Repetition Combining vs Simple Repetition

March 6th, 2025

Background and Objectives

1. During the November 2024 High Speed Loop (HSL) tests at MxV test facility in Pueblo CO, Ondas validated the significant improvement in receiver sensitivity when running Repetition/Combining vs no repetitions. This makes communication much more robust and helps maintain good Next Generation Head of Train End of Train (NGHE) connectivity in difficult conditions. The results of the HSL test are summarized in Ondas HSL test report presentation.
2. The MxV HSL test facility is in flat terrain, typical of many parts in the country. The test conditions, however, do not represent other scenarios including non-flat terrain, longer trains and higher train speeds (the speed at MxV was limited to 40 mph). There is a need to project the NGHE connectivity performance of the radio beyond the HSL test conditions.
3. The objective of this document is to compare the performance of Ondas IEEE 802.16t Direct Peer to Peer (DPP) based NGHE solution in various channel conditions, using the following repetition schemes:
    a. No repetitions
    b. Simple repetitions (this is also referred to as "message repetitions"):
        i. At the transmitter: Each NGHE message is repeated 8 times
        ii. At the receiver: All 8 instances of a received message are decoded, and one error free instance is selected if available. The other instances are not used.
    c. Repetition/combining:
        i. At the transmitter: Each DPP burst encapsulating an NGHE message is partitioned into codewords. Each codeword is repeated 8 times.
        ii. At the receiver: All 8 instances of each codeword are combined before demodulation, i.e., all instances are used in the decoding of the received signal.

    Note 1: IEEE 802.16t DPP supports a repetition factor between 1 (no repetitions) and 128 (127 repetitions). The value 8 was selected for the HSL NGHE tests at MxV because its gain of 9 dB was sufficient for this scenario. We recommend collecting NGHE connectivity data on tracks across the country to determine what repetition factor should be used. We also recommend adding an automatic repetition factor selection mechanism to select the appropriate repetition factor in each direction, independent of the other direction based on the instantaneous channel conditions.

    Note 2: All 3 schemes employ QPSK with a Convolutional Coding rate ½. Both simple repetitions and repetition/combining employ repetition factor 8.

4. The results presented in this document apply to IEEE 802.16t DPP but the performance improvement due to repetition/combining relative to no repetitions and relative to simple repetitions holds true for other radio technologies.

Advantages of Ondas IEEE 802.16t DPP Solution Beyond Repetition / Combining

1. While repetition/combining has a significant contribution in making communication more robust, the underlying radio technology with no repetitions is also very important. Here are the IEEE 802.16t DPP advantages beyond repetition/combining:
    a. Operation in various channel configurations including:
        i. Using the same channel for communication in both directions. This doubles frequency utilization relative to legacy.
        ii. Using a distinct channel for communication in the HOT to EOT direction (this is also referred to as F to R direction) and in the EOT to HOT direction (this is also referred to as R to F direction). This is the same as in legacy S-9152 AAR air interface protocol.
        iii. Combine multiple non-adjacent channels available to the railroads in the 450 MHz band to further increase the NGHE capacity if needed.
    b. IEEE 802.16t offers a wide range of Modulation and Coding Schemes (MCS), from QPSK with Convolutional Turbo Coding (CTC) rate ½ and up to 64QAM with CTC rate 5/6. Ondas selected QPSK ½ for NGHE HSL testing (this requires a minimum CINR of only 3 dB), but any of the other MCSs can be selected automatically in each direction independent of the other direction as per the instantaneous channel conditions.
    c. IEEE 802.16t offers a configurable symbol rate. For a 12.5 kHz wide channel, this can be configured up to about 11 ksymbols / sec so the entire bandwidth authorized by the FCC is used.
    d. Over the air waveform is OFDM:
        i. A Cyclic Prefix (CP) is used to align multiple replicas of the signal in multipath typical of HOT-EOT
        ii. The waveform is resilient to frequency shift caused by Doppler
2. Ondas NGHE solution may also offer the following advantages:
    a. Higher TX power at the HOT, at the EOT or at both. Ondas' recommendation is to maintain the TX power of 8 Watts at the EOT while increasing the TX power at the HOT to 30 Watts or even higher. This is needed to balance the link budget in both directions given the higher noise floor at the EOT.
    b. The repetition factor could be distinct for F to R and for R to F communication. This will also help balance the link.
    c. Ondas NGHE platforms are backward compatible with the legacy AAR S-9152 air interface protocol.

    d. When operating in legacy mode, Ondas NGHE platforms can perform BCH error correction to improve performance. S-9152 only requires BCH error detection.
    e. Perform CSMA/CA against TX frequency, RX frequency or both.
    f. Capture extensive logs including packet loss, RSSI signal & RSSI noise vs time and location.

