UAT-WP-8-04A
Results to Date of BER Tests on Pre-MOPS UATs

6 November 2001

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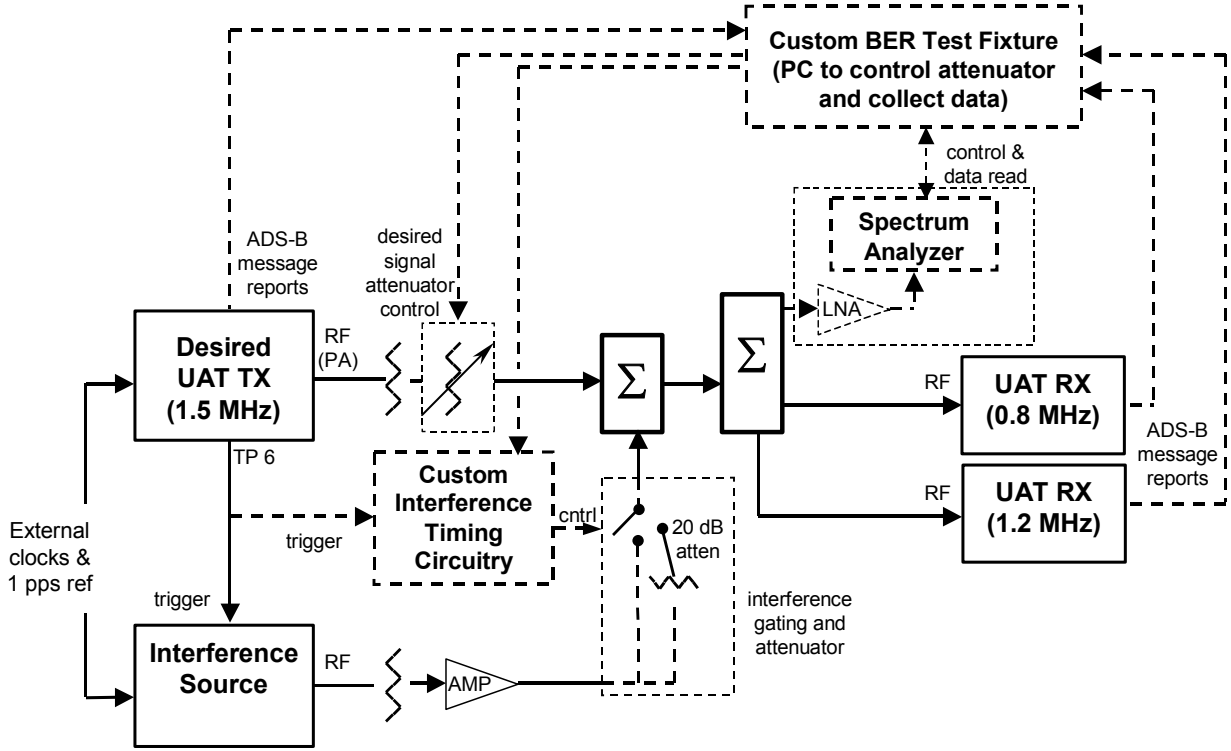
Outline

- Approach
- Results:
  - DME Interference
  - Link 16 Interference
  - Single UAT + White Gaussian Noise
- Status

BER Test Setup



Fixed attenuators and amplifiers are adjusted to provide:

- a desired-signal level at the UAT RX inputs of -20 dBm when signal attenuator is set to 0 dB, and

- a peak interference level at the UAT RX inputs of -20 dBm when interference is gated on and the 20 dB interference attenuator is bypassed.

Definition of Signal, Interference & Noise Levels (Spectrum Analyzer Settings)

- UAT (as desired or interfering signal)
  - Frequency of Peak Level in 5-MHz Span around 981 MHz
    - Tends to occur at UAT mark or space frequency
  - 1 MHz Resolution BW
  - 1 MHz Video BW / Max Hold
- DME
  - Frequency of Peak Level in 5-MHz span around 981 MHz
    - Occurs near DME center frequency
  - 1 MHz Resolution BW
  - 1 MHz Video BW / Max Hold
- Link 16
  - Frequency of Peak Level in 5-MHz Span around Link 16 freq (981, 984, 987, … 1002 MHz)
  - 3 MHz Resolution BW
  - 3 MHz Video BW / Max Hold
- White Gaussian Noise
  - Frequency of Peak Level in 5-MHz Span around 981 MHz
    - Occurs randomly throughout span
  - 1 MHz Resolution BW
  - 300 Hz Video BW

BER Testing Approach

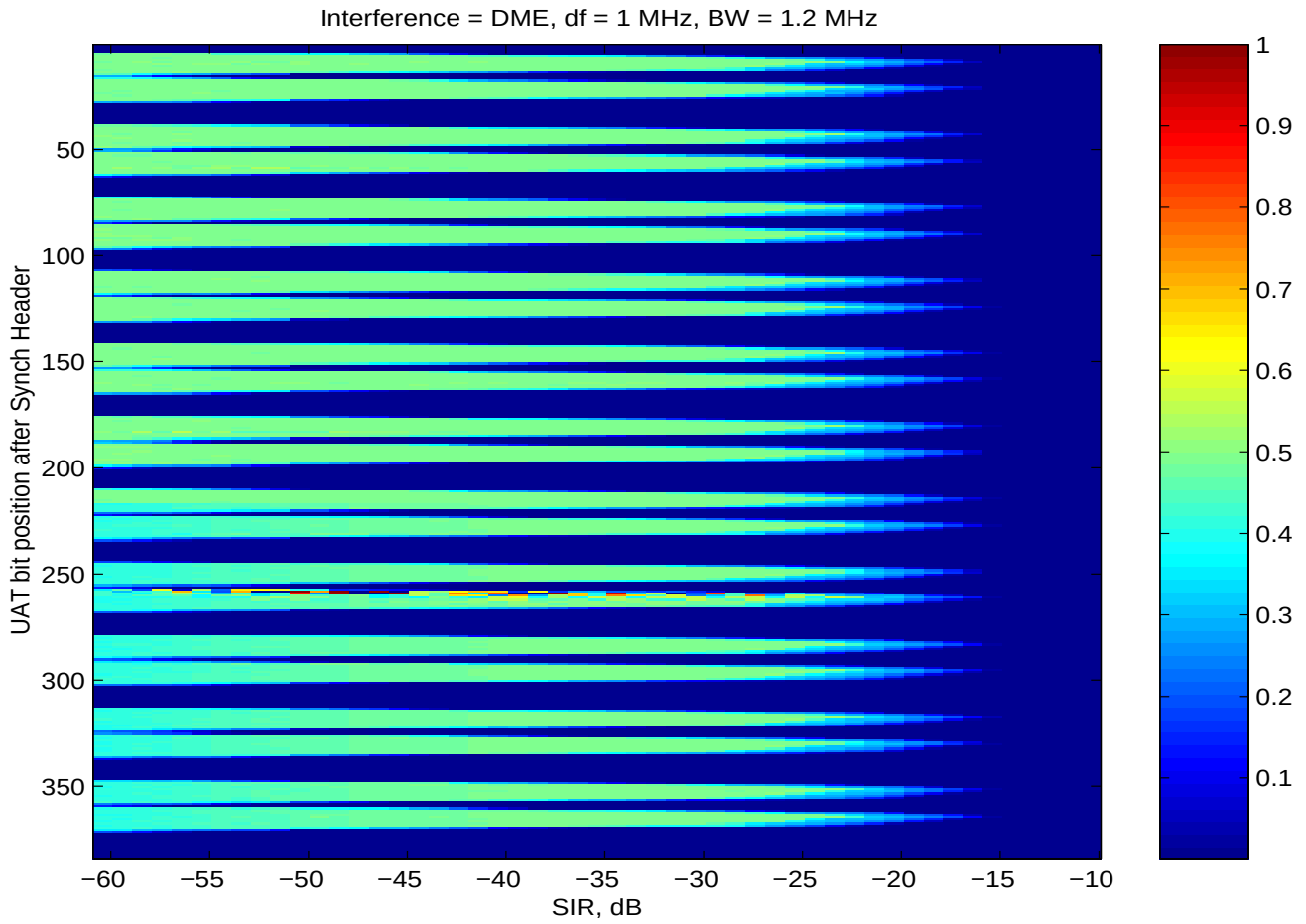
- Desired signal = UAT Long message
- For pulsed (DME and Link 16) interference:
  - Pulse positions held fixed relative to UAT message
    - Specially clocked & gated DME and Link 16 transmitters provided by JSC
  - 5 to 12 interference pulses per UAT message
    - 30 (high SIR) or 15 kHz (low SIR) DME rate
    - 38 kHz Link 16 rate (every other hop)
  - No interference pulses during UAT synch header
  - Approx. 60,000 pulses measured for each SIR, interference type, and frequency offset
- BER computed separately for each of 384 payload/FEC bit positions
  - Reported TX and RX messages were compared bit-by-bit, regardless of whether or not they decoded
- Interference level fixed at ~ -40 dBm or –20 dBm while UAT signal level varied

Difficulties Encountered In Measuring Bit Errors

- Non-random bits in message Sequence Number (bits 257-272) gave variable results
  - Most slowly changing bits (257-260) showed largest effect
  - Could be due to asymmetric bit error probabilities (0-to-1 vice 1-to-0)
    - e.g. unequal probabilities for sent bit, plus off-frequency interference
  - Modified pseudo-random data generation to make all bits change fast
    - But didn't use on DME or Link 16 tests
      - –Wanted to minimize change to JSC MER test setup
- Raw bit data reported by TX and RX units was not always reliable
  - Both TX and RX units occasionally reported spurious raw messages
  - RX units occasionally reported (or we caused) raw messages with bytes shifted left one or more positions
  - Work-around was to reject any report of received message with >30% average BER over last 21 bytes

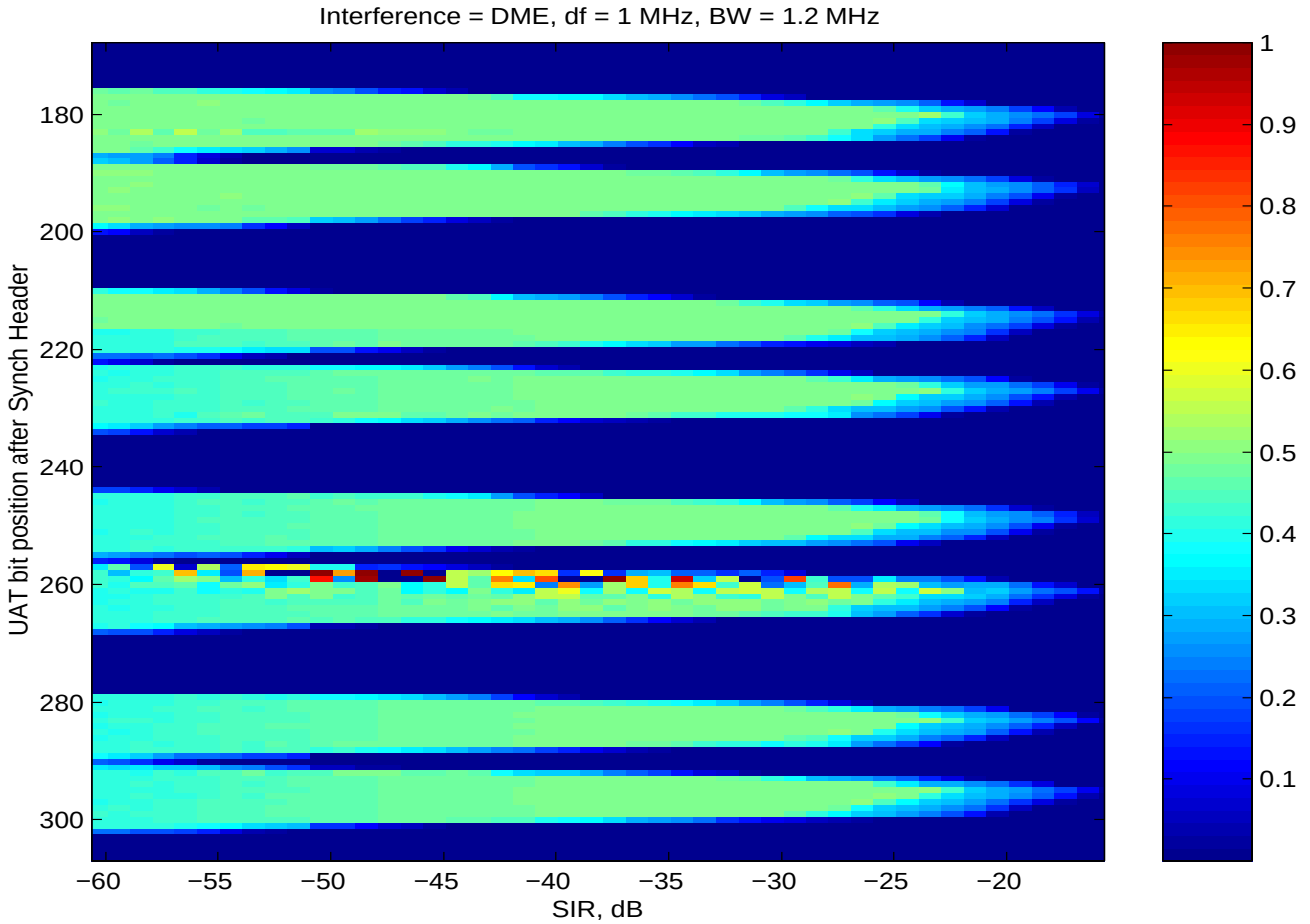
Sample Raw BER Data For A Single Interference Type--

