Next Generation HOT / EOT

Phase 2 Testing – Pueblo, CO

Version: 1.10

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1. Revision History

Rev. No.	Updated Date	Description	Updated by
1.0	November 18th, 2024	Initial draft version	Guy Simpson
1.1	November 22nd, 2024	Content update	Menashe Shahar
1.2	November 25th, 2024	Content update	Vishal Kalkundrikar
1.3	November 26th, 2024	Content update	Menashe Shahar
1.4	November 27th, 2024	Content update	Vishal Kalkundrikar
1.5	November 27h, 2024	Review and formatting	Guy Simpson
1.6	November 29h, 2024	Reference resolution	Guy Simpson
1.7	November 30th, 2024	Review	Menashe Shahar
1.8	November 30th, 2024	Review	Guy Simpson
1.9	December 2nd, 2024	Add clarification	Menashe Shahar
1.10	December 3rd, 2024	Address MxV comments	Menashe Shahar Jeanette Chickles

2. Contents

3. List of Figures

4. Introduction

This document describes Phase 2 of the Next Generation Head-of-Train / End-of-Train (NGHE) test activity undertaken on the High-Speed Test Loop at MxV Rail's test facility in Pueblo, Colorado from November 4th, 2024, through November 7th, 2024.

The testing was performed by Ondas Networks with the support of Siemens Mobility.

5. Test Equipment

The Ondas Networks test equipment consists of the following units:

5.1 Ondas Networks Magellan HOT Emulator

The Ondas Networks Magellan HOT Emulator is based on an Airlink Venus radio platform integrated with a Polyphaser RRF-450-NFM-L 450MHz Band Pass Filter and a Raspberry Pi server to provide remote control via a cellular modem and traffic generation functionality.

The system is contained in a Pelican 1500 equipment case with the following external connections:

- DC power input
- 450 MHz RF antenna
- Cellular modem antenna
- GNSS antenna
- Grounding post

The system can be powered from the locomotive's 74 VDC supply or from an external 24 VDC Lithium battery pack contained in a weatherproof portable case.

5.2 Ondas Networks Magellan EOT Emulator

The Ondas Networks Magellan EOT Emulator is based on an Airlink Venus radio platform integrated with a Polyphaser RRF-450-NFM-L 450MHz Band Pass Filter, and a Raspberry Pi server to provide remote control via a cellular modem and traffic generation functionality.

The system is contained in a Pelican 1500 equipment case with the following external connections:

- DC power input
- 450 MHz RF antenna
- Cellular modem antenna
- GNSS antenna
- Grounding post

The system is powered by an external 24 VDC Lithium battery pack contained in a weatherproof portable case.

A standard Siemens EOT enclosure has been modified to house the 450 MHz RF and combined Cellular / GNSS antennas.

5.3 Ondas Networks Indoor Wayside Contention System

The Ondas Networks Indoor Wayside Contention system comprises an Airlink Venus Radio, a Polyphaser RRF-450-NFM-L 450MHz Band Pass Filter, and an Ondas Field Management System containing a Raspberry Pi server to provide remote control via a cellular modem and traffic generation functionality.

The system is powered by a 110 VAC supply from a standard outlet.

Connections are provided for the pole-mounted 450 MHz RF, Cellular and GNSS antennas.

5.4 Ondas Networks Outdoor Wayside Contention System

The Ondas Networks Outdoor Wayside Contention system comprises an Airlink Venus Radio, a Polyphaser RRF-450-NFM-L 450MHz Band Pass Filter, and a Raspberry Pi server to provide remote control via a cellular modem and traffic generation functionality.

The system is packaged into a self-contained outdoor enclosure with integrated Cellular and GNSS antennas. An external connector is provided for the 450 MHz RF antenna.

The system is powered by a 110 VAC supply from a standard outlet.

