C Spire Rural Broadband Consortium Bulletin:

Massive MIMO Testing Results

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Introduction

The C Spire Rural Broadband Consortium is exploring different broadband technologies that can be used in rural environments. C Spire (the Operator), in conjunction with Nokia (the Network Vendor), deployed a Band 41 (2.5 GHz) macro site to evaluate massive MIMO (mMIMO) feasibility as a broadband technology in mixed rural environments. The mixed morphology environment studied included two small towns with surrounding farming communities and scattered homes. The massive MIMO equipment was placed on an Operator-owned, Operator fiber-fed macro tower located in the more loosely organized small town; the other town with more closely spaced businesses and homes is located around 1.5-2 miles west of the site. [1]

The small towns each have a population of around 500 and have suburban-like neighborhoods spread between and around the two town centers. The areas on the north, south, and east sides of the macro tower are made up of scattered homes, some in loosely organized neighborhoods as well as scattered farmhouses interspersed with fields, forest, and some mildly hilly terrain. As a result, many houses do not have line of sight (LOS) to the tower.

Most massive MIMO deployments have been in dense urban and urban environments, boasting up to 5 times (or more) capacity gain over a passive antenna and radio head system. The capacity and resulting per-user throughput improvements of mMIMO are partially due to the use of two-dimensional beamforming (the ability to focus beams in both vertical and horizontal directions), but they are primarily a result of higher-order MU-MIMO (using the same time-frequency resources for different users who are de-correlated in space). The high volume of devices in urban environments makes beamforming necessary to reduce interference from/to nearby users and the MU-MIMO combining algorithms feasible due to the high number of potential user pairings. The Consortium set out to explore massive MIMO capabilities in a rural environment with far fewer and more scattered users to determine the place of mMIMO in the rural technology toolbox. This is a high-level summary of the test results.

Equipment and Network Specs

The 64T64R massive MIMO radio [2] was deployed in a 3-sector configuration at a height of 282 feet above ground. The massive MIMO solution was capable of downlink (DL) carrier aggregation (CA) with 3x20 MHz bandwidth, uplink (UL) CA with 2x20 MHz bandwidth, 16 DL MU-MIMO streams, 8 UL MU-MIMO streams, as well as support for 4x4 DL SU-MIMO, DL 256QAM, and UL 64QAM. Some features were not activated in the field, however; the in-field system was only enabled for 2x2 DL SU-MIMO, 64QAM DL, and 16QAM UL. As a result, peak uplink and downlink throughput were reduced.

High performing Nokia Fastmile CPEs were used as end-user devices. These CPEs were capable of downlink 3 CA with 256QAM and 2x2 SU-MIMO. On the UL, the CPE uses 64QAM with either 2 CA SISO or 2x2 SU-MIMO with a single carrier.

The massive MIMO system was deployed with a micro-core network (MCN), an LTE core-in-box solution capable of supporting a limited number of base stations. The MCN was kept isolated from the existing Operator mobility network and the public internet. A 1 Gbps backhaul link was provided between the MCN and the core, and all policy limitations were removed from the core elements to enable full 1 Gbps capacity to the eNodeB.

Test Cases and Set-up

The Consortium performed both single-user and multi-user tests. The single-user tests were meant to understand basic coverage versus performance in various scenarios from LOS to NLOS. These results were used to create a "rainbow chart," which correlates RSRP, CINR, and throughput. This gives guidance to installers so that they can determine approximate customer experience upon installation. Multi-user testing was used to uncover basic scheduler performance and MU-MIMO capacity gains. Multi-user testing was performed single-beam and multi-beam, with CPEs clustered in a single-beam or scattered into multiple beams, respectively. Multi-user testing was performed both with three 20 MHz carriers (and CA) active as well as with a single 20 MHz carrier.

Because the system was not connected to the internet, traffic was generated using iperf3. While the original plan called for a large temporary user base for an extended period of time (2 weeks or more), this was not practical, due in part to the COVID-19 pandemic. Ultimately, only four CPEs were fielded simultaneously.

Results

Single-user testing was performed at ~30 locations in the alpha and gamma sectors; the results were used to build the rainbow chart shown in Table 1. The chart was "binned" by RSRP, as that is one of the easiest metrics to obtain in the field. At least 3 locations were obtained per RSRP "bin." The desired service level was 100 Mbps DL and 10 Mbps UL (100/10 Mbps), [1] but there appeared to be some limitation to the maximum download a single CPE could receive, particularly in a 3-carrier aggregation configuration. The uplink throughput achieved at high (DL) RSRP and CINR, however, was near the theoretical maximum for the CPE's capabilities.

DL RSRP (dBm)	DL CINR (dB)	DL Throughput (Mbps)	UL Throughput (Mbps)	Color Code
-70 to -60	33.3	90.7	20.8	Excellent
-80 to -70	31.3	82.7	21.0	
-90 to -80	30.3	80.8	12.9	Very Good
-100 to -90	25.8	77.3	15.1	
-110 to -100	19.0	88.9	8.5	Good
<-110	9.3	85.1	5.4	Fair

Table 1: Single-User Multi-carrier Testing Rainbow Chart

Due to the downlink throughput constraint, the chart is color-coded for a 50/5 Mbps service. Even at a very low RSRP, this service level was achievable, at least for a single device. Once more than one device was active in a sector, this signal level (and CINR) dropped and became more unreliable. Obviously, real-world deployment guidelines would be updated with experience in multi-user scenarios. Note that UL RSRP and UL CINR were not collected.