Each vertical slice shows BER (color) measured at a single SIR value



Detail of Raw BER Plot,

showing bad data at bits 257-260+, and impact of rejecting reports with high BER over last 21 bytes (bits 217+)



Post-Measurement Processing

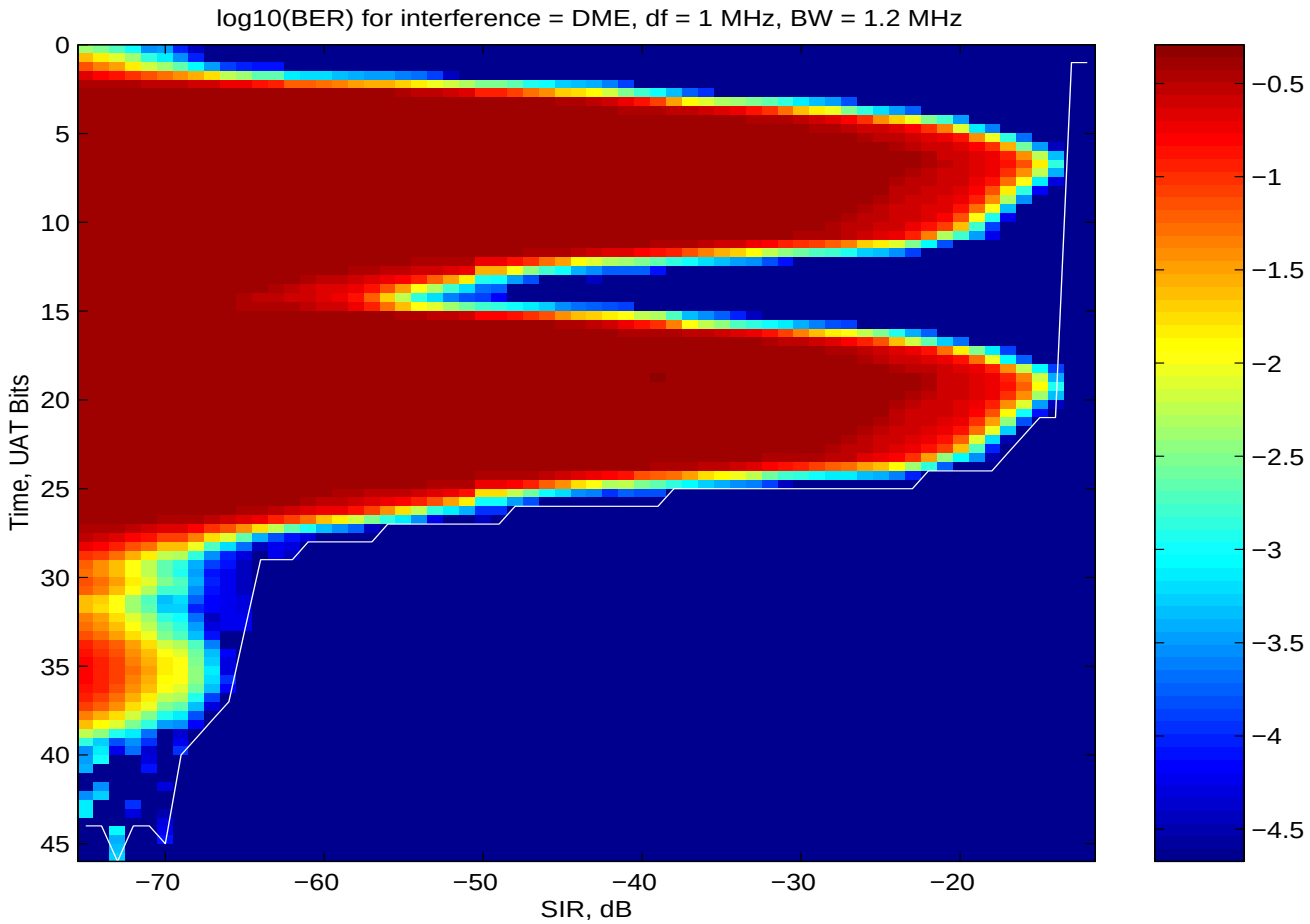
- Average together all pulses (or pulse pairs) within a message
  - Align them in time with one another
    - Non-integer bit offsets
  - Average all samples within +/- 0.5 bit
    - For positions spaced every 0.5 bit
- Procedures for handling data anomalies
  - Non-random Sequence Number bits
    - Remove bits 257-260 from averages
  - Data in bits 217-384 biased low by rejecting bad reports
    - Data renormalized upward by fixed multiplier determined as best fit
- Receiver noise subtraction
  - For very low SIRs, excess bit errors due to receiver noise (BER_N , computed from average BER when no pulse was present) were subtracted as $BER_I = (BER_{I+N} – BER_N) / (1 – 2 * BER_N)$
  - Enabled BER estimation down to –95 dBm

Interference = DME

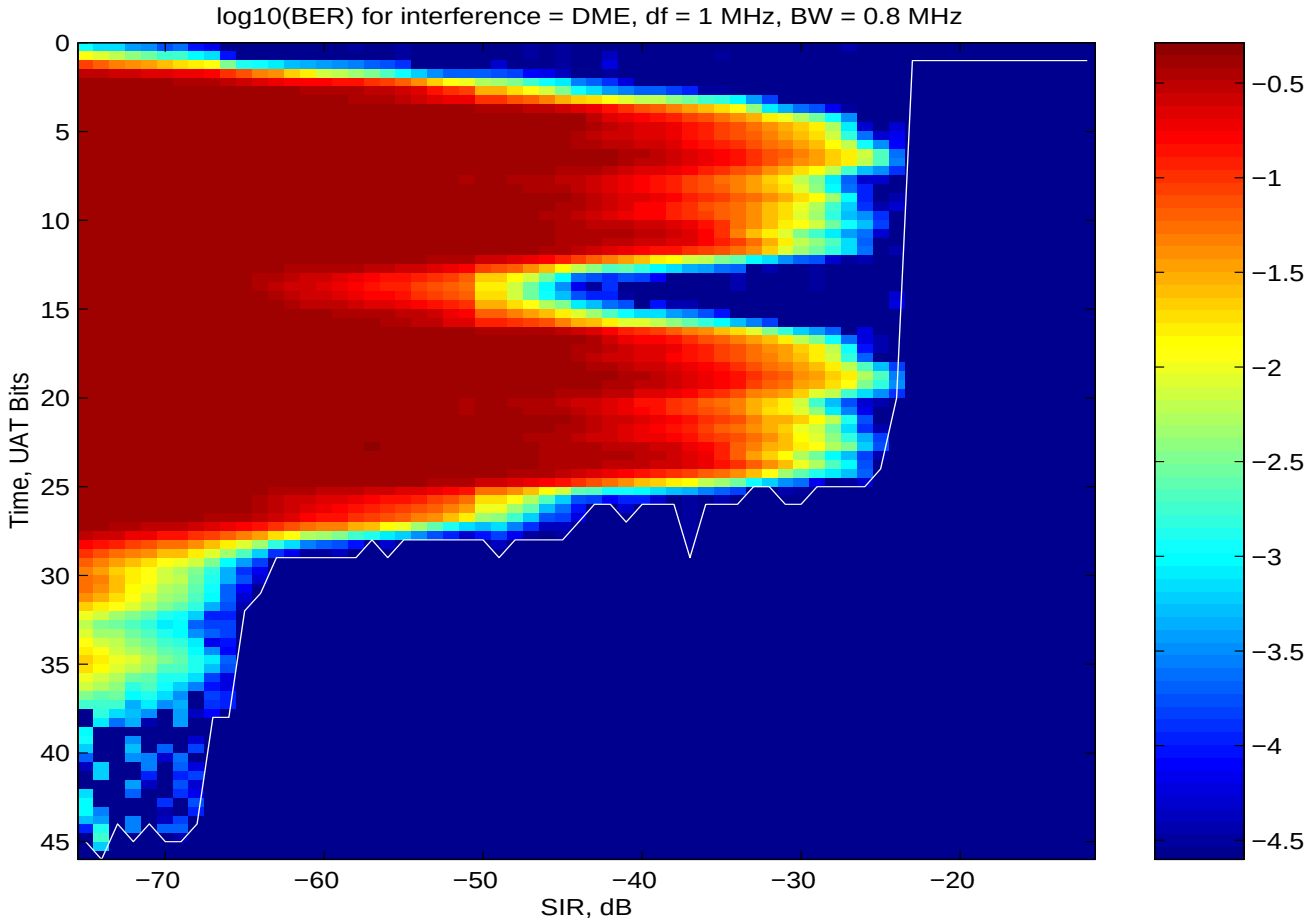
Summary Plots for DME Interference (BER Vs. Time & SIR)

- Summarizes all measured DME data
  - –For each ∆freq (0 for On-channel, 1 for Adjacent-channel)
  - – For each Bw (0.8 or 1.2 MHz)
  - –Averaged over all interference pulses within a UAT message
- $\log_{10}$ {BER} encoded as color

DME Interference, Δfreq = 1 MHz
Bw = 1.2 MHz



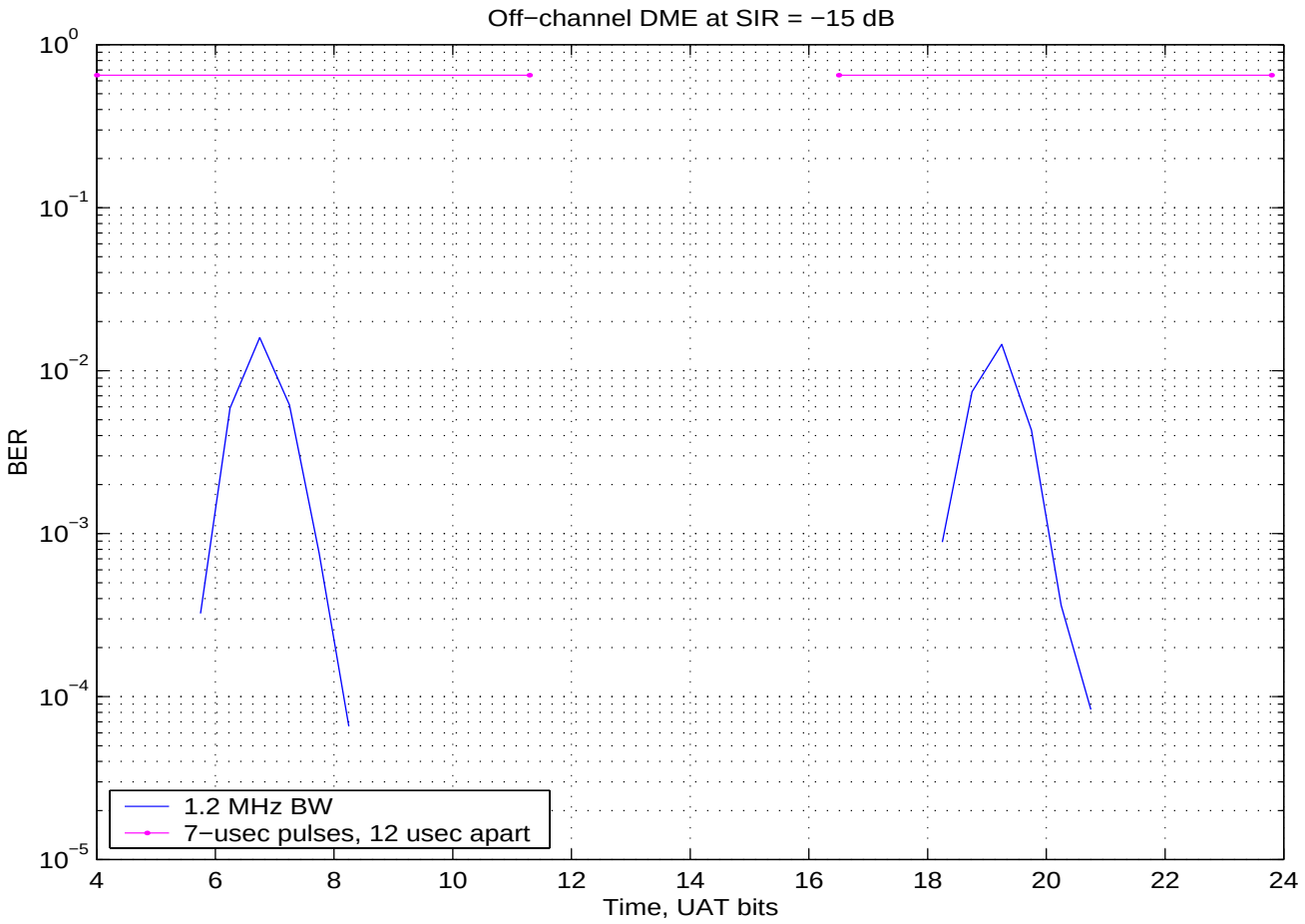
DME Interference, Δfreq = 1 MHz
Bw = 0.8 MHz