6. Equipment Installation

6.1 Ondas Networks Magellan HOT Emulator

The Ondas Networks Magellan HOT Emulator was installed in the second locomotive (UP 4177) of the consist, placed on top of the equipment rack as shown in the photograph below:

Figure 6-1 Magellan HOT Emulator Installation

The Ondas Networks Magellan HOT battery pack was placed on the floor next to the equipment rack as shown in the photograph below:

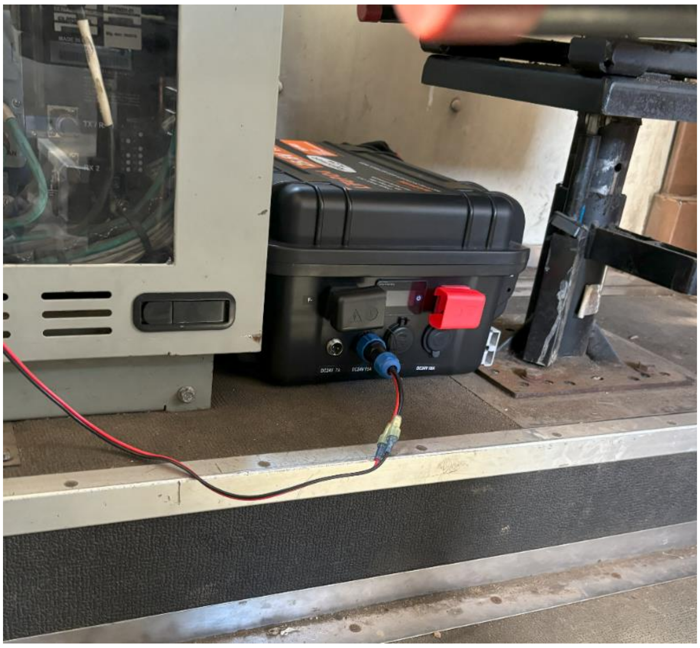

Figure 6-2 Magellan HOT System Battery Pack Installation

An alternate power source was run from a spare breaker on the locomotive DC distribution panel.

A combined Cellular / GNSS antenna was mounted on the roof of the locomotive – secured with zip ties.

6.2 Ondas Networks Magellan EOT Emulator

The Ondas Networks Magellan EOT Emulator and battery pack was installed on the coupler platform of the last car of the consist, secured by jack-straps as shown in the photograph below:

Figure 6-3 Magellan EOT System Installation

As shown, the Ondas Networks Magellan EOT Antenna Unit was installed on the coupling of the last car of the consist, secured using the standard coupler attachment.

6.3 Ondas Networks Indoor Wayside Contention System

The Ondas Networks Indoor Wayside Contention System was installed on the floor of the Diamond Bungalow as shown in the photograph below:

Figure 6-4 Indoor Wayside Contention System Installation

The Cellular and GNSS antennas were mounted on the exterior of the Diamond Bungalow as shown in the photograph below:

Figure 6-5 Indoor Wayside Contention System Cellular and GNSS Antennas

The 450 MHz RF antenna was mounted on a wooden pole next to the Diamond Bungalow as shown in the photograph below:

Figure 6-6 Indoor Wayside Contention System RF Antenna

6.4 Ondas Networks Outdoor Wayside Contention System

The Ondas Networks Outdoor Wayside Contention System was installed next to Tower 2 and connected to the 450 MHz RF antenna mounted on the wooden pole as shown in the photograph below:

Figure 6-7 Outdoor Wayside Contention System Installation

7. Operational Observations

Several issues were encountered during the setup and execution of the Phase 1 testing. These had been addressed in advance of the Phase 2 test program and no significant issues were experienced.

8. Test Execution Observations

The power output of HOT Emulator System was measured as 32.4 dBm (1.74 watts) using a Keysight V3500A RF Power Meter.

Following initial performance benchmarking no further attenuation was added between the output of the HOT Emulator System and the locomotive antenna. The JFW Industries variable attenuator was set to 0 dB.

9. Test Results

The following sections provide a summary of the test results.

Given the extensive testing, the results have been separated into discrete spreadsheets. Links to each spreadsheet on the Ondas SharePoint folder are embedded in the tables.