Repetition / Combining vs Simple Repetitions and No Repetitions - Performance Analysis

1. The performance analysis was performed using MATLAB simulation. The following parameters were used in the simulation:
    a. Both simple repetitions and repetitions/combining use 8 repetitions
    b. Both simple repetitions and repetition/combining use QPSK with Convolutional Coding (CC) rate ½.

       Note: DPP supports both CC and Convolutional Turbo Coding (CTC). CTC provides 2 dB better performance than CC but the difference in performance between repetition/combining and simple repetitions is independent of the use of CC or CTC.

    c. Packet size: 36 bytes. Note that the packet error rate for a given bit error rate increases with the packet length as $PER=1-(1-BER)^n$ where n is the number of bits in the packet. The NGHE R to F Status message with positioning is the longest NGHE message with 53 bytes. The F to R NGHE Command and Ack messages, however, are much shorter with 13 and 8 bytes respectively.
    d. 3 Multipath model:
        i. Delays: 0.022 ns, 2.33 ns, and 5.31 ns. This corresponds to distances of 100 meters (a nearby tracks), 1 mile (a random wayside object) & 2 miles (a mountain or hill)
        ii. Average extra path loss in each path on top of a common path loss: 5, 10 & 15 dB.
    e. Train length: 0.5 miles

2. Figure 1 below shows the percentage packet error rate vs EN/N0 (dB) for repetition combining, simple repetitions and no repetitions in an Additive White Gaussian Noise (AWGN) channel mode. We can see about 10 dB better performance for repetition combining vs no repetitions which is close to the expected 9 dB (10 log 8) improvement. We can see however that repetition/combining also outperforms simple repetitions by more than 6 dB. Also note the steep rapid increase in percentage packet loss for simple repetition for Eb/N0 below 2 dB. It appears that at this Eb/N0, the probability of an error free instance of the message is too low. Even if repeated 8 times, the probability of one error message instance remains too low. Note also that repetition combining supports operation in negative Eb/N0. i.e., well under the noise floor.