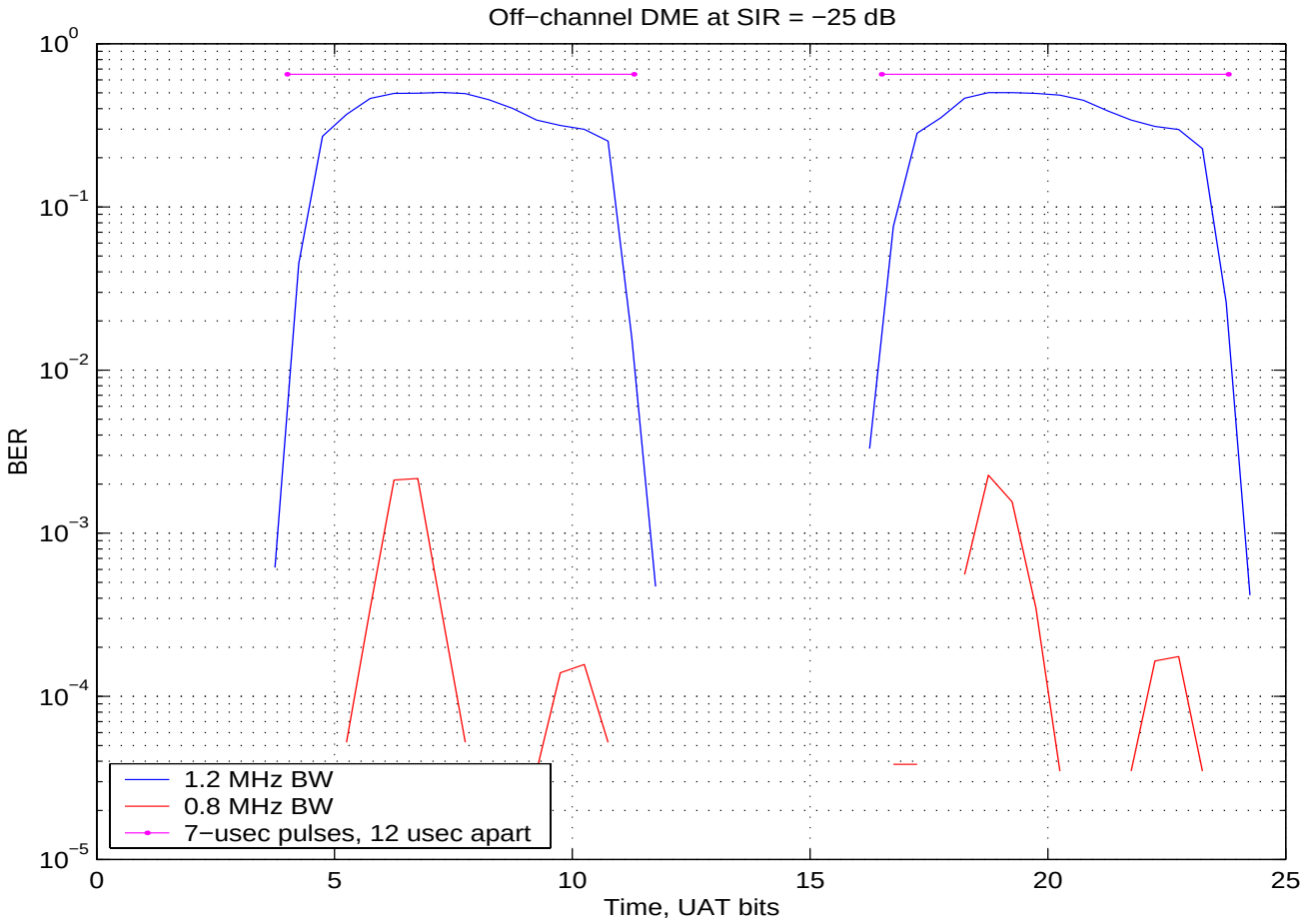
BER Vs. Time Plots for DME Interference

- Vertical slice through color plot at selected fixed values of SIR
- For adjacent-channel DME only
- Compares 1.2 MHz and 0.8 MHz BWs

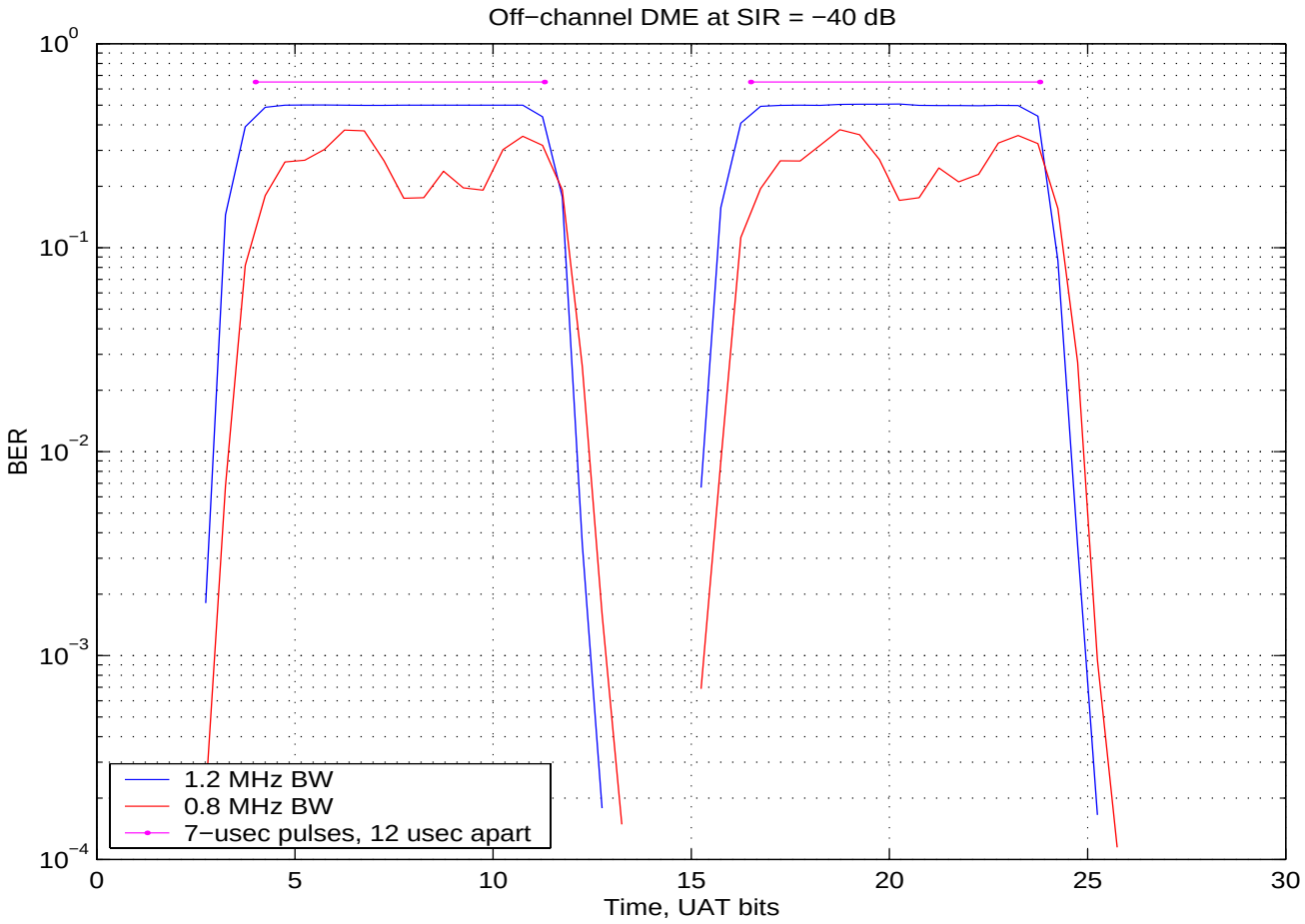
SIR = -15 dB


Off−channel DME at SIR = −15 dB
BER
Time, UAT bits
1.2 MHz BW
7−usec pulses, 12 usec apart

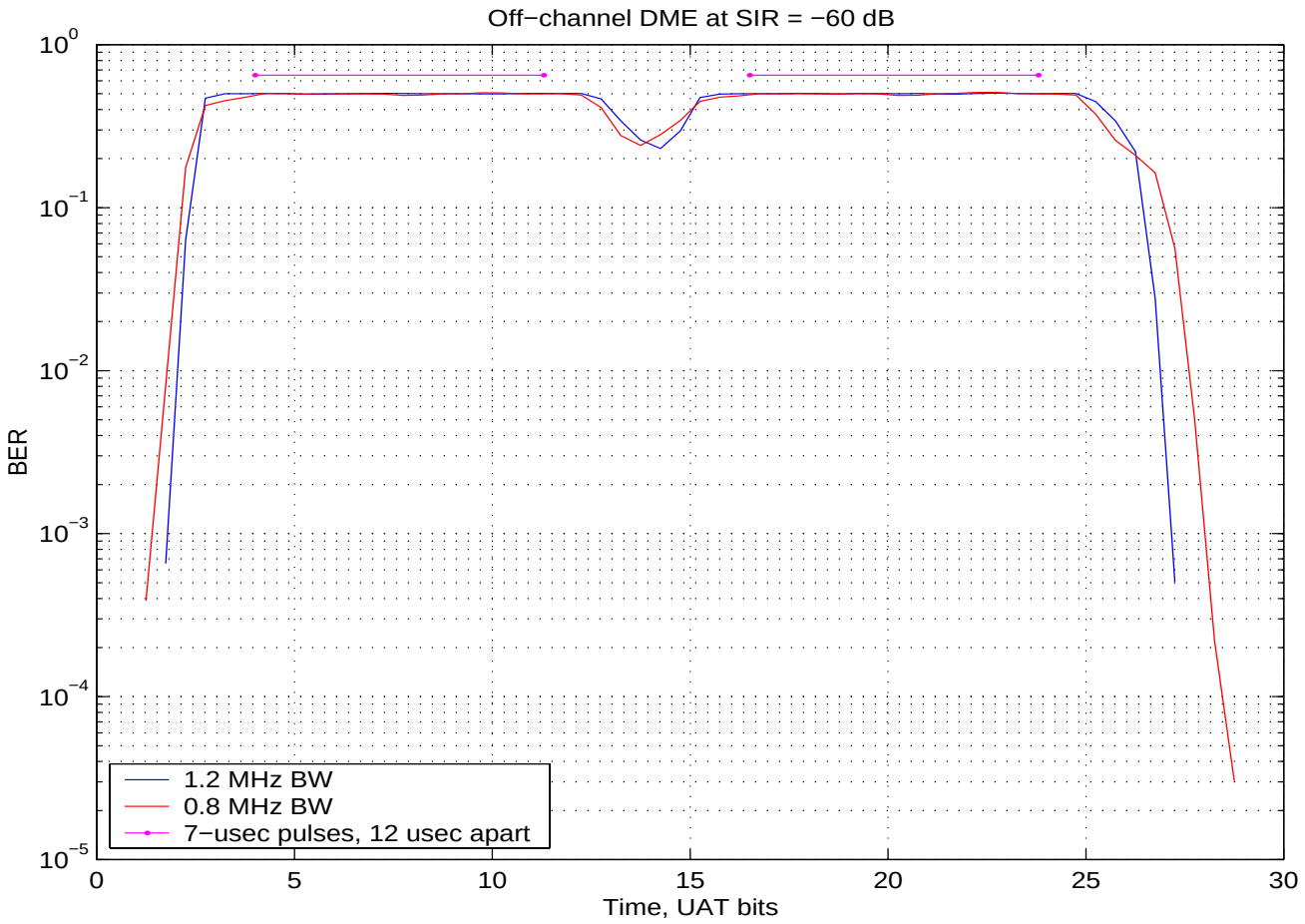
SIR = -25 dB


Off−channel DME at SIR = −25 dB
BER
Time, UAT bits
1.2 MHz BW
0.8 MHz BW
7−usec pulses, 12 usec apart