9.1 Test Day 1 - November 5th, 2024

Test Name	Test Result Spreadsheet SharePoint Link	Attenuation (dB)	# of Codeword Transmissions	With Position?	Contention Rate	EOT-to-HOT Packet Loss %	HOT-to-EOT Packet Loss %
HSL7	HSL7 simplex noPos 0dB 8reps - Ondas Networks.xlsx	0	**8**	No		4.5	17.3
HSL7	HSL7 simplex noPos 5dB 8reps - Ondas Networks.xlsx	5	**8**	No		8.3	28.2
HSL7	HSL7 simplex noPos 10dB 8reps - Ondas Networks.xlsx	10	**8**	No		18.5	40.3
HSL8	HSL8 simplex noPos 5dB 0reps - Ondas Networks.xlsx	5	1	No		12.2	34.4
HSL9	HSL9 simplex noPos 2dB 0reps - Ondas Networks.xlsx	2	1	No		9.7	27.5
HSL22	HSL22 simplex wPos 0dB 0reps - Ondas Networks.xlsx	0	1	Yes		18.5	27
HSL12	HSL12 simplex noPos 0dB 0reps wHighCont - Ondas Networks.xlsx	0	1	No	High	8.3	21.7

Figure 9-1 Test Day 1 Results Summary

9.2 Test Day 2 - November 6th, 2024

Test Name	Test Result Spreadsheet SharePoint Link	Attenuation (dB)	# of Codeword Transmissions	With Position?	Contention Rate	EOT-to-HOT Packet Loss %	HOT-to-EOT Packet Loss %
HSL 7 (slow)	HSL7slow simplex noPos 0dB 8reps - Ondas Networks.xlsx	0	**8**	No		4.1	20.2
HSL13	HSL13 duplex noPos 0dB 0reps wHighCont - Ondas Networks.xlsx	0	1	No	High	10.8	27.8
HSL23	HSL23 duplex wPos 0dB 0reps - Ondas Networks.xlsx	0	1	Yes		13.6	38.6
HSL23a	HSL23a duplex wPos 0dB 8reps - Ondas Networks.xlsx	0	**8**	Yes		7	27.5
HSL26	HSL26 simplex wPos 0dB 0reps wHighCont - Ondas Networks.xlsx	0	1	Yes	High	17.7	26.9
HSL11	HSL11 duplex noPos 0dB 0reps wMedCont - Ondas Networks.xlsx	0	1	No	Medium	14.6	27.6
HSL7c (vendor)	HSL7c simplex noPos no_filter no_va 8reps - Ondas Networks.xlsx	0	**8**	No		5.8	17.3
HSL24a	HSL24a simplex wPos 0dB 8reps wMedCont - Ondas Networks.xlsx	0	**8**	Yes	Medium	9.8	24.2
HSL30 (expand)	HSL30expand simplex noPos 0dB 8reps - Ondas Networks.xlsx	0	**8**	No		7.7	56 (*)

Figure 9-2 Test Day 2 Results Summary

(*) The high packet loss in the F to R direction in this test is due to the train stoppage at a spot with poor connectivity for F to R communication.

9.3 Animated Videos

A selection of animated videos of each test case are available in the Ondas SharePoint folder NGHE HSL Animations

9.4 Packet Drop Plots

The results of each test case executed have been plotted to identify successful and dropped packets by location using Google Earth. The plots are compiled in the document NGHE Phase 2 Test Plots.pdf on the Ondas SharePoint server.

10. Test Observations

10.1 Repetition/Combining Benefits

a. The tests proved again the 8 repetition/combining[1] benefits of enabling packets decoding at very low RSSI; down to –127 dBm[2]. This can be seen in the EOT-to-HOT logs. Due to the elevated noise floor in the EOT, the receiver sensitivity in the HOT-to-EOT direction was 10 dB lower. Nevertheless, the repetition/combining gain (9 dB for 8 repetition/combining), applies to HOT-to-EOT communication as well.

b. Table 10-1 below shows examples of packet decoding at -126 dBm and – 127 dBm, at different time stamps, taken from the file “HSL7_simplex_noPos_ 5dB_8 reps“ in the EOT-to-HOT direction.

