Radio over Fiber technology for 5G Cloud – Radio Access Network Fronthaul

Using a highly linear fiber optic transceiver with IIP3 > 35 dBm, operating at noise level of -160dB/Hz, we demonstrate 71 km RF over Fiber LTE-Ultra transmission links with five 20 MHz intra-band aggregated carriers for a total of 100 MHz with 3% Total EVM (rms) for 64QAM modulation. Results meet the ≤ 8% requirement for 64QAM set in 3GPP specification 36.104 for signal transmission between base station and remote radio head. This demonstrates that the CPRI/OBSAI transmission layer can be completely eliminated and replaced with much higher bandwidth, lower cost and lower power direct RF over Fiber LTE transmission. The technology can be implemented using wavelength division multiplexing and offers a solution for implementing next generation 5G fronthaul Cloud Radio Access Networks with BBU to RRH separation exceeding 100km.

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Introduction

Future implementation of Cloud RAN 5G networks will require pooling of large numbers of base band units (BBUs) into datacenters and deployment of networks of high bandwidth low latency connections to the corresponding remote radio heads (RRHs). Some of the challenges for such implementation are the length of the connections and associated latency, bandwidth constraints imposed by current CPRI/OBSAI user data rates and increasing costs of equipment at the RRH. All above issues are significantly reduced or completely eliminated if LTE or future 5G RF signals are directly transported between the BBU and RRHs in their raw base band or final RF form without the need of additional intermediate processing for CPRI/OBSAI.

Radio frequency over fiber (RFoF) transmission has been a topic of multi-year research and demonstrations, but until recently no one had actually been able to design and fabricate a cost efficient, small form factor fiber optic transceiver that combines in the same device - very high linearity, operation near shot noise level and high RF gain. High linearity, typically very challenging for optical modulation techniques, is especially critical for carrier aggregated signals, because unwanted 3rd order inter-modulation, transfers noise onto adjacent carriers, which leads to symbol noise and Error Vector Magnitude (EVM) degradation.

We have developed an RFoF transceiver that has IIP3 > 35 dBm, operates at the noise level of -160 dB/Hz and has RF gain of -12 to -14 dB. For the receive side we use a high linearity UTC photodiode, again specifically developed for RFoF applications. The following sections describe initial test results with LTE-Advanced signals on prototypes build using this technology. Details of the actual transceiver design will be provided in a separate publication.

Measurements and test results

To generate and analyze LTE-Advanced signals we use Anritsu MS2830A 6GHz Signal analyzer with add-on options for 6GHz Vector Signal Generator, bandwidth extension to 125MHz and software modules for LTE-Advanced IQ Producer, Vector Modulation Analysis and LTE-Advanced FDD Downlink Measurement. For all testing we use E-UTRA Downlink Test Model 3.1 (E-TM3.1) with 64QAM modulation, initially with a single 20 MHz carrier and then with 5 aggregated 20MHz carriers for 100MHz transmission bandwidth. For performance metrics we use in all measurements Total EVM (rms) and ACP (ACLR). The test system baseline performance for E-TM3.1 64QAM, measured with 50cm of coax cable between the RF generator and Signal analyzer has Total EVM (rms) =

0.29% and ACP < -61 dBc as shown in Figures 1 and 2. For all measurement we use 100kHz resolution bandwidth (RBW), which sets the RF signal measurement noise floor at ~ 100dBm.

Figure 1 Base line EVM using 50cm or coax cable. RF power -12dBm.