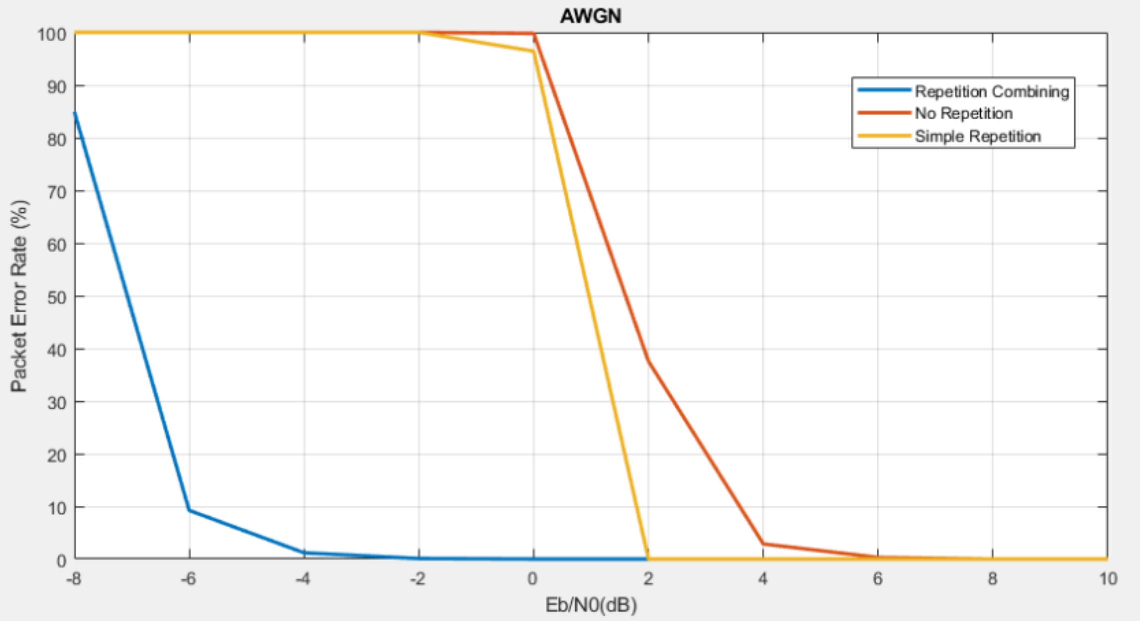


Figure 1: Percentage packet error rate vs Eb/N0(db) for repetition combining, simple repetition and no repetition with AWGN channel model.

3. Table 1 below shows the receiver sensitivity performance improvement of Ondas DPP radio using repetition combining, as the number of repetitions increases. The second column shows the performance measurements done at Ondas lab. Ondas expects to further improve the receiver sensitivity performance as shown in the 3rd column.

Repetition Factor	Measured Receiver Sensitivity in a 12.5 kHz wide channel in dBm	Expected Receiver sensitivity in a 12.5 kHz wide channel in dBm
1	-120	-120
2	-122	-123
4	-124	-126
8	-126	-129

Table 1: Receiver sensitivity vs repetition factor

4. For comparison, here is the receiver sensitivity of various radios operating in a12.5 kHz wide channel, used by railroads. The performance is taken from the products' data sheets:
   a. Legacy BCP & WCP: -116 dBm
   b. Ritron DTX-445: 0.25 µV for 12 dB SINAD = -119 dBm
   c. Motorola MTR3000: 0.30 µV for 12 dB SINAD = -118 dBm
   d. Kenwood NX-700: 0.28 µV for 3% BER = -119 dBm
   e. Ritron DTXM ("NXDN data radio") 0.28 µV = -119 dBm
   f. Meteorcomm PTC 220 (16 kb/s @ BER < 10-4): -111 dBm

5. The repetition combining 9 dB receiver sensitivity improvement relative to no repetitions with 8 repetitions for AWGN channel model, holds good regardless of noise floor. In perfect conditions, i.e., in the absence of man-made interference, the noise floor for a 12.5 kHz wide channel is -174 + 10 *log (bandwidth in Hz) = -133 dBm. In real life however, man-made interference is always present, and the noise floor is higher. For example, in the HSL tests, we measured the noise floor at the EOT to be 10 dB higher than at the HOT.
6. Figures 2, 3 & 4 below show the percentage packet error rate vs Eb/N0 in dB for repetition combining, simple repetitions and no repetition, with a channel model including AWGN noise, multipath and doppler. The multipath model considers reflections from 3 wayside objects located 100 meters, 1 mile and 2 miles from the train. The doppler frequency shift is analyzed in Appendix A. It is due to the movement of the train relative to the static wayside objects reflecting the signal.

The figures show that while multipath and doppler degrades performance in all cases as the speed of the train increases, repetition combining helps maintain a descent packet error rate performance while operation with simple repetitions and no repetitions becomes extremely unreliable. This shows that the repetition combining gain is much higher than 9 dB (the gain for AWGN channel) in the presence of multipath and doppler.