Message Type	Sequence # or Nonce	Time sent (HH:MM:SS:MS)	MCS	RSSI (dBm)	CINR (dB)	Latency (s)
Status	50	18:18:33:964	QPSK 1/2	-126	0	0.209
Status	71	18:22:02:208	QPSK 1/2	-127	0	0.264
Status	107	18:28:04:316	QPSK 1/2	-127	0	0.249
Status	108	18:28:14:334	QPSK 1/2	-126	0	0.233
Status	111	18:28:44:405	QPSK 1/2	-127	0	0.259

Figure 10-1 Examples of packet decoding at RSSI down to – 127 dBm with 8 repetitions/combining

c. In the HSL7 test when 10 dB additional VA was used with 8 repetitions, EOT-to-HOT packet loss was 18% while the HSL22 test with 0 repetitions[3] and 0 dB VA had a similar EOT-to-HOT, 18% packet loss. This indicates a 10 dB gain for repetition/combining factor 8.

10.2 EOT vs HOT Noise Floor

a. The EOT noise floor was about 10 dB higher than the HOT noise floor in both 457 and 452 MHz channels. Figures 10-2 and 10-3 below show scans of EOT vs HOT noise floor at 452 MHz and at 457 MHz respectively. The scans were captured by the NGHE HOT and EOT radio scanner in the absence of EOT or HOT transmission. The shape of the figures follows the 15 kHz wide IF filter frequency response and the noise floor of interest is within the IF filter passband. The higher noise floor at the EOT vs HOT is also seen in the periodic RSSI measurements captured in the EOT and HOT logs (see figure 10-4 below). These periodic measurements are independent of the RSSI measurements when packets are received, and they show again the 10 dB higher noise floor at the EOT compared to HOT.

[1] *8 repetitions/combining refers to a forward error correction scheme in which the DPP burst is partitioned into codewords and each codeword is transmitted 8 times.*

[2] *As per figure 10-5, RSSI > - 125 dBm is needed for low packet error rate with 8 repetitions. With RSSI = -127 dBm, packets are occasionally decoded.*