For all LOS locations, RSRP was ≥-98 dBm, while all NLOS locations had an RSRP of ≤-90 dBm. All locations measured in the alpha sector were NLOS, while gamma sector locations were a mix of LOS and NLOS locations. Alpha sector locations had, on average, better downlink throughput and worse uplink throughput for the same RSRP bins.

Multi-user testing was performed within a single beam and in multiple beams. The goal for single-beam testing was to demonstrate basic scheduler practices of sharing capacity, while multi-beam testing was to understand full MU-MIMO performance, with the thought that each beam was a capacity multiplier. Single beam testing was performed in two scenarios, each in both a 3-carrier configuration and a single-carrier configuration:

1) 3 CPEs, gamma sector, urban area (businesses and other buildings in the clustered small town)
2) 3 CPEs, beta sector, rural area (farmland)

Multi-beam testing was performed with three scenarios:

1) 2 CPEs, alpha sector, both single-carrier and 3-carrier configurations
2) 2 CPEs, gamma sector, single carrier only
3) 4 CPEs, gamma sector, single carrier only

For each test, measurements were taken both individually (1 CPE) and simultaneously (multiple CPEs), and the results were compared. Overall, adding CPEs (i.e., users), both in the single-beam and multi-beam scenario, increased the total throughput produced by the mMIMO radio, but it did not necessarily max out the overall system, particularly for downlink 3-carrier tests.

Table 2 shows how the total amount of capacity used increased with multiple simultaneous users compared to single user measurements at the same locations. For single-beam testing, the RSRP signal level in both the urban and rural clusters was somewhat lower (<-95 dBm) while CINR was good. In several of the tests, one of the CPEs failed to connect and pass traffic. Multi-beam testing was performed in excellent RF conditions, under the assumption that MU-MIMO requires good RSRP and CINR. The alpha sector locations had lower RSRP and CINR levels than the gamma sector locations (by around 10 dB and 5 dB respectively). While the 2-CPE tests were performed using short bursts (60 seconds per link), the 4-CPE test was run for 30 minutes per link. The 4-CPE scenario produced the most gain on the uplink, more than doubling UL throughput over single-user tests.

Test Scenario	Average RSRP	Average CINR	DL Throughput Increase	UL Throughput increase
Single beam	-101 dBm	20 dB	159%	93%
2-CPE Multi-beam	-76 dBm	31 dB	136%	148%
4 CPE Multi-beam	-66 dBm	34 dB	130%	222%

Table 2: mMIMO Capacity: Multi-User Throughput vs. Single User

It was interesting to note that, on average, single-user single carrier DL throughput was higher than when three carriers were active with CA, but the multi-user throughput gain for single carrier operation was less than for multi-carrier. The uplink, however, seemed less constrained for both single and multi-carrier scenarios. The uplink appeared to perform primarily as expected, with little impact on total capacity (and a reduction in per-user throughput) in single-beam scenarios and a more noticeable improvement in capacity in multi-beam scenarios.

Diving into the multi-user tests a bit more and comparing them to the theoretical maximum of the system, a couple of interesting things emerge, as seen in Table 3. First, as noted previously, improvements in capacity between single and multi-beam scenarios are most noticeable for uplink. Second, there is an improvement in capacity when increasing the number of users and beams for both uplink and downlink. While each of the scenarios would indicate that MU-MIMO was providing modest gain on the downlink, there appears to be significant improvement in the uplink for the multi-beam scenarios, as the number of CPEs increased. One other thing to note is that while the multi-beam scenarios should have produced near theoretical maximum throughput as the CPEs were in excellent RF conditions, the single-beam tests were in poorer RF conditions and thus would likely not be capable of theoretical maximum throughput in either uplink or downlink.

Scenario	DL throughput vs. Theoretical Max	UL Throughput vs. Theoretical Max
3 CPE Single-beam clusters	103%	60%
2 CPE Multi-beam	106%	159%
4 CPE Multi-beam	116%	222%

Table 3: Single Carrier Multi-User Compared to Theoretical

In summary, while adding CPEs to the massive MIMO system does increase the amount of throughput carried by the mMIMO radio, it appears that the radio still has a lot of theoretical capacity to spare.

Final Thoughts

Massive MIMO is highly effective at increasing capacity (and average user throughput) in dense urban and urban environments. Massive MIMO appears to be less effective in the rural environment tested, at least in terms of DL capacity gains. Based on the theoretical capacity of the mMIMO system and the performance capabilities of the CPEs tested, much higher DL throughput results were expected, although the UL improvements were solid. There were limitations to the test environment, including an unexpected restriction on single-user downlink throughput, and a relatively small number of CPEs used for testing, however. It is possible that using a larger number of CPEs spread throughout the sector that more actively push traffic would produce better results, particularly in terms of MU-MIMO DL capacity improvements. However, given the limited tests performed in this market, it would appear that more work needs to be done before mMIMO can become a widely used tool in the rural broadband technology toolbox.

References

[1] "Case Study: Mixed Environment – Operator-only Business Model – 2.5 GHz Macro Access," C Spire Rural Broadband Consortium case study, Oct 2020, https://www.cspire.com/resources/docs/rural/CS_RuralBroadband_CaseStudy3_202010.pdf.

[2] https://www.nokia.com/networks/solutions/massive-mimo/#overview