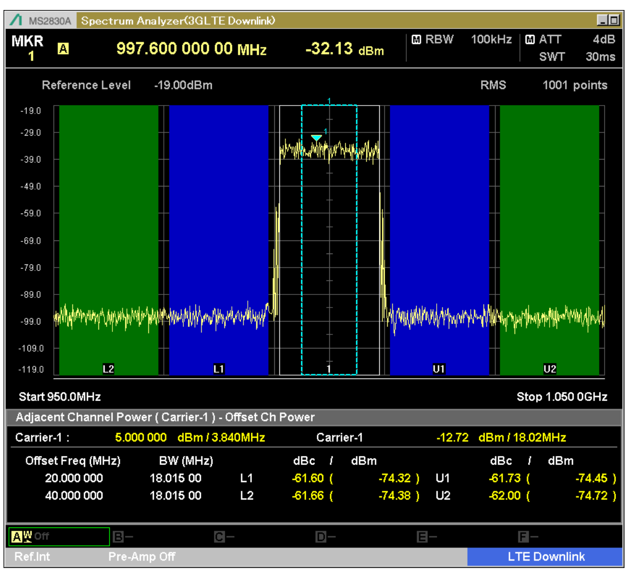

Figure 2 ACP for system base line measurement using 50cm or coax cable. RF power -12dBm.

To characterize the performance of the RFoF LTE link we use 4 different lengths of fiber: 1m, 25km, 50km and 71km. All fibers were standard single mode SMF-28 type. The 1m fiber link gives base line performance of the transmitter-receiver without the fiber propagation incurred noise impediments and degradation. The RFoF link in this measurement was implemented only with a transmitter and receiver with no additional amplification. Since the RFoF link has intrinsic RF gain of -12 to -14 dB in order to compare to the system base line measurement, which was carried with -12 dBm generator RF power, we increased the input power to 1 dBm. Figure 3 shows the 64QAM constellation and Total EVM (rms) = 0.33%. Which is only 0.04% increase from the instrument noise floor.

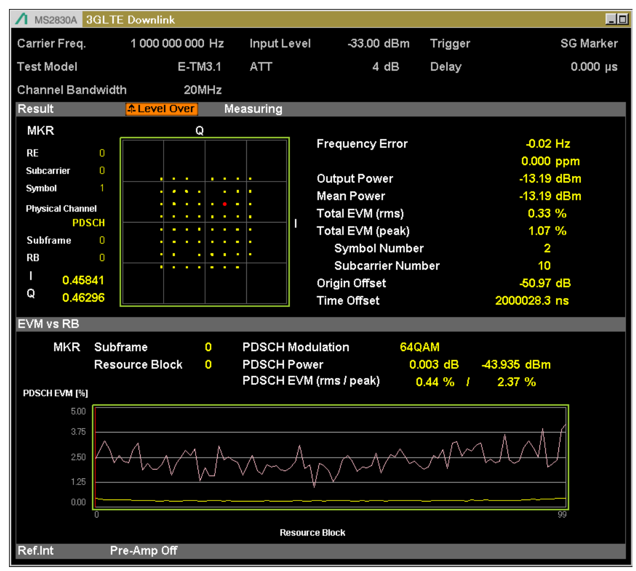

Figure 3 EVM for RFoF LTE base line measurement using 1m fiber. RF power 1dBm. Optical power 12.5 dBm.

The corresponding ACP is given on Figure 4 with value of -58.63 dBc, which is 3 dB decrease compared to the measurement test system ACP base level. The plot also shows the onset of small noise shoulders in the adjacent L1 and U1 bands, which was separately confirmed to be due to the cascaded nonlinearity of the frequency generator and transmitter. For all measurements the current on the photodiode did not exceed 20mA which is far below the device 1 dB saturation point of 60 mA. Therefore in the RFoF link the nonlinearity was dominated entirely by the transmitter side. The measured RF signals in Figures 2 and 4 are within 1 dB and given the 12 dB difference in drive power we confirm that the RF gain of the RFoF link is ~ -13 dB.

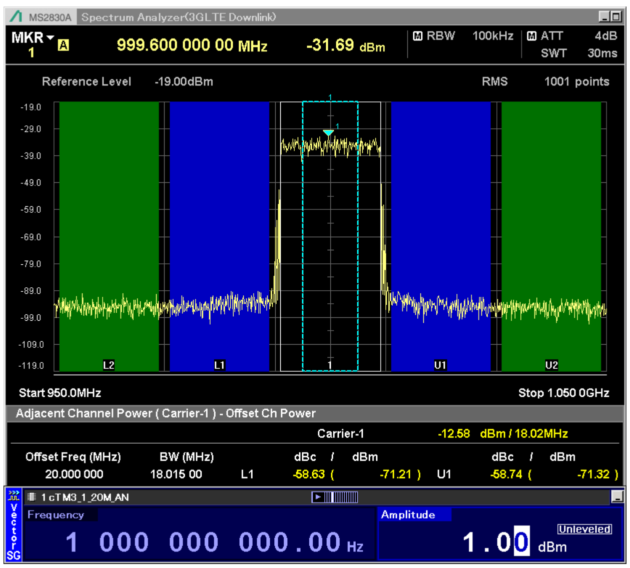

Figure 4 ACP for RFoF LTE base line measurement using 1m fiber. RF power 1dBm. Optical power 12.5 dBm.