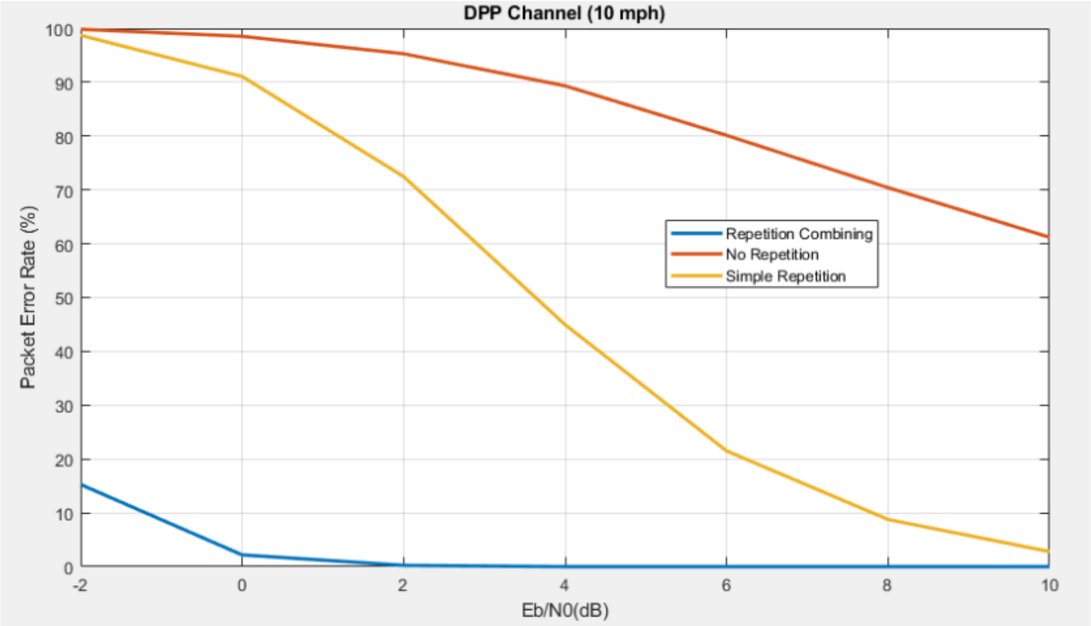


Figure 2: Percentage packet error rate vs Eb/N0 for repetition combining, simple repetitions and no repetition, for a channel model including AWGN, multipath and doppler when the train is moving at 10 mph.

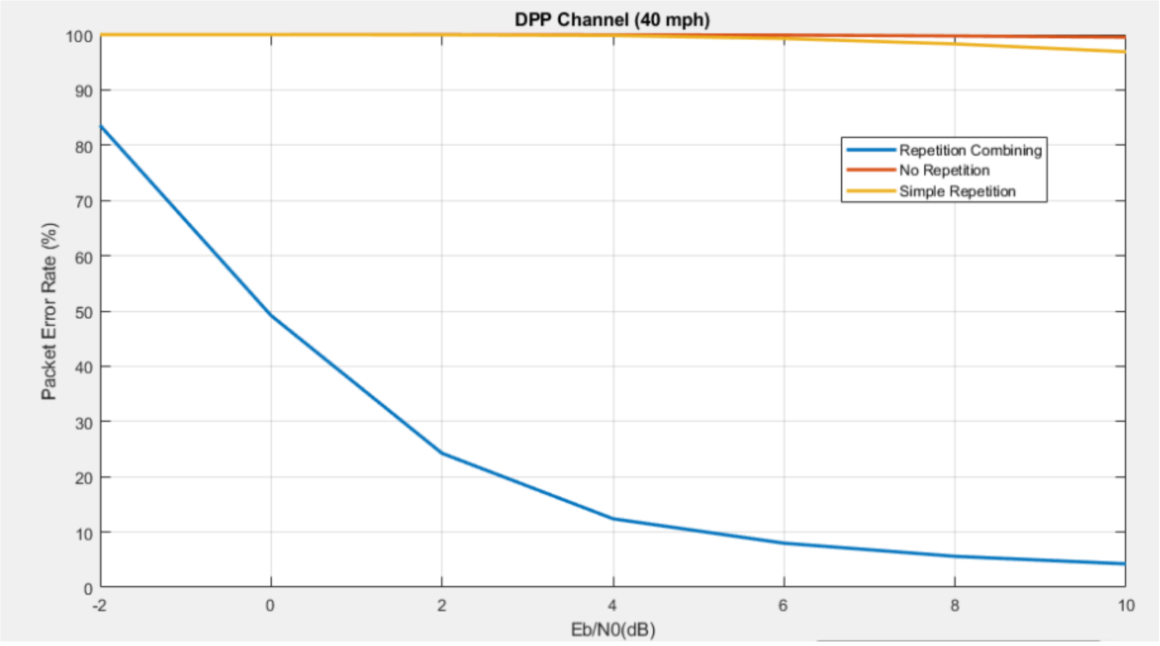


Figure 3: Percentage packet error rate vs Eb/N0 for repetition combining, simple repetitions and no repetition, for a channel model including AWGN, multipath and doppler when the train is moving at 40 mph.