[3] *“0 repetitions” is equivalent to “# of codeword transmissions” of 1.*

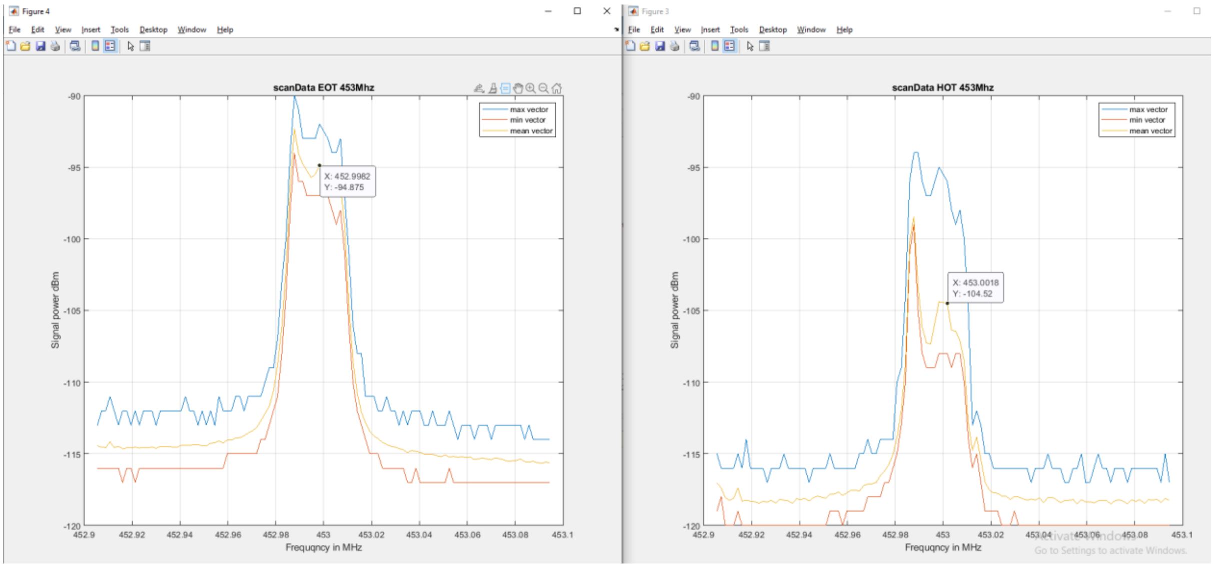

Figure 10-2 EOT vs HOT Noise Floor at 452 MHz

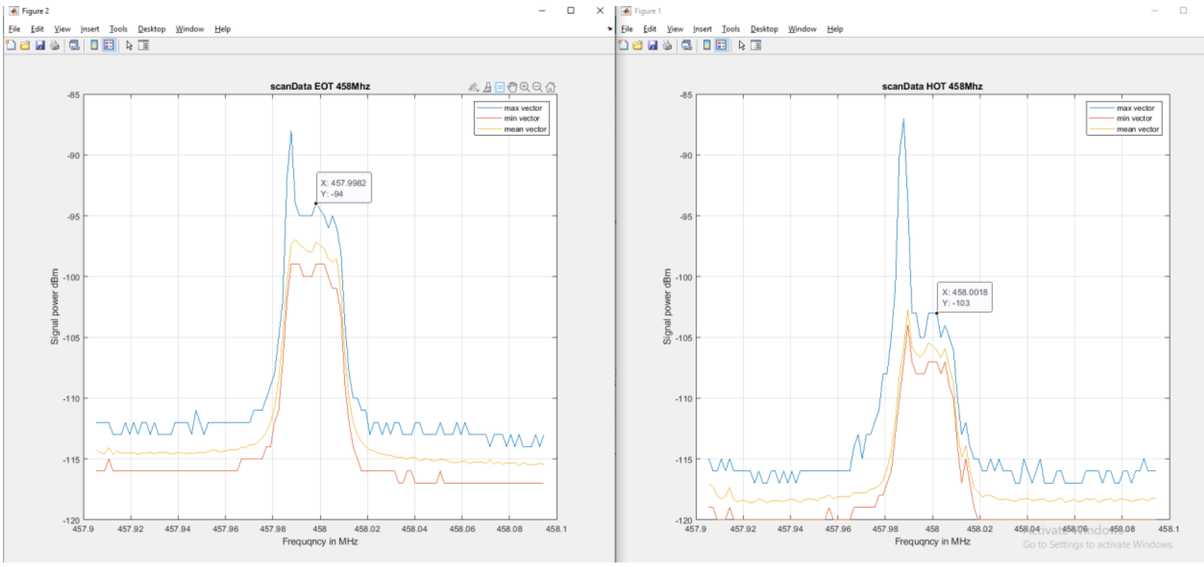

Figure 10-3 EOT vs HOT Noise Floor at 457 MHz

HOT Location RSSI measurements (Noise) when there is no TX:

```
[2024-11-05 19:29:18.052] Periodic RSSI-> Min: -127 Max: -119
[2024-11-05 19:29:18.054] Periodic RSSI-> Min: -127 Max: -119
[2024-11-05 19:29:18.058] Periodic RSSI-> Min: -127 Max: -120
[2024-11-05 19:29:18.059] Periodic RSSI-> Min: -127 Max: -118
```

EOT Location RSSI measurements (Noise) when there is no TX:

```
[2024-11-05 19:29:18] Periodic RSSI-> Min: -127 Max: -110
[2024-11-05 19:29:18] Periodic RSSI-> Min: -127 Max: -109
[2024-11-05 19:29:18] Periodic RSSI-> Min: -127 Max: -110
[2024-11-05 19:29:18] Periodic RSSI-> Min: -127 Max: -109
```

Figure 10-4 Concurrent excerpts from periodic RSSI measurements in the HOT and EOT radio logs

b. The higher noise floor at the EOT degraded its receiver sensitivity by about 10 dB relative to the receiver sensitivity of the HOT. The receiver sensitivity of the DPP based NGHE link vs repetition factor was measured in our lab as shown in table 10-5 below. The HOT receiver sensitivity in the HSL tests was consistent with the table below, i.e., -119 dBm for no repetitions and – 125 dBm[4] for 8 repetitions. Due to its elevated noise floor however, the receiver sensitivity of the EOT was about 10 dB lower, i.e., -109 dBm for no repetitions and -115 dBm with 8 repetitions.

Note that unlike in the previous FAST testing, all filters (including RF filters at 452 and 457 MHz, 15 kHz IF filter and digital filter) worked well in both HOT and EOT.