In order to investigate the linear performance of the RFoF LTE link we drop the RF drive power to -15dBm with results displayed on Figures 5 and 6. There is 0.3% increase in the EVM and detected signal RF power decreases ~ 15 dB, which is in line with input RF power reduction. The ACP decreases to -45 dBc due to the reduced signal to noise ratio, since we use the same acquisition RWB and noise floor of ~- 100dBm. With the reduced RF drive the noise shoulders due to inter-modulation disappear in Figure 6.

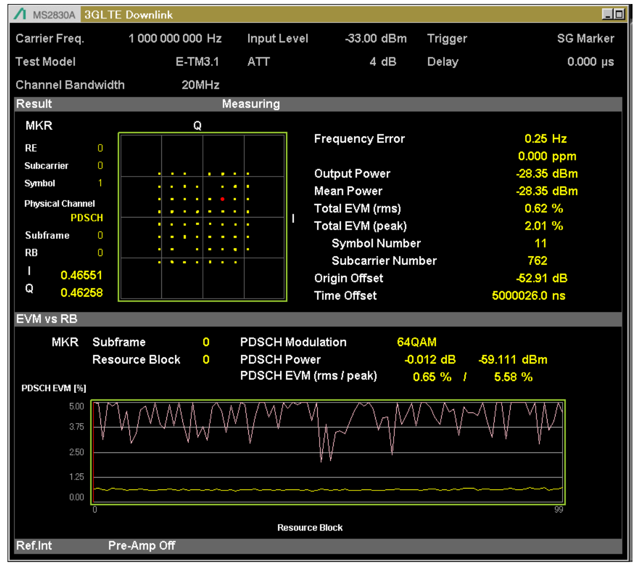

Figure 5 EVM for RFoF LTE base line measurement using 1m fiber. RF power -15dBm. Optical power 12.5 dBm.

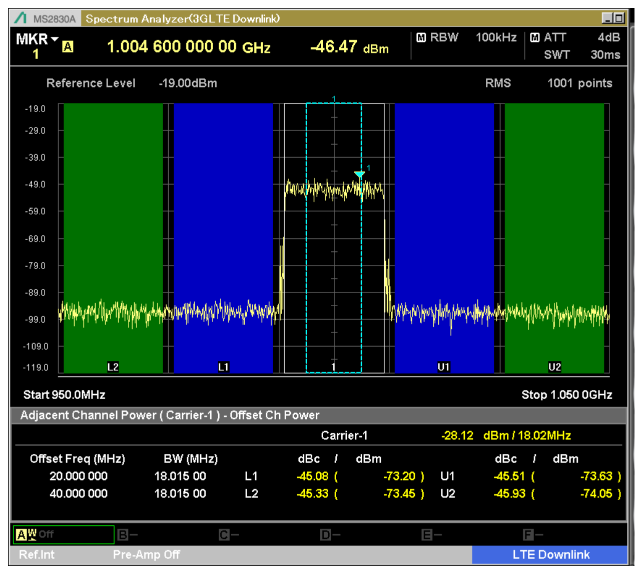

Figure 6 ACP for RFoF LTE base line measurement using 1m fiber. RF power -15dBm. Optical power 12.5 dBm. The measurement is limited by the RBW set noise floor.

When long stretches of fiber are used, in our case 25km, 50km and 71km there are several key tradeoffs for the performance optimization of the RFoF LTE link.