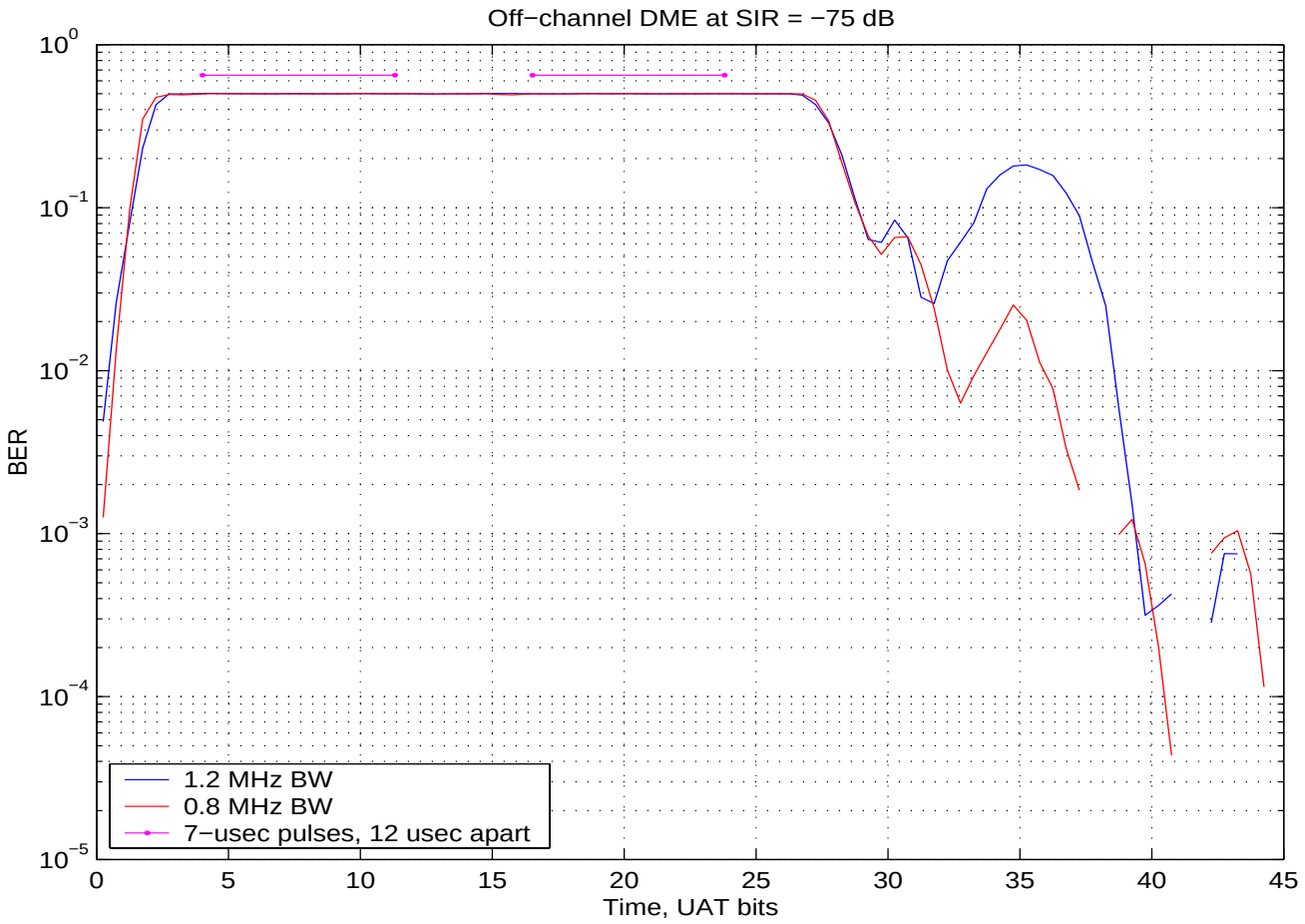
SIR = -40 dB


Off−channel DME at SIR = −40 dB
BER
Time, UAT bits
1.2 MHz BW
0.8 MHz BW
7−usec pulses, 12 usec apart

SIR = -60 dB


Off−channel DME at SIR = −60 dB
BER
Time, UAT bits
1.2 MHz BW
0.8 MHz BW
7−usec pulses, 12 usec apart

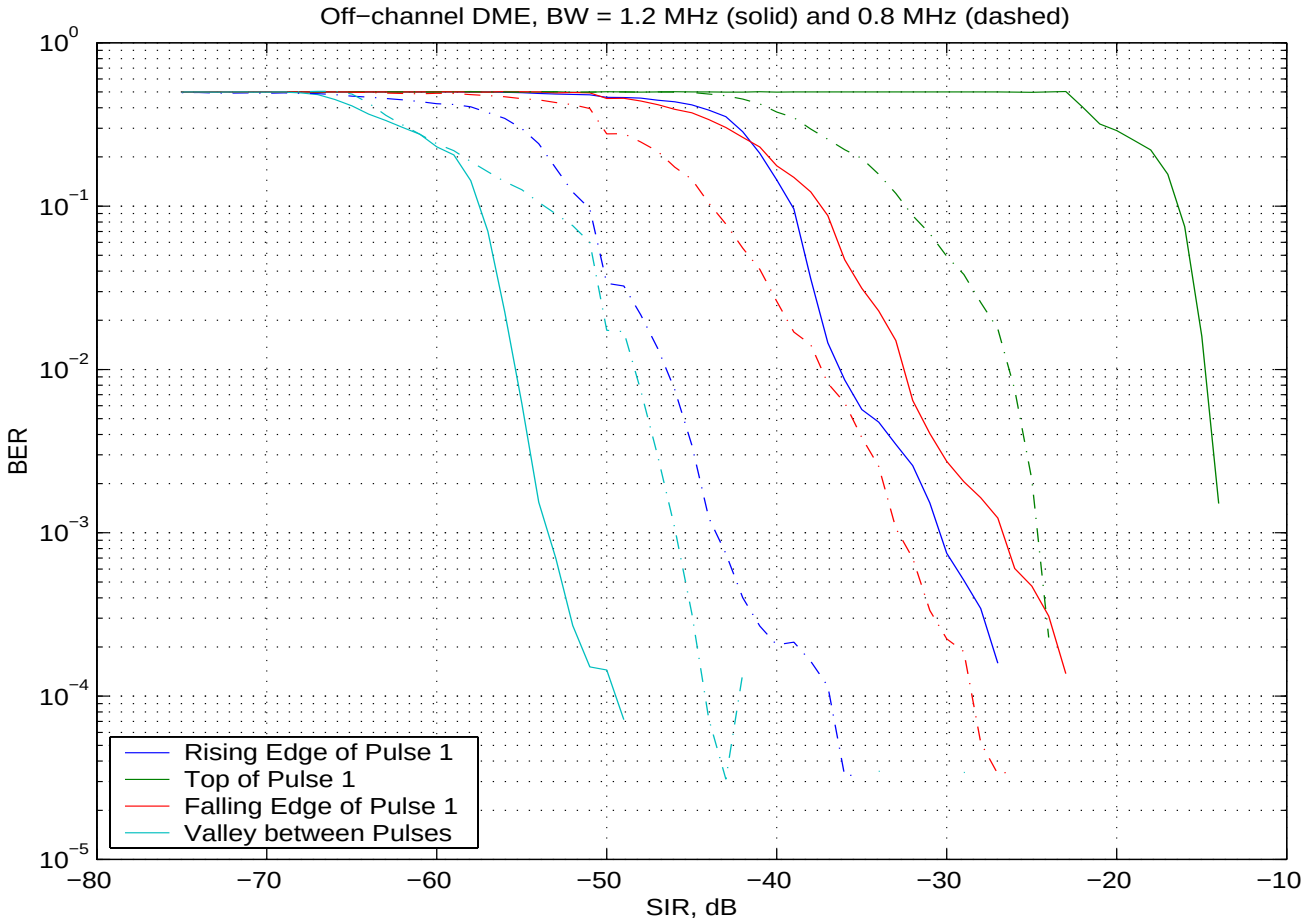
SIR = -75 dB


Off−channel DME at SIR = −75 dB
BER
Time, UAT bits
1.2 MHz BW
0.8 MHz BW
7−usec pulses, 12 usec apart

BER Vs. SIR Plot for DME Interference

(Horizontal slice through color plot at selected time values)

Off-Channel DME

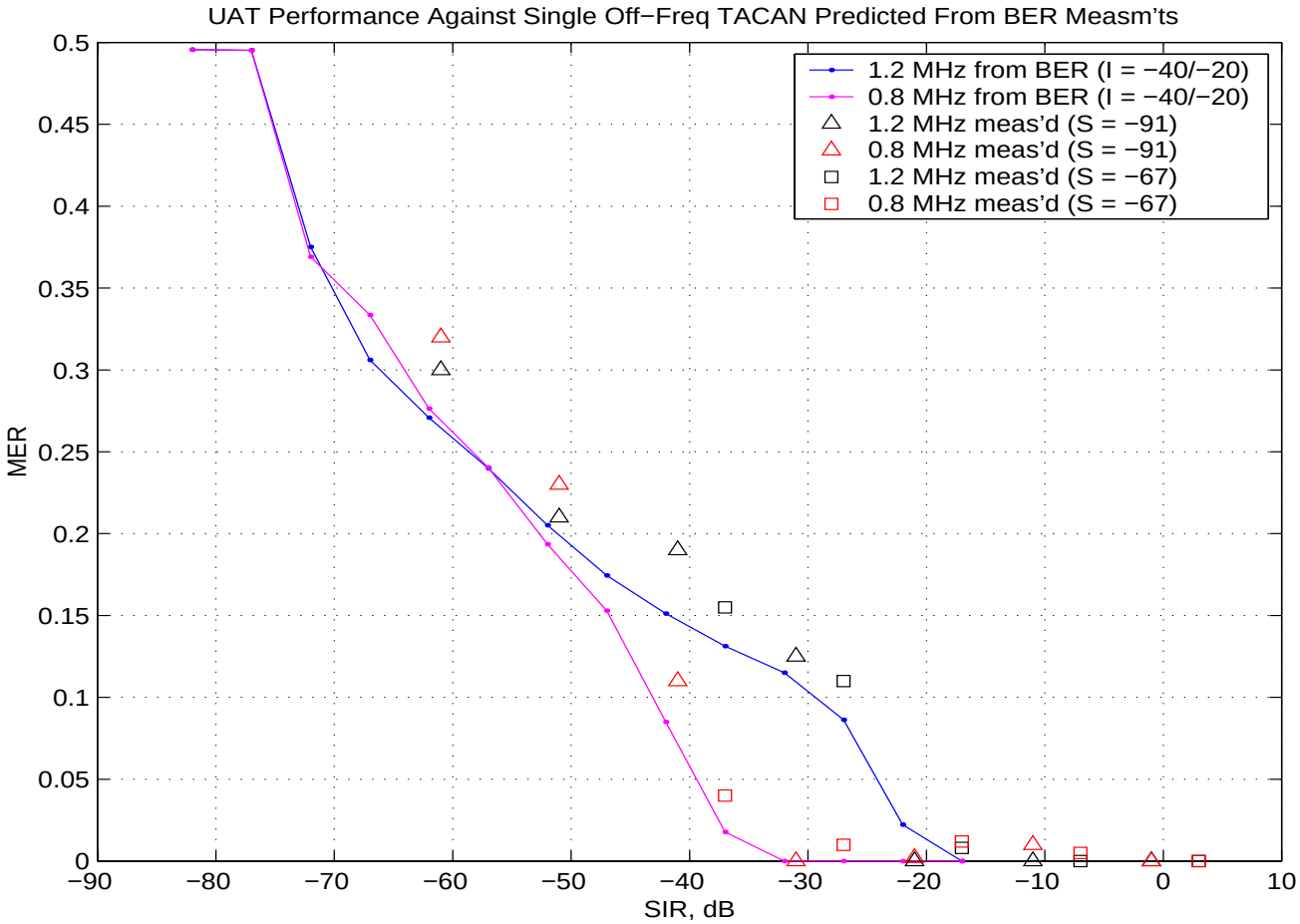


Comparison of UAT MER & BER Test Results Against DME

- Approach:
  - Computer simulation converts BER test results into MER predictions
  - These MER predictions are compared with MITRE/JSC-measured MER
- Simulated/measured scenario:
  - DME
    - Single DME transponder
    - 3600 pulse-pairs/second (TACAN), 60-usec+Poisson timing statistics
    - Adjacent-channel (1 MHz away)
  - “Pre-MOPS” UAT
    - 0.8 or 1.2 MHz bandwidth
    - RS(48,34) coding
- Results:
  - BER-based model predicts MER 3-5% (or 4-5 dB) lower than measured
  - Bad MER computation? Bad BER, MER or SIR measurements?