Case	# of Codeword Transmissions	RSSI (dBm)	Packet Loss (%)
1	1	-118	3.23
2		-118	5.48
3		-119	15.48
4		-119	15.48
5	2	-121	1.61
6		-121	1.61
7		-122	10.97
8		-122	10.00
9	3	-123	6.13
10		-123	7.74
11		-124	28.06
12		-124	29.03
13	4	-124	3.87
14		-124	3.87
15		-125	18.71
16		-125	18.39

Figure 10-5 DPP receiver sensitivity vs repetition factor

c. The elevated noise floor at the EOT is not due to any specific interference. We initially suspected the EOT antenna grounding, but we verified it was fine. We also verified in our lab that the EOT and HOT radios have the same receiver sensitivity performance when operating in the same environment.

d. Assuming the local noise level is the same at the EOT and HOT antenna, the noise floor is determined by the receive gain applied to the local noise. The vendor specs of the HOT and EOT antennas show similar gain in open space but while for the HOT, the open space scenario holds good, the EOT antenna operates near the rear wall of the last car in the consist which acts as a large reflector. We conducted a simulation to derive the actual EOT antenna pattern when factoring in an 8'x8' reflector, 1' away from the EOT antenna and found the close to omni open space antenna pattern changing into a 9 dBi gain antenna pointing in the rear direction, which explains the elevated EOT noise floor.

The details of our analysis are provided in the document "EOT Noise Floor Analysis" already provided.

10.3 Additional Attenuation

The attenuation added between the HOT and the HOT antenna increased the path loss in both HOT-to-EOT and EOT-to-HOT directions by the same amount. Due to the elevated noise floor at the EOT and the resulting degraded receiver sensitivity, the packet loss in HOT-to-EOT was, in all tests, much higher than in EOT-to-HOT direction.

As a result, the addition of attenuation was limited by the packet loss in the HOT-to-EOT direction. For example, the percentage packet loss for the HSL7 test in the EOT-to-HOT direction was 4.49% with 0 dB additional attenuation, 8.33%

[4] *The receiver sensitivity with 8 repetitions is expected to be 9 dB better than with no repetitions but is currently only 6 dB better. We believe the full 9 dB improvement will be realized by extending the gain adjustment sequence in the DPP burst which is currently the weakest link in the receiver performance.*

with 5 dB attenuation and 18.59% with 10 dB attenuation. The corresponding percentage packet loss in the HOT-to-EOT direction was 17.31% for 0 dB attenuation, 28.21% for 5 dB attenuation and 40.38% for 10 dB attenuation.

Given the high percentage packet loss in HOT-to-EOT direction, even with 0 dB additional attenuation, and that different attenuation could not be applied in each direction, we decided to continue the tests with 0 dB additional attenuation for both 8 repetitions and 0 repetitions.

Note the additional attenuation is applied to the TX power of 32.4 dBm (1.6 watts) of the Magellan test unit, i.e., 6.6 dB below the TX power of 39 dBm (8 Watts) of a legacy EOT.

Below is the typical percentage packet loss observed with 0 dB of additional attenuation, for both 0 and 8 repetitions:

Repetitions	EOT-to-HOT Packet Loss	EOT-to-HOT Packet Loss
8	5%	15%
0	15%	30%

10.4 Packet Loss vs Location

Packet loss occurred mostly when the train was in a straight line in both the eastern and western stretches of the Hi-Speed Loop. The packet loss in the eastern stretch was the worst. We believe the western stretch was a little better due to the objects (stationary consist and container wall) which helped in reflecting the signal between the HOT and EOT.

This behavior can be seen in figure 10-6 below showing HOT-to-EOT packet loss for test HLS7 with 8 repetitions and 10 dB additional attenuation. The green dots indicate the HOT antenna location when a Command message transmitted by the HOT was successfully received by the EOT. The red dots indicate the HOT antenna location when a Command message transmitted by the HOT was not received by the EOT.

Figure 10-6 Packet loss for HSL7 HOT-to-EOT, 8 repetitions with 10 dB additional attenuation with the train traveling in a clockwise direction.

10.5 Reason for Packet Loss

The main reason for packet loss is RSSI below receiver sensitivity as demonstrated by the information below showing the relationship between RSSI and packet loss.

Figure 10-7 shows an instance of packets being lost when the RSSI is decreasing, and packets being received again when the RSSI starts to increase.