Gain: There are 3 key contributors (1) Input RF signal level, (2) Optical power injected into the fiber, (3) electrical gain after optical detection. Optical gain can also be introduced to offset propagation loss, but we did use any for the reported results. For each of the different fiber lengths we balanced the input RF, optical power and the gain after the photodiode to minimize the EVM.

Noise floor: The major noise source for optical transmission of RF is the noise generated by the laser due to relaxation oscillations, typically referred as Relative Intensity Noise (RIN). We have developed and use for the RFoF LTE transceiver a directly modulated DFB laser that operates at or below -160 dB/Hz. Maintaining such noise level is only possible if the laser coherence is not disturbed by external feedback and particularly by Stimulated Brillouin Scattering (SBS) from the fiber back into the laser. The transceiver was implemented with sufficient optical isolation to minimize the impact from any back scattered optical field. For the different optical lengths we used optical power between 0dBm to 11dBm as listed below in each individual case. Our findings are that as long as the transceiver was properly isolated the 71km links optimized for injected power into the link between 8 to 11dBm.

Linearity: Our goal for this work is aggregation of multiple carriers, which requires very low third order inter-modulation. Figure 7 shows IIP3 measurement of 36dBm for the RFoF link.

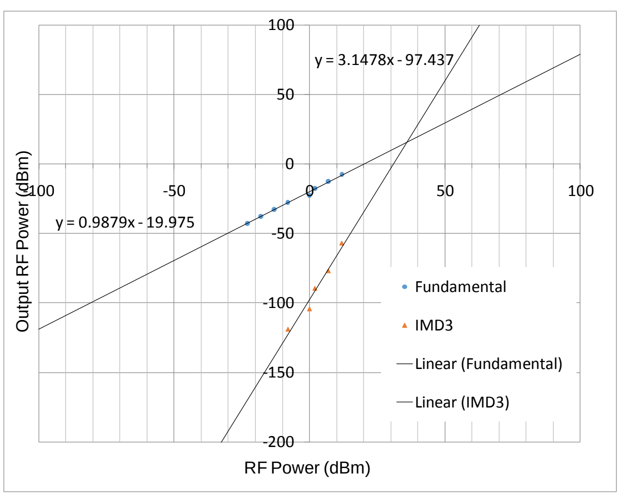

Figure 7 IIP3 measurement for the RFoF link at 1 GHz. Similar results were measured at 3 GHz.

The final transmitter linearity depends on the selection of operating point on the Light vs current (LI) curve. A plot of the transmitter bias current versus output power for the range of RF modulation is shown in Figure 8. A polynomial fit shows that the coefficient in front of the third order element is $3*10^{-7}$ which indicates very low third order nonlinearity.

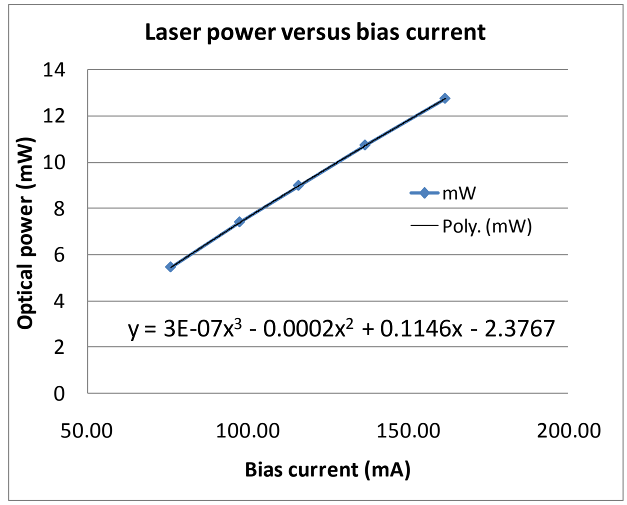

Figure 8 Transmitter output optical power versus drive current for the range of RF modulation. A polynomial fit shows very low third order non-linearity.

For all measurements described in this paper the transmitter was DC biased and operated with RF in the range shown in Figure 8. For the RFoF LTE link operation with only intrinsic gain (no additional electrical gain before or after) at 50 km length we measure EVM (rms) = 1.4%, which gives the option to build very high linearity links within this range. For longer stretches in order to increase the signal to noise ratio and still keep a RBW of 100kHz we added an amplifier after the photodiode. The amplifier had OIP3= 29 dBm, which became the linearity limiting factor of the transmission chain.