Measured Vs. BER-Predicted MER

Single Adjacent-Channel DME @ 3600 pulse pairs/sec

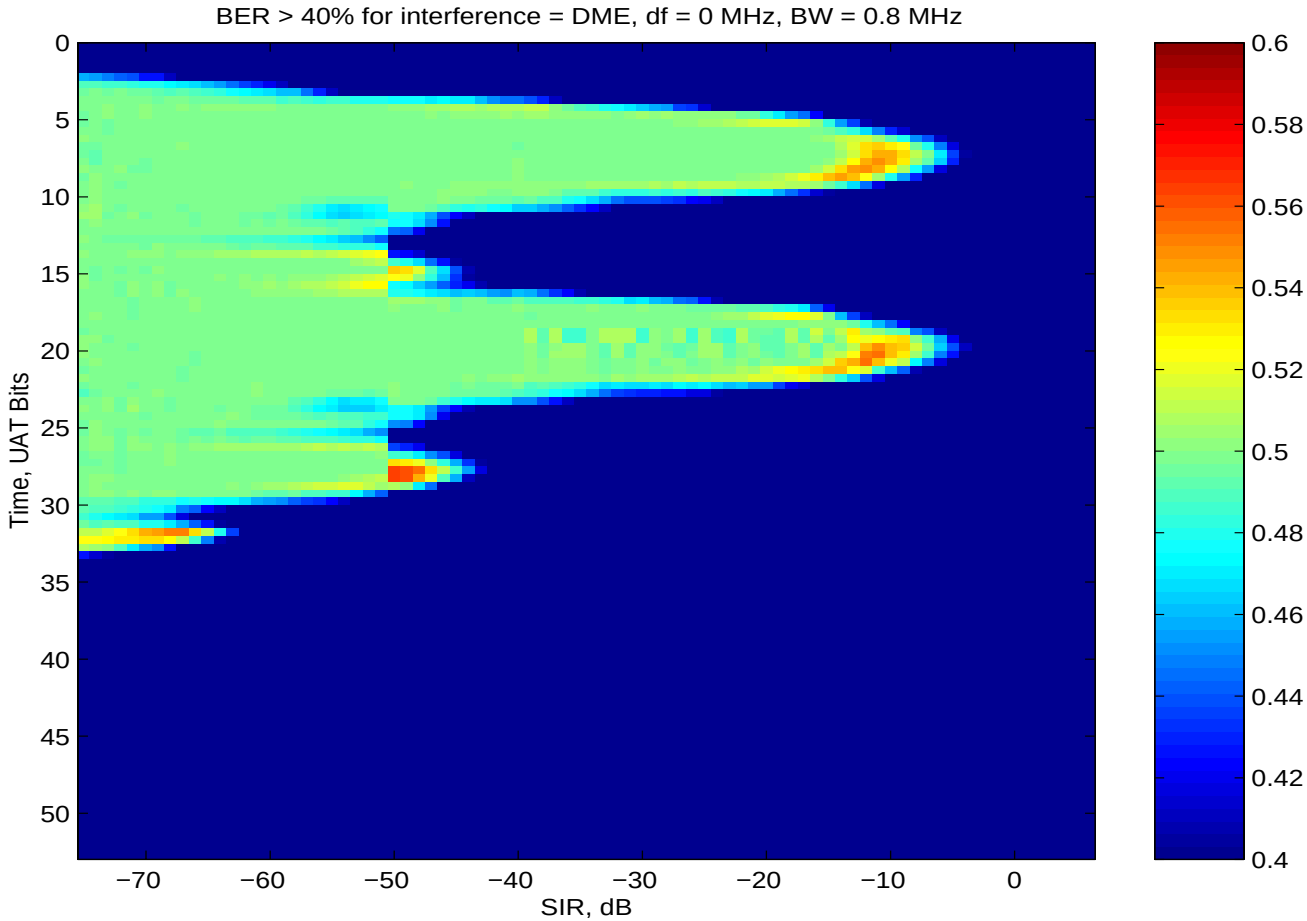


BER Observations for DME Interference

- 0.8 MHz filter doesn't provide hoped-for 20 dB improvement over 1.2 MHz filter for Adjacent-channel DME
  - Agrees with MER measurements
- Significant "pulse stretching" occurs at very low SIR values
  - In part due to what looks like a ~7.5-usec echo, down ~ 40 dB
- BER vs. SIR curves are not parallel
  - Can't properly model using simple Pulse amplitude vs. Time profile
  - Could be due to dynamic response of demodulator thresholding algorithm
- BERs above 50% were measured under certain conditions
  - Up to ~ 56%
  - Appear real rather than experimental error
    - Might be due to nonlinear thresholding algorithm in demodulation
  - Would not affect network performance simulations

BER > 50% Measured in some cases

(e.g. DME Interference, Δfreq = 0 MHz, BW = 0.8 MHz)



Other Observations

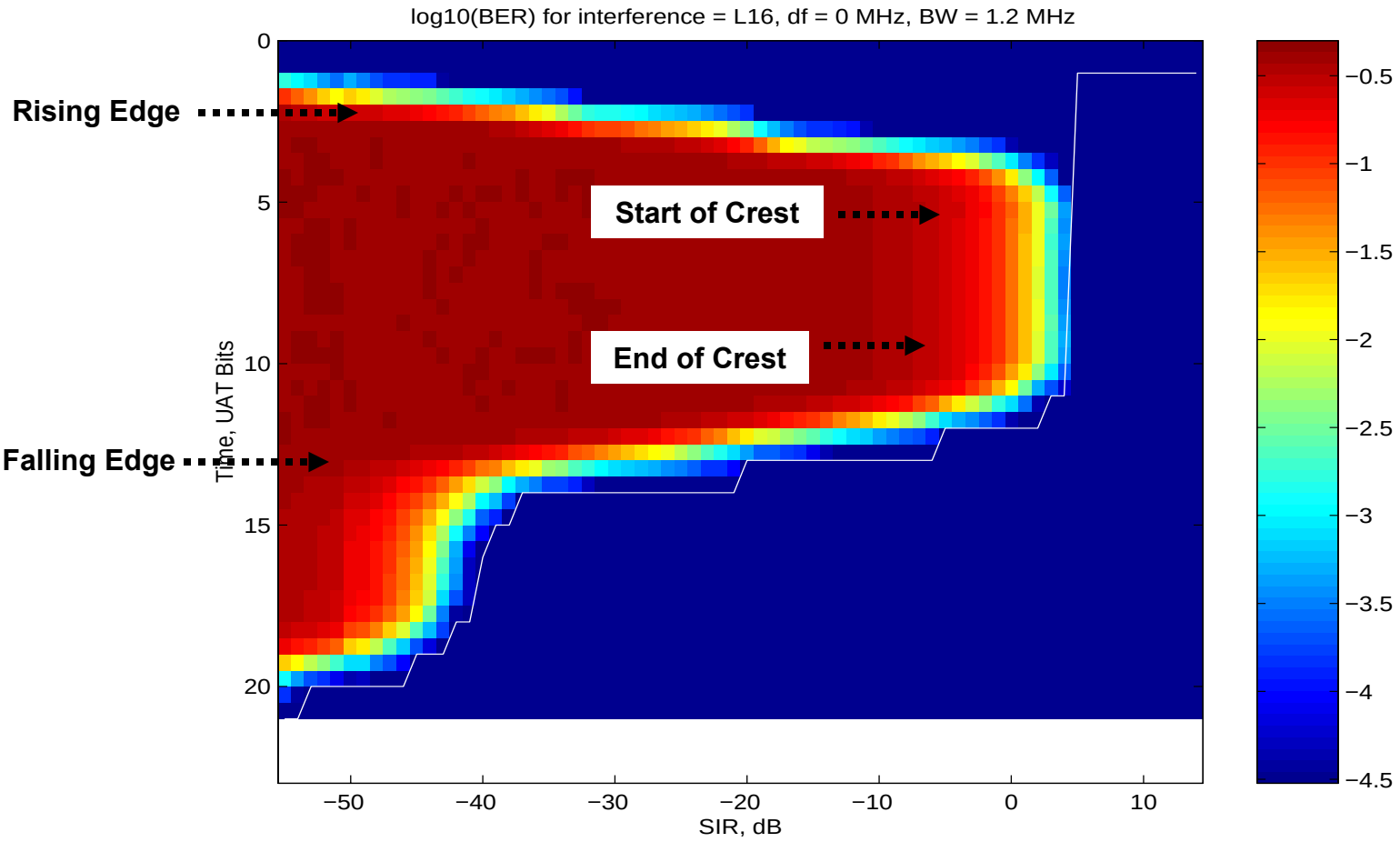
- Reed Solomon decoder appears to behave as modeled
  - In 100,000 messages looked at:
    - No messages were incorrectly decoded
    - All messages with <=7 byte errors were decoded
    - No messages with >7 byte errors were decoded
- BER Correlation analysis
  - Correlation of successive bit errors not yet analyzed
  - No significant correlation seen between DME pulse rising and falling edges
    - This result supports measured pulse stretching as real rather than time jitter in experimental setup
      - –Time jitter would produce negative correlation

Interference = Link 16

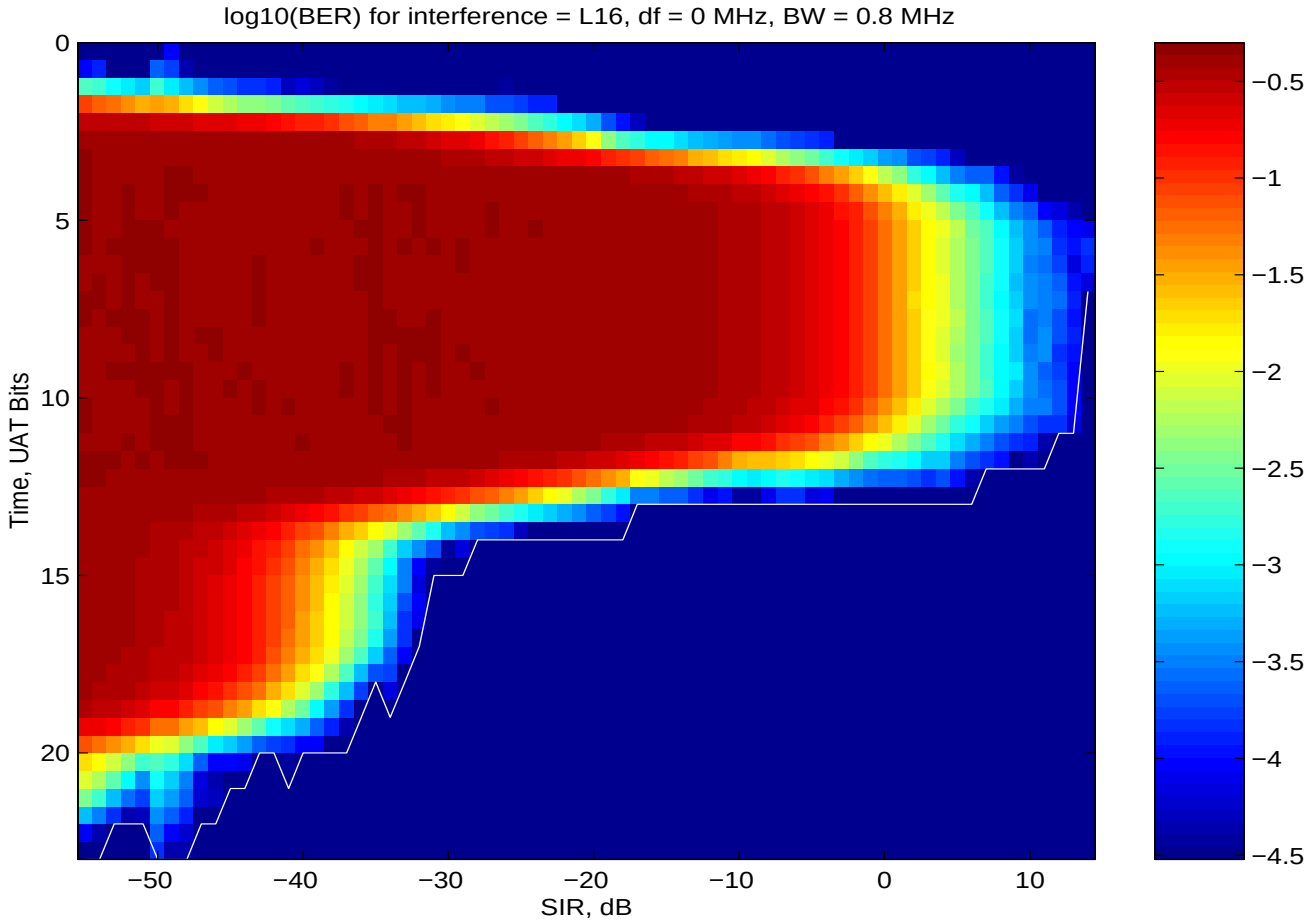
Summary Plots for Link 16 Interference (BER Vs. Time & SIR)