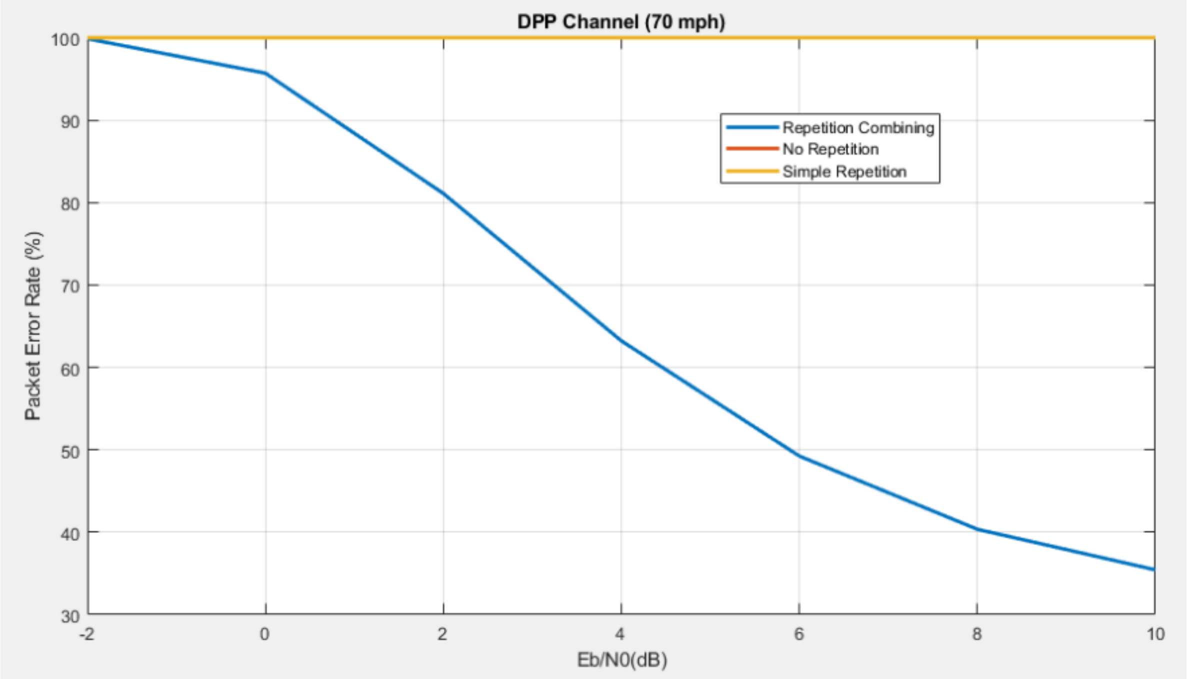


Figure 4: Percentage packet error rate vs Eb/N0 for repetition combining, simple repetitions and no repetition, for a channel model including AWGN, multipath and doppler when the train is moving at 70 mph.

7. To better understand the reason for the improved performance of repetition combining with multipath and doppler, we plotted the power of the received signal in the presence of multipath and doppler for various train speeds. This is

shown in figures 5, 6, 7 & 8 below. In all cases, we used the same train length (0.5 mile) and multipath model as described on page 4. We can see from these figures rapid power variations and fading. The frequency and depth of the fading increases as the speed of the train increases. Also, the rise and fall of the fades become faster and it becomes more difficult for the AGC to adjust the gain. Simple repetition is not able to find a clean interval to get even one error free instance of the message through.