Single 20MHz carrier 25 km RFoF LTE link

Settings: optical power = 0 dBm, RFin= 2 dBm, after PD LNA gain = 26dB.

Results: EVM = 0.72% and ACP ~ -46 dBc.

Figure 9 Measured EVM = 0.72% for 25km fiber.

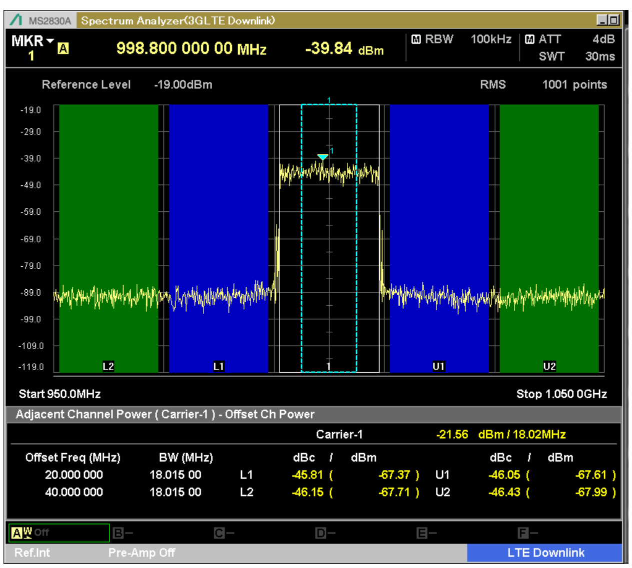

Figure 10 Measured ACP ~ -46dBc for 25km fiber.

Single 20MHz carrier 50 km RFoF LTE link

Settings: optical power = 8 dBm, RFin= 3 dBm and after PD LNA gain = 26dB.

Results: EVM = 0.96% and ACP > -44 dBc.

Figure 11 Measured EVM = 0.96% for 50km fiber.

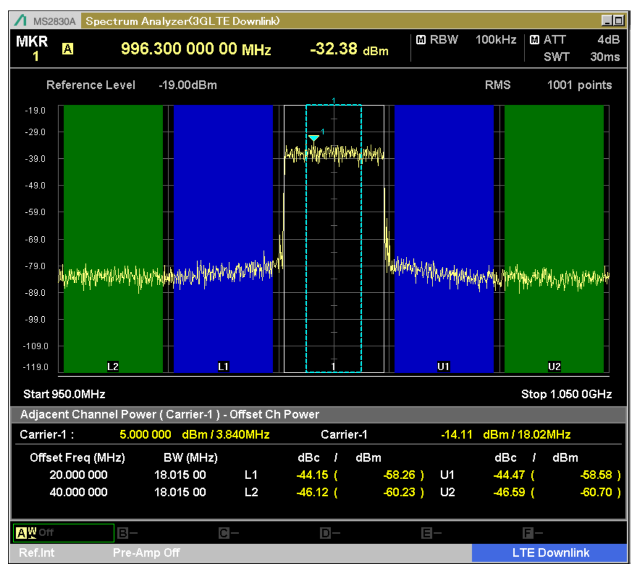

Figure 12 Measured ACP > -44dBc for 50km fiber.

Single 20MHz carrier 71 km RFoF LTE link

Settings: optical power = 8 dBm, RFin= 3 dBm and after PD LNA gain = 26dB.

Results: EVM = 1.28% and ACP > -42.2dBc.

Figure 13 Measured EVM = 1.28% for 71km fiber.