- Summarizes all measured Link 16 data
  - –For each ∆freq (0, 3, 6, … 21 MHz)
  - – For each Bw (0.8 or 1.2 MHz)
  - –Averaged over all interference pulses within a UAT message
- $\log_{10}$ {BER} encoded as color

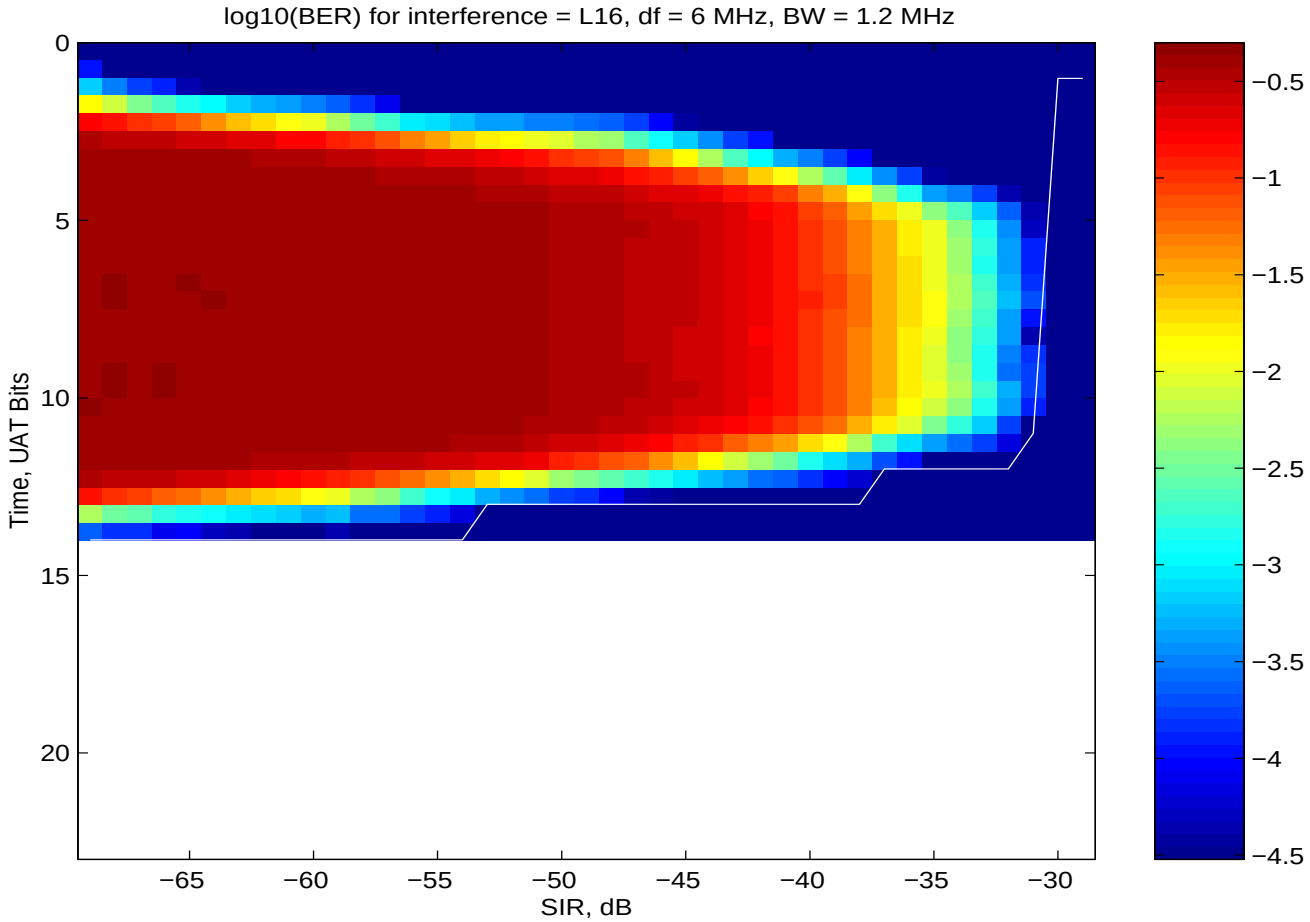
Link 16 Interference, Δfreq = 0 MHz
Bw = 1.2 MHz
(including time definitions used in later plots)



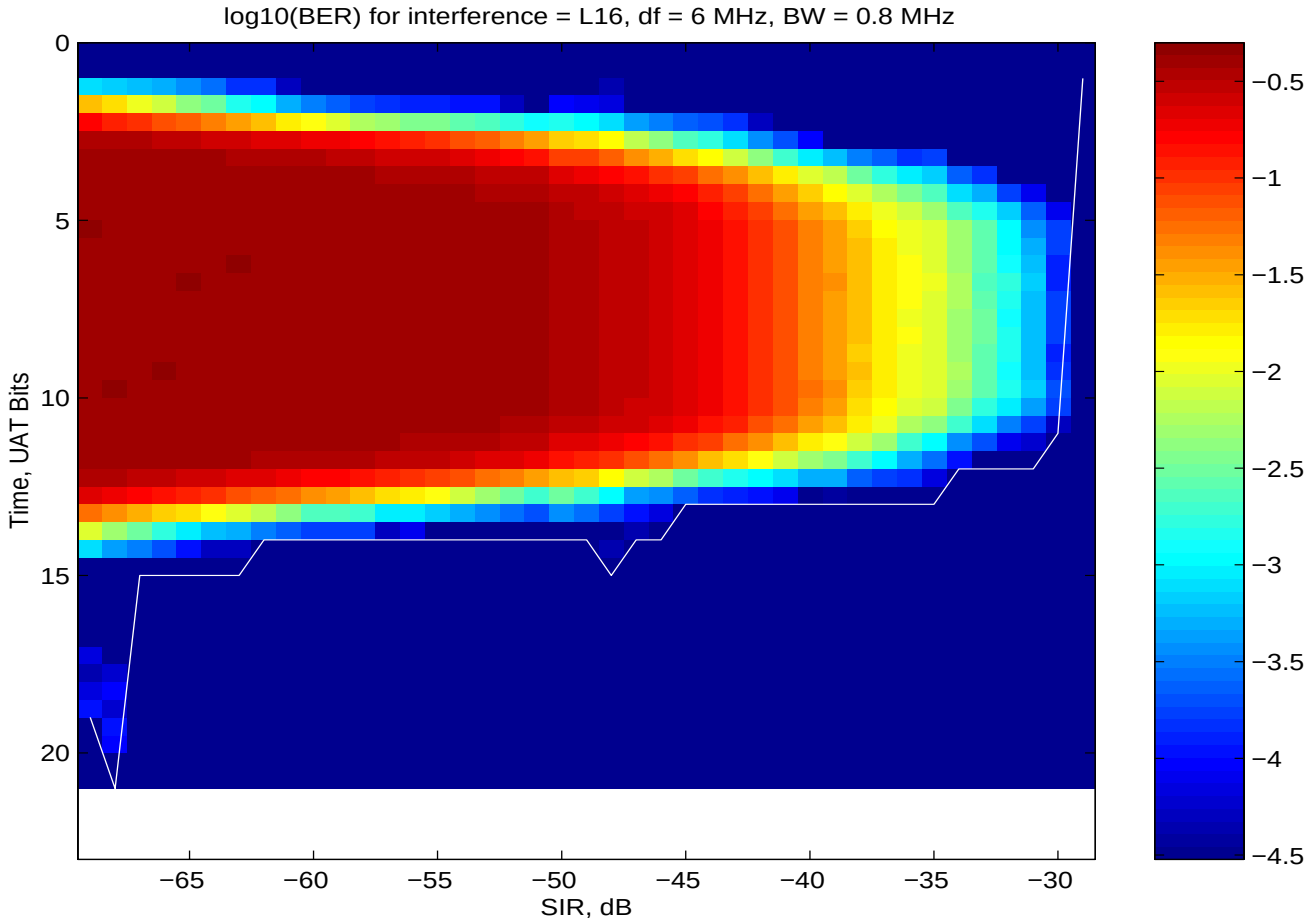
Link 16 Interference, Δfreq = 0 MHz
Bw = 0.8 MHz



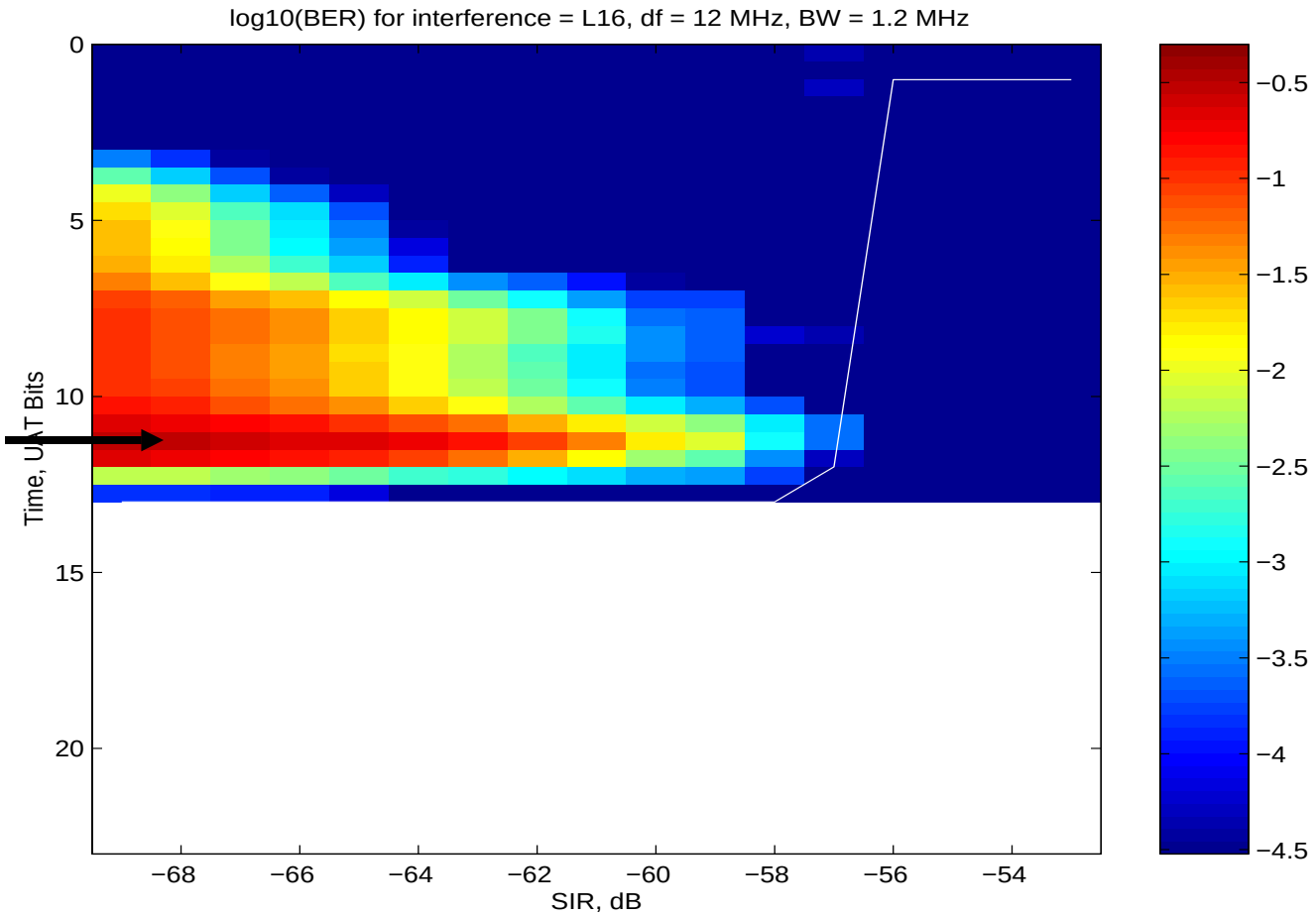
Link 16 Interference, Δfreq = 6 MHz
Bw = 1.2 MHz