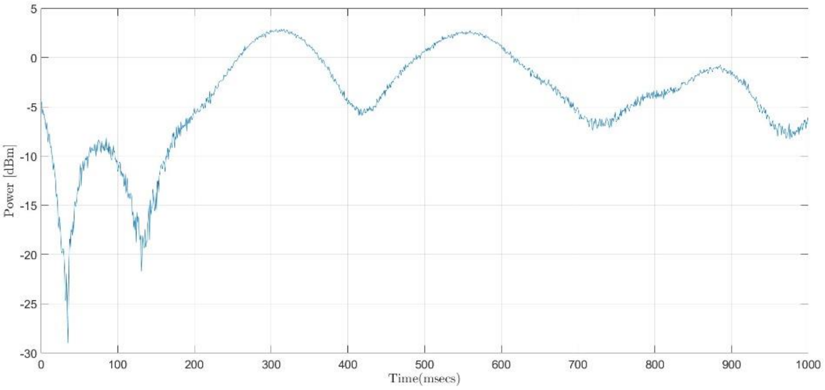


Figure 5: Received signal strength over time when the train moves at 10 mph

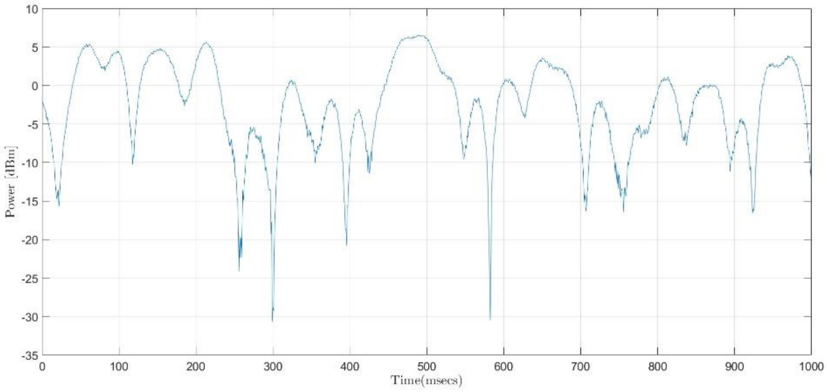


Figure 6: Received signal strength over time when the train moves at 30 mph

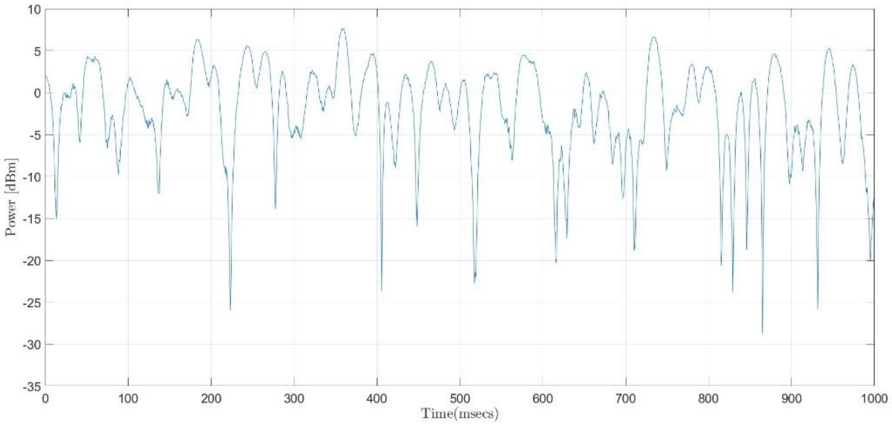


Figure 7: Received signal strength over time when the train moves at 50 mph

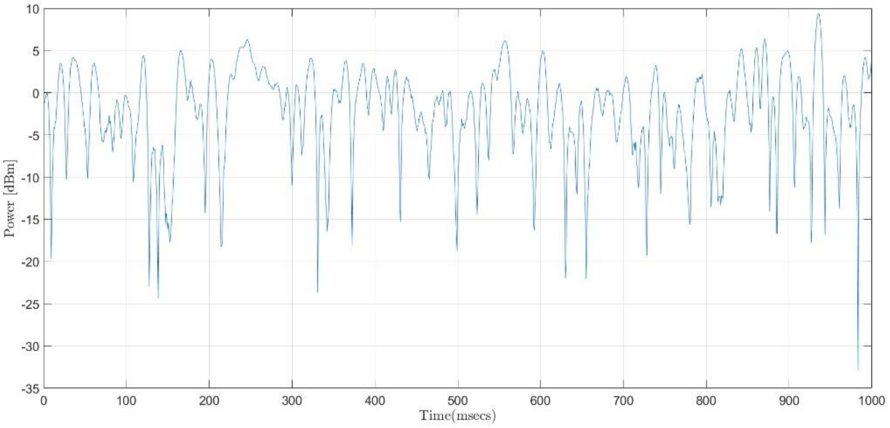
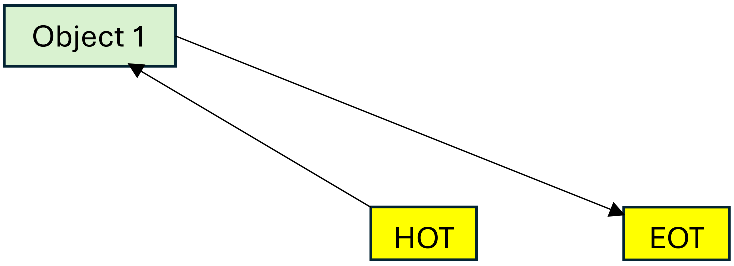