Message Type	Sequence # or Nonce	Time sent (HH:MM:SS:MS)	MCS	RSSI (dBm)	CINR (dB)	Latency (s)
Status	105	18:27:44:267	QPSK 1/2	-121	3	0.198
Status	106	18:27:54:294	QPSK 1/2			
Status	107	18:28:04:316	QPSK 1/2	-127	0	0.249
Status	108	18:28:14:334	QPSK 1/2	-126	0	0.233
Status	109	18:28:24:357	QPSK 1/2			
Status	110	18:28:34:383	QPSK 1/2			
Status	111	18:28:44:405	QPSK 1/2	-127	0	0.259
Status	112	18:28:54:425	QPSK 1/2	-119	0	0.242
Status	113	18:29:04:447	QPSK 1/2	-117	7	0.219

Figure 10-7 Log from HSL7 simplex, 5dB attenuation, 8 repetitions, EOT-to-HOT direction

The relationship between packet loss and RSSI is also shown in Figure 10-8 below. This information is derived from the HSL7 0 dB attenuation test case in the EOT-to-HOT direction, but the same RSSI per location is valid for any test with 0 dB extra attenuation, regardless of the repetition factor.

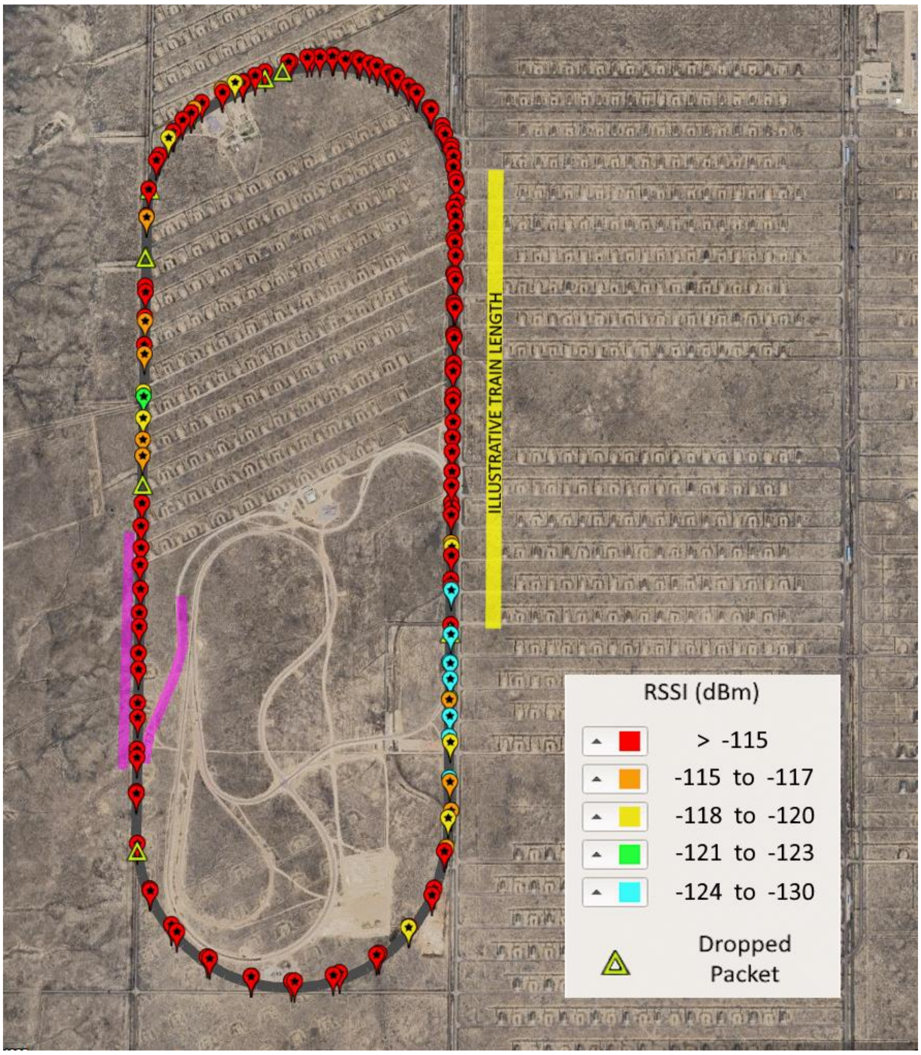

Figure 10-8 HSL7 EOT to HOT RSSI Levels and Packet Loss with train traveling in clockwise direction

In this Google Earth plot, the RSSI at the receiver location (HOT) is plotted and color coded according to the legend provided. We can see that in the projected locations at which packet loss occurred was typically preceded by lower RSSI levels, typically below -118 dBm.