Link 16 Interference, Δfreq = 6 MHz
Bw = 0.8 MHz

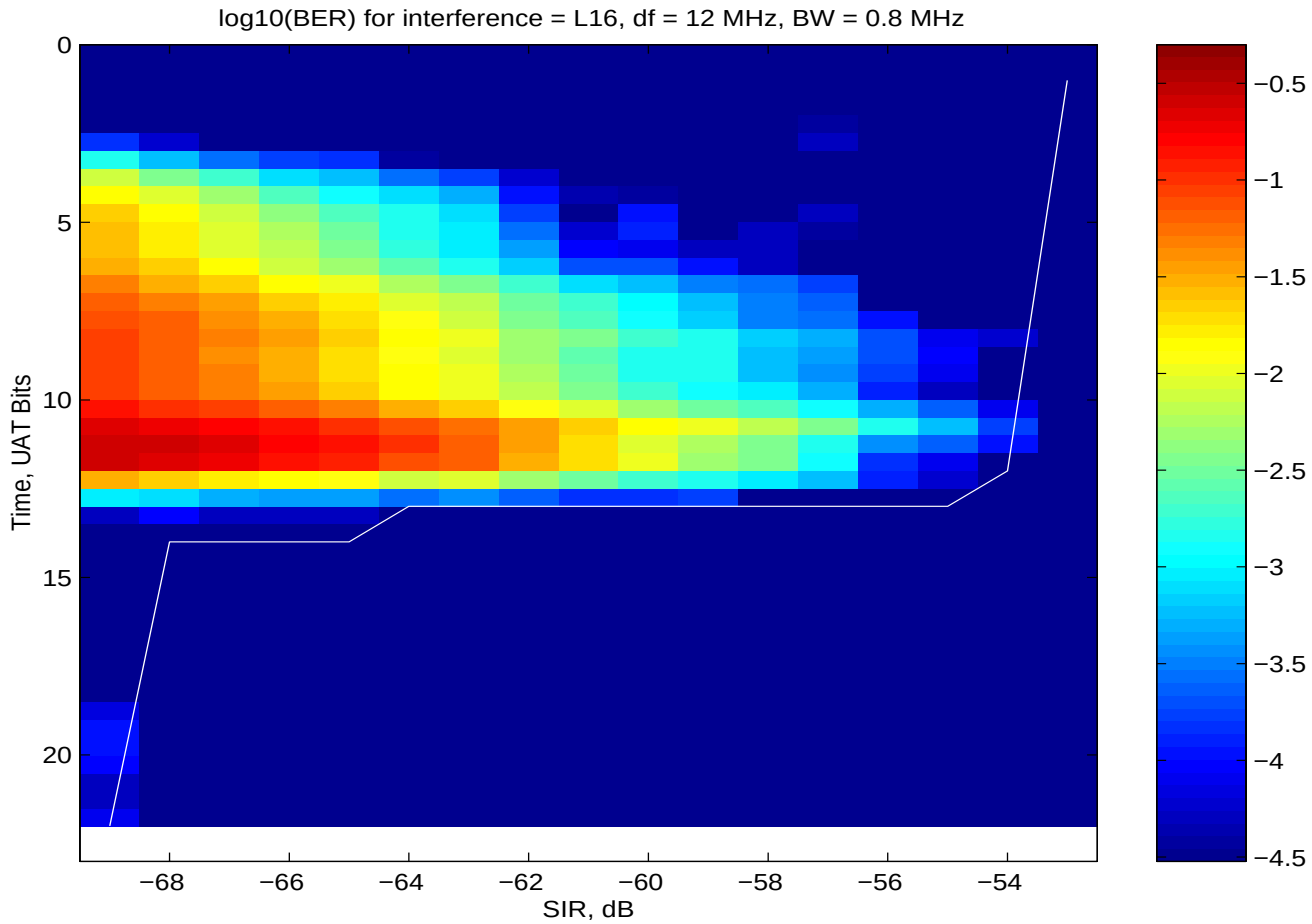


Link 16 Interference, Δfreq = 12 MHz
Bw = 1.2 MHz



Peak at high df

Link 16 Interference, Δfreq = 12 MHz
Bw = 0.8 MHz

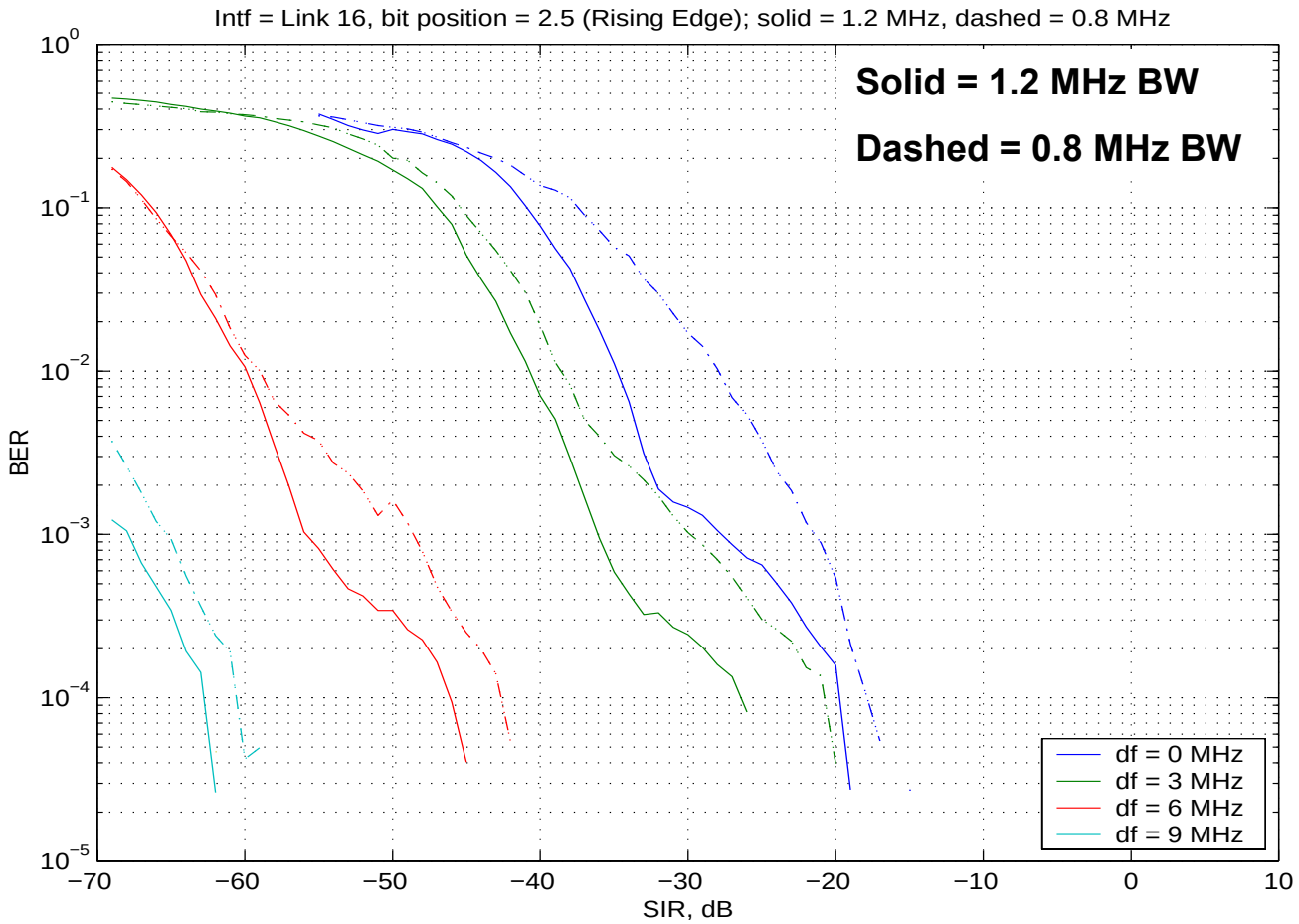


BER Vs. SIR Plots for Link 16 Interference

(Horizontal slice through color plot at selected time values)

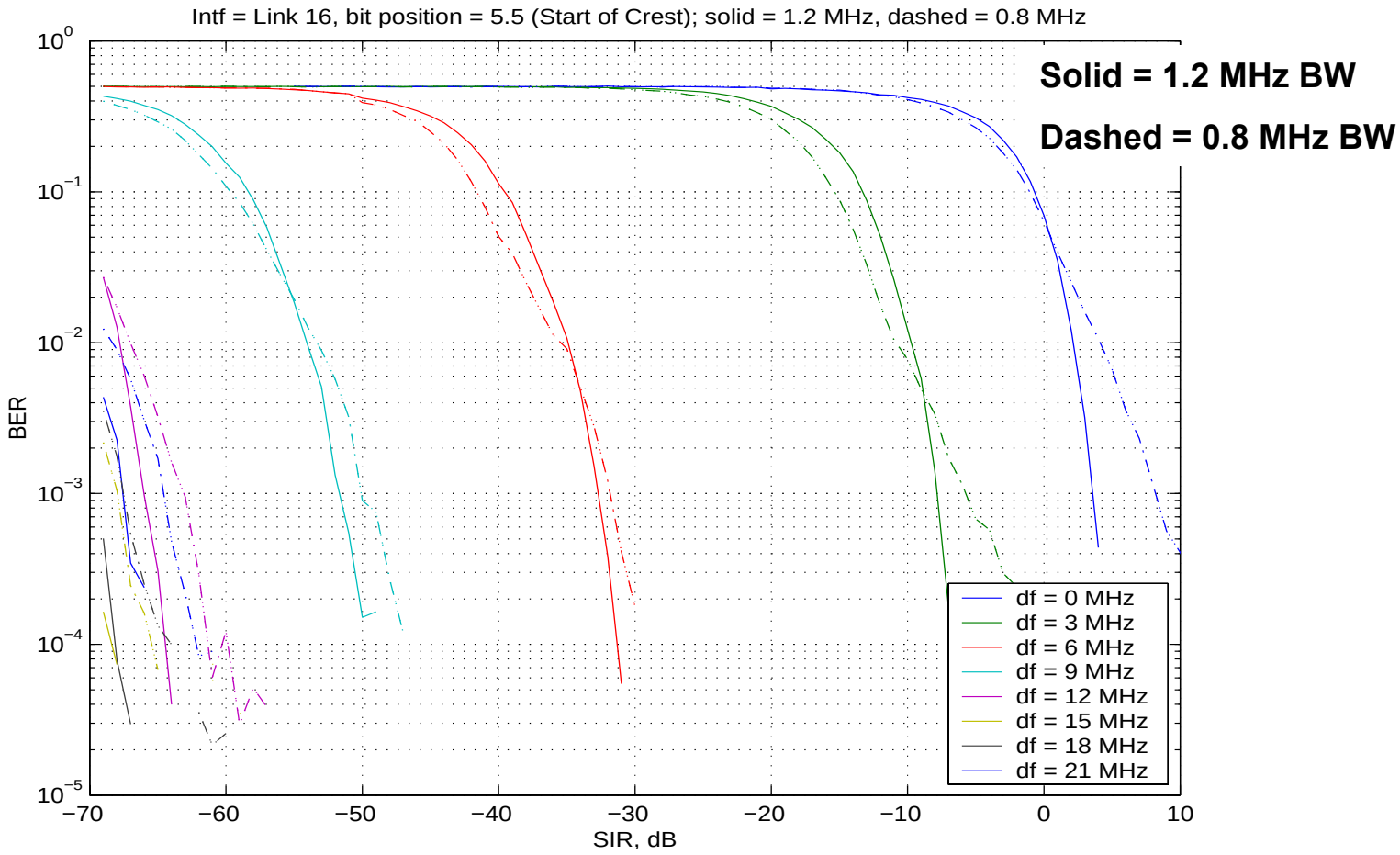
Bit Position 2.5 (Rising Edge of Link 16)

for various frequency offsets and receiver BWs



Bit Position 5.5 (Start of Link 16 Crest)