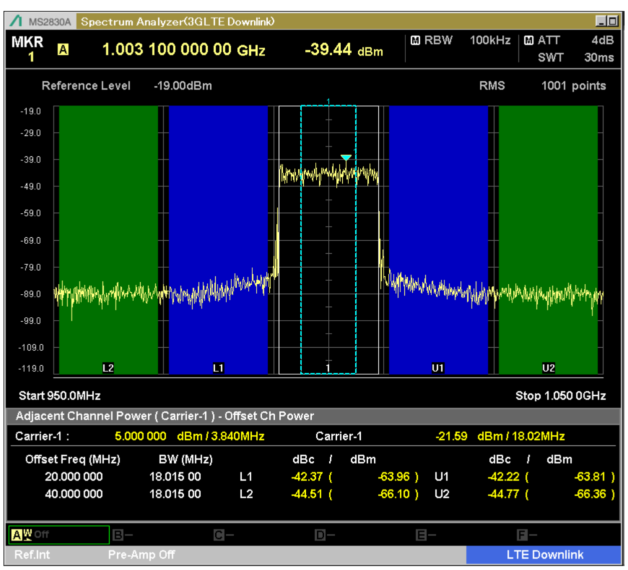

Figure 14 Measured ACP > -42.2dBc for 71km fiber.

Five 20 MHz aggregated carriers for total 100MHz bandwidth, 50cm coax – tool baseline

Settings: Carrier Aggregation (CA), RFin= -15dBm

Results: EVM = 0.89%

Figure 15 Measured EVM = 0.89%, CA 50cm coax.

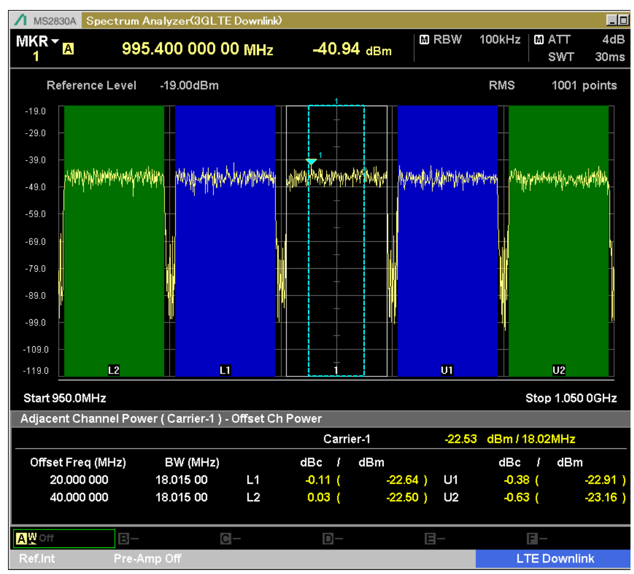

Figure 16 Measured ACP, CA 50cm coax.

Five 20 MHz aggregated carriers for total 100MHz bandwidth, 25 km fiber

Settings: optical power = 8 dBm, RFin= 0 dBm and after PD LNA gain = 26dB.

Results: EVM = 2.73%

Figure 17 Measured EVM = 2.73%, CA 25km.

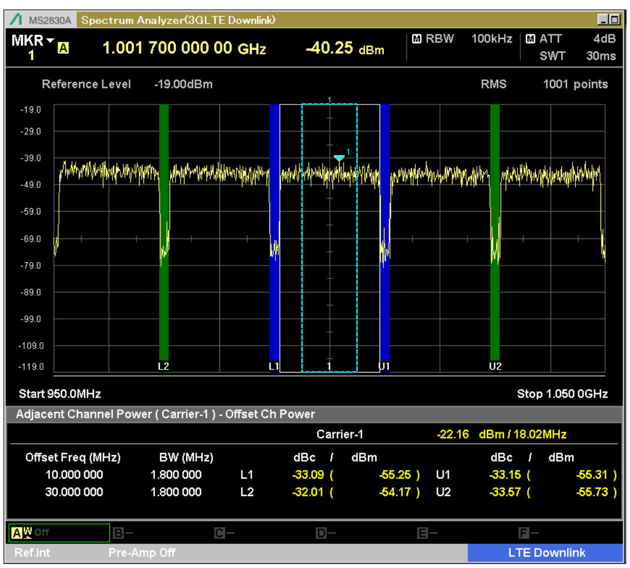

Figure 18 Measured ACP, CA 25km.

Five 20 MHz aggregated carriers for total 100MHz bandwidth, 50 km fiber

Settings: optical power = 10.9 dBm, RFin= 0 dBm and after PD LNA gain = 26dB.