10.6 452 MHz vs 457 MHz

The performances at 452 MHz and 457 MHz were the same. Due to improved filtering, we did not see the performance degradation at 452 MHz experienced in the FAST loop tests. For example, in the HSL7 test with 0 dB attenuations and 8 repetitions, the EOT-to-HOT direction experienced a 4.5% packet loss at 457 MHz, while the HSL23a test, also with 0 dB attenuation and 8 repetitions EOT-to-HOT direction had a similar 7 % packet loss at 452 MHz.

10.7 Simplex vs Duplex

The Simplex and Duplex performance without contention was the same. For example, in the HSL9 Simplex test with 2dB attenuation and no repetitions the EOT-to-HOT direction experienced a 9.7% packet loss, while the HSL13 Duplex test, with 0dB attenuation, no repetitions the EOT-to-HOT direction had a 10.8% packet loss.

10.8 Test Results with Contention

The CSMA/CA mechanism with deferral worked very well in both Simplex and Duplex modes. The extra percentage packet loss due to collisions was very low. For example, in the HSL12 Simplex test with contention, the EOT-to-HOT direction experienced a 12.8% loss, while the HSL9 without contention had a 9.7% loss. In the HSL11 Duplex test with contention the EOT-to-HOT direction experienced a 15% packet loss, while in the HSL13 test case without contention the packet loss was 11%. Note that the contention traffic for the contention tests was generated randomly.

11. Recommendations

1. Explore possible improvements to the EOT antenna and/or mounting on the train to reduce the gain of the antenna pattern in the rearward's direction. We recommend comparing the noise floor of alternate solutions using the Magellan platform connected to the antenna as done with the Siemens EOT. Also, we recommend comparing the noise floor of the Siemens EOT with internal and external antennas. These tests can be done on a static railcar.

   The reason for using Magellan is its capability to run a scanner application as well as providing periodic noise RSSI measurements.

2. Assuming the EOT noise floor problem is a "fact of life", it can be addressed by increasing the transmit power and/or repetition/combining factor in the HOT-to-EOT direction as compared to the EOT-to-HOT direction. Here are possible configurations to make the link symmetrical:

   a. Use 10 dB higher transmit power at HOT. The EOT transmits at 8 Watts (39 dBm) so this implies transmitting at 49 dBm (80 Watts) from the HOT.

   b. Use repetition factor 8 for HOT-to-EOT communication and no repetitions in EOT-to-HOT communication. This is equivalent to increasing the TX power by 9 dB.

   c. Increase both TX power and repetitions at the HOT. For example, if the HOT TX power is increased by 4 dB to 20 Watts (43 dBm) and a repetition factor 4 (equivalent to 6 dB extra power) is used for HOT-to-EOT communication, the total increase would be the required 10 dB.

   Note that the HOT is not subject to the same input power constraints of the EOT and therefore increasing the TX power at the HOT is more feasible. Also, the HOT-to-EOT message length is shorter than the EOT-to-HOT status message, especially when positioning is used. As such, the impact of using repetitions in HOT-to-EOT direction on duty cycle is smaller.

3. The HSL test environment with the 1.2-mile-long train, is most likely not the worst-case scenario for NGHE communication. We believe the repetition/combining technology used in the Ondas 802.16t DPP based NGHE solution, can best address various communication scenarios by providing a wide range of repetition factors. Repetition factors can range from zero up to 128 repetitions, with an associated repetition gain of up to 21 dB.

   An automatic repetition factor selection algorithm can be implemented. With this, the lowest repetition factor will be selected automatically in HOT-to-EOT and in EOT-to-HOT directions, independent of each other, as needed to address the instantaneous wireless channel conditions.