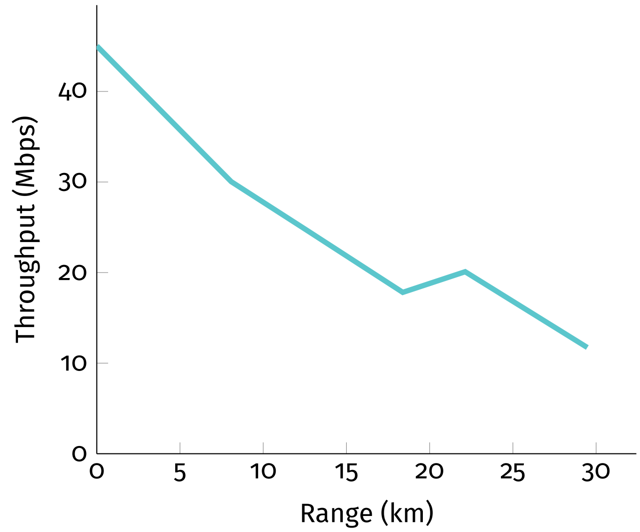


Figure 14: Throughput vs. range for a single client on 4.5 MHz of spectrum at 13 m above ground height.

enabling it to scale up capacity and range even further with more base station radios, as shown by the projected results in Figure 13.

Range Performance

As shown in Figures 11 and 14, Faros is able to easily provide 25 Mbps broadband connectivity to over 10 km away on just 4.5 MHz of spectrum. Clients F and G are mounted at very low height with obstructions in their wireless paths; however, with just one more channel available F would achieve broadband speeds. Notably, even at near ground level under severely occluded NLoS conditions, client G was able to connect at 17.1 km away.

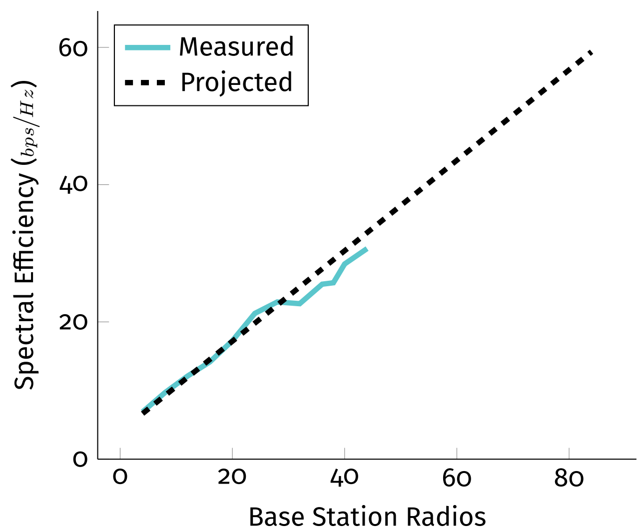


Figure 15: Spectral efficiency vs. number of base station radios with up to 16 spatial streams at close range, and up to 32 streams for projected.

Moreover, Faros is able to reliably connect at 29.5 km from the base station, even with a relatively low client height of 13 m. This range is primarily limited by the horizon. These results were achieved with two spatial streams up to 22 km away, after which the base station automatically switched to one spatial stream for optimal performance.

Notably, the client antenna height is dependent on range, frequency, and topology. For example, TVWS clients close to the base station can be mounted on the eaves of a house, or even indoors, but as the range and obstructions increase, a taller mast is required for good service.

Base Station Scale

Skylark's Faros Massive MIMO solution provides the important ability to economically scale with requirements of the deployment. By seamlessly scaling up the number of base station radios, Faros is able to provide additional range and capacity as needed. As shown in Figure 15, the number of base station radios drastically affects performance, scaling from 6.9 bps/Hz to 30.7 bps/Hz as the number of base station radios grows from 4 to 44. Notably, for each measurement the optimal number of spatial streams was chosen, which ranged from 2 to 16. With more base station radios this increase in capacity continues, as Faros is able to serve up to 32 spatial streams with the additional spatial diversity, demonstrated by the projected spectral efficiency in Figure 15. While increasing range decreases performance, as illustrated in Figure 13, this degradation can be counteracted with more base station radios.

CONCLUSION

Affordable, ubiquitous broadband Internet access is a critical equalizer for communities and businesses worldwide, and bridging the digital divide is a key challenge for the 21st century. With the ability to serve multi-gigabit aggregate speeds to over 1,000 mi^2 from a single tower with relatively little radio spectrum, the Skylark Wireless Faros Massive MIMO solution revolutionizes the economics of providing broadband to unserved and underserved populations worldwide.