Results: EVM = 2.58%

Figure 19 Measured EVM = 2.58%, CA 50km.

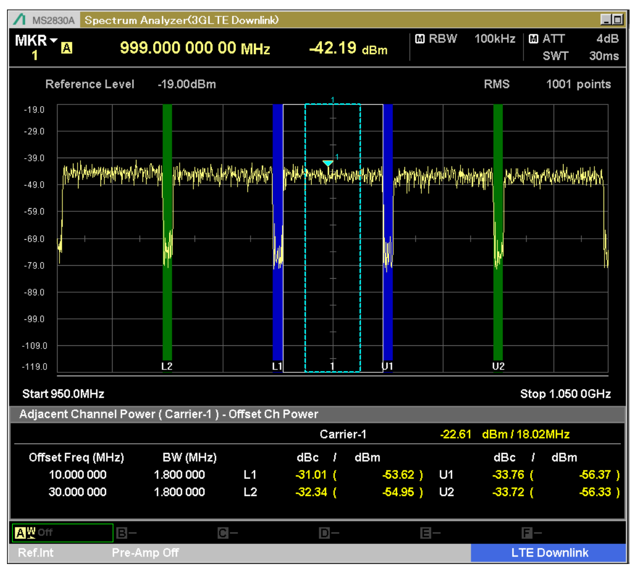

Figure 20 Measured ACP, CA 50km.

Five 20 MHz aggregated carriers for total 100MHz bandwidth, 71 km fiber

Settings: optical power = 8 dBm, RFin= -2 dBm and after PD LNA gain = 26dB.

Results: EVM = 3.03%

Figure 21 Measured EVM = 3.03%, CA 71km.

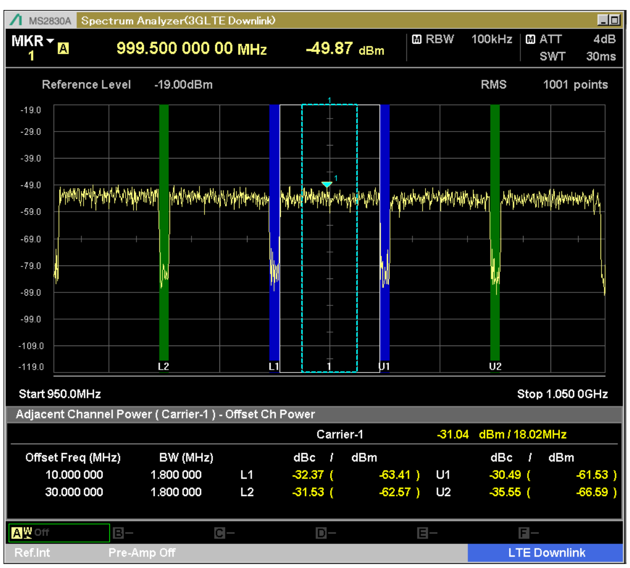

Figure 22 Measured ACP, CA 71km.

Figure 23 Picture of the used transmitter. Supply power 5V. Dimensions 40x64x15 mm^3.

Conclusions

We have developed and successfully demonstrated a highly linear, low noise RFoF link which is capable of transmitting five 20 MHz intra-band aggregated carriers with 64QAM modulation over 71km of single mode fiber and achieve total EVM (rms) of 3%. Standard test signals were used based on E-ULTRA BS test model E-TM3.1. These results meet the ≤ 8% requirement for 64QAM set in 3GPP specification 36.104. This approach for direct transmission of RF LTE signals between BBU and RRH allows complete elimination of CPRI/OBSAI layer from the fronthaul and unlocks untapped bandwidth for future 5G networks with DWDM PON implementation. In addition significant cost, power and maintenance savings can be realized do the dramatic simplification of the RRH architecture.

Current ongoing enhancements of the transmitter linearity will allow further improvmeent of ACLR and transport of OFDM, FBMC signals with 1 GHz and higher bandwidths beyond 100km using single mode optical fiber links. Using the 1550 nm C-band 80-100 such channels can be implemented on 50 GHz ITU DWDM grid, which can provide the foundation for 5G Cloud-RAN fronthaul.