Figure 8: Received signal strength over time when the train moves at 70 mph

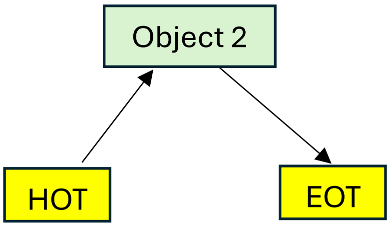
Appendix A: NGHE Doppler Scenarios

The object reflecting the signal between the HOT and EOT may be located ahead of the locomotive, between the locomotive and the end of the train or behind the end of the train. The three cases are shown as scenario 1, 2 and 3 respectively. The doppler frequency shift for each of these scenarios is analyzed below.

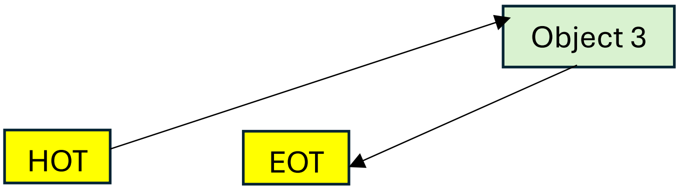
Scenario 1



Scenario 2



Scenario 3



The formula for Doppler frequency is given by,

$$\boldsymbol{f_o} = \frac{v \pm v_o}{v \pm v_s} \boldsymbol{f_s},$$

Where, v = velocity of EM waves,

vs = source velocity,

vo = observer velocity,

fs = source frequency,

fo = observer frequency.

When the source approaches the object, the sign is ‘+’.

When the source moves away from the object, the sign is ‘-’.

Scenario 1,

Doppler $\boldsymbol{f_{o1}}$, from HOT approaching object 1,

$$\boldsymbol{f_{o1} = \frac{v}{v+v_s} f_s,}$$

Doppler $\boldsymbol{f_{or}}$, from EOT approaching object 1,

$$\boldsymbol{f_{or} = \frac{v+v_s}{v} f_{o1},}$$

$$\boldsymbol{f_{or} = f_s}$$

Scenario 2,

Doppler $\boldsymbol{f_{o1}}$, from HOT moving away from object 2,

$$\boldsymbol{f_{o1} = \frac{v}{v-v_s} f_s,}$$

Doppler $\boldsymbol{f_{or}}$, from EOT approaching object 2,

$$\boldsymbol{f_{or} = \frac{v+v_s}{v} f_{o1} => f_{or} = \frac{v+v_s}{v-v_s} f_s}$$

Scenario 3,

Doppler $\boldsymbol{f_{o1}}$, from HOT moving away from object 3,

$$\boldsymbol{f_{o1} = \frac{v}{v-v_s} f_s,}$$

Doppler $\boldsymbol{f_{or}}$, from EOT moving away from object 3,

$$\boldsymbol{f_{or} = \frac{v-v_s}{v} f_{o1},}$$

$$\boldsymbol{f_{or} = f_s}$$

Now, for fs=450 MHz and vs=79 mph, v=6.7*10^8 mph (speed of light),

In scenario 1, observed frequency, fo = fs = 450 MHz (Doppler = 0)

In scenario 2, observed frequency, fo = (6.7*10^8+79)*fs/(6.7*10^8-79) = 450.000106 MHz (Doppler = 106 Hz)

In scenario 3, observed frequency, fo = fs = 450 MHz (Doppler = 0)