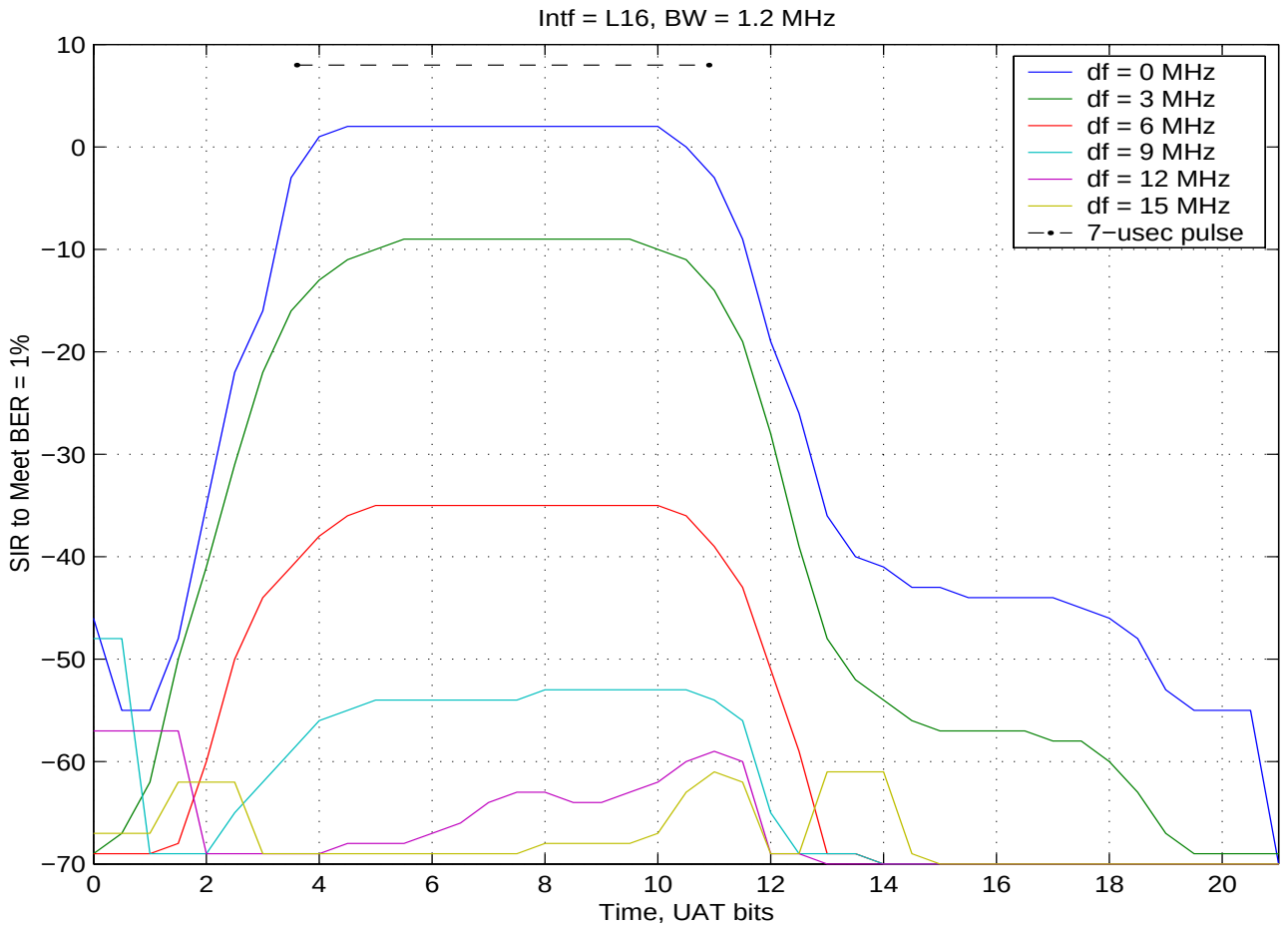
for various frequency offsets and receiver BWs



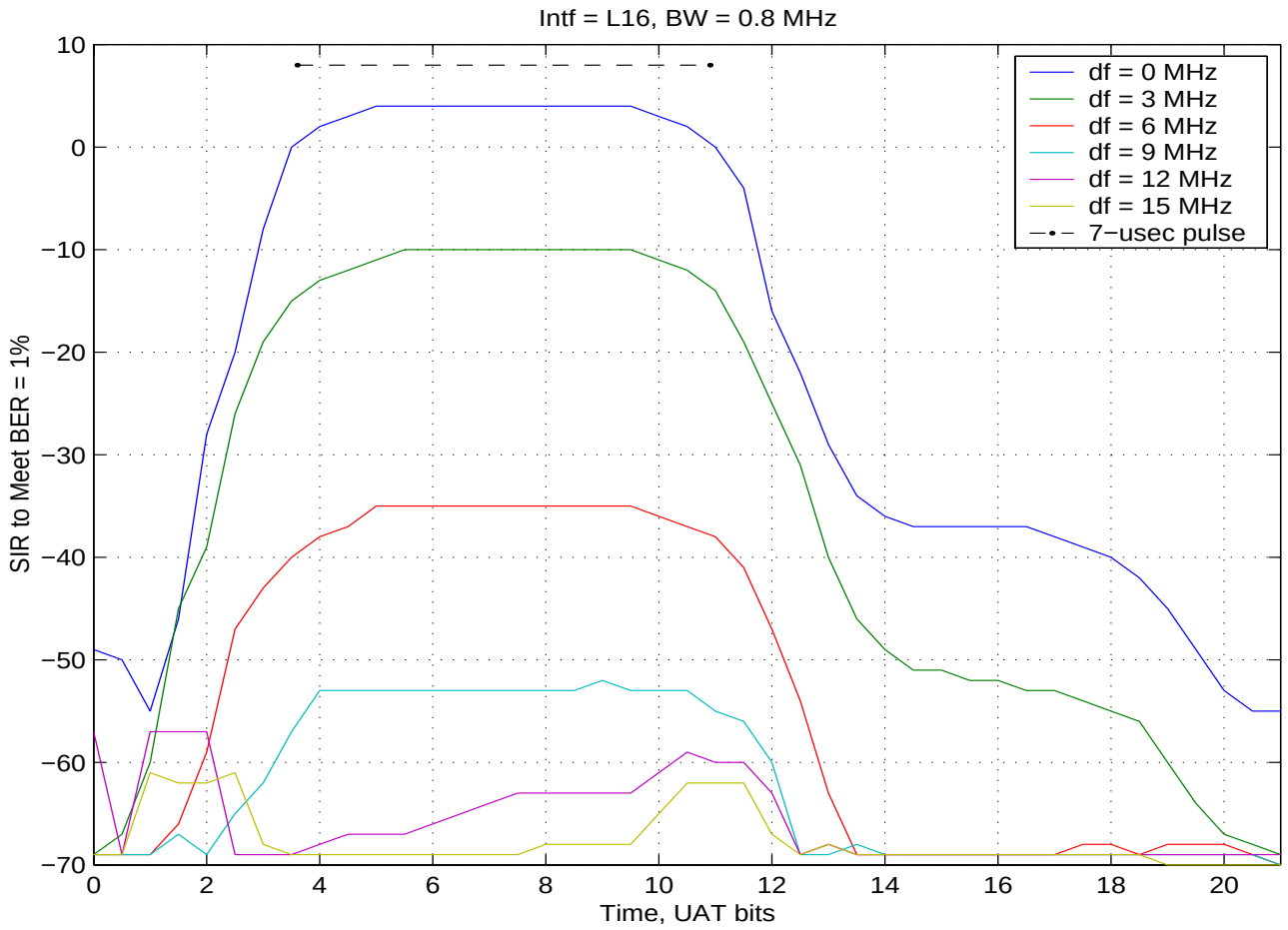
Required SIR Vs. Time Plots for Link 16 Interference

(SIR required to meet BER <=1% at various frequency offsets)

SIR Required to Meet BER <=1%
BW = 1.2 MHz



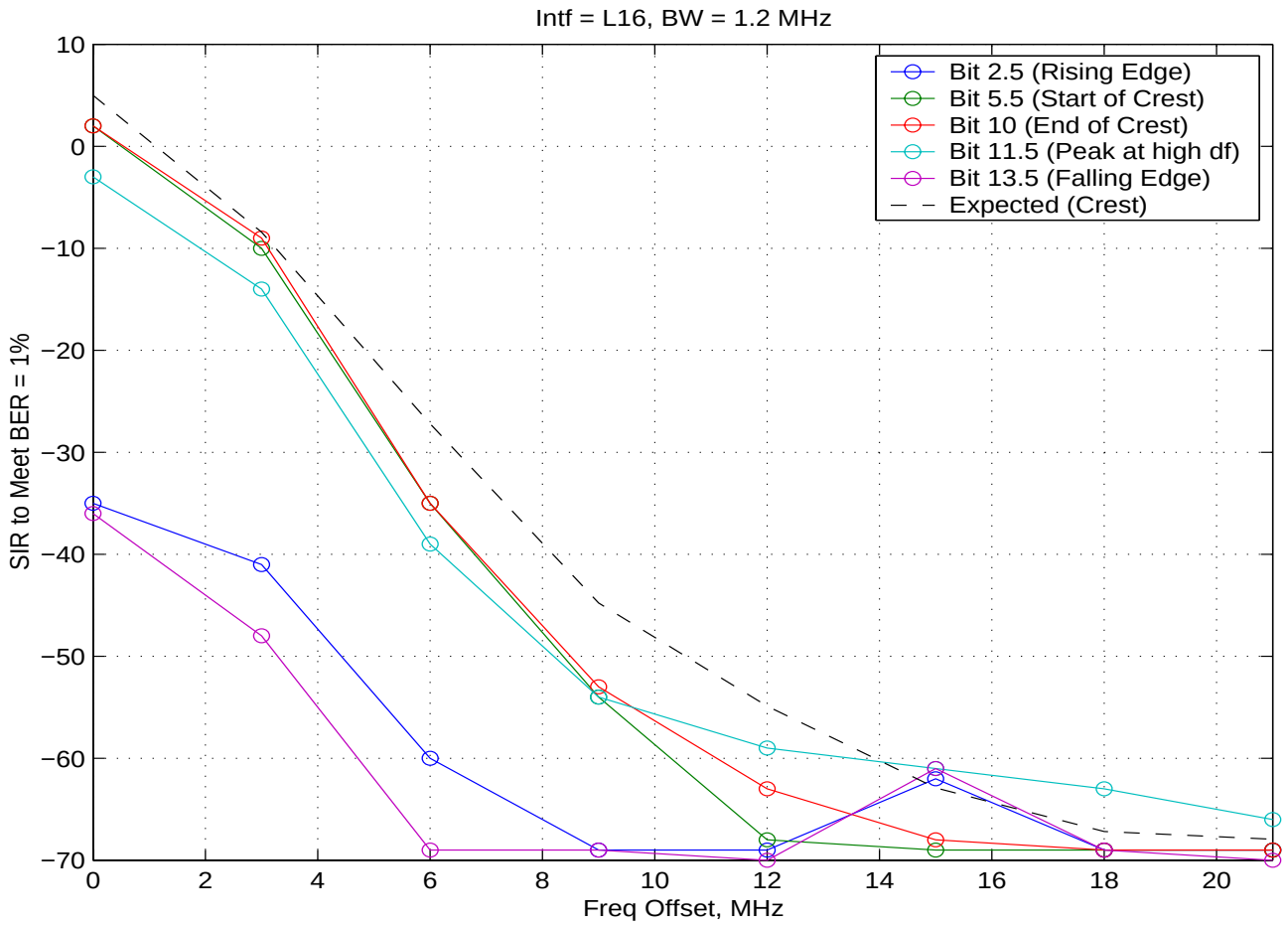
SIR Required to Meet BER <=1%
BW = 0.8 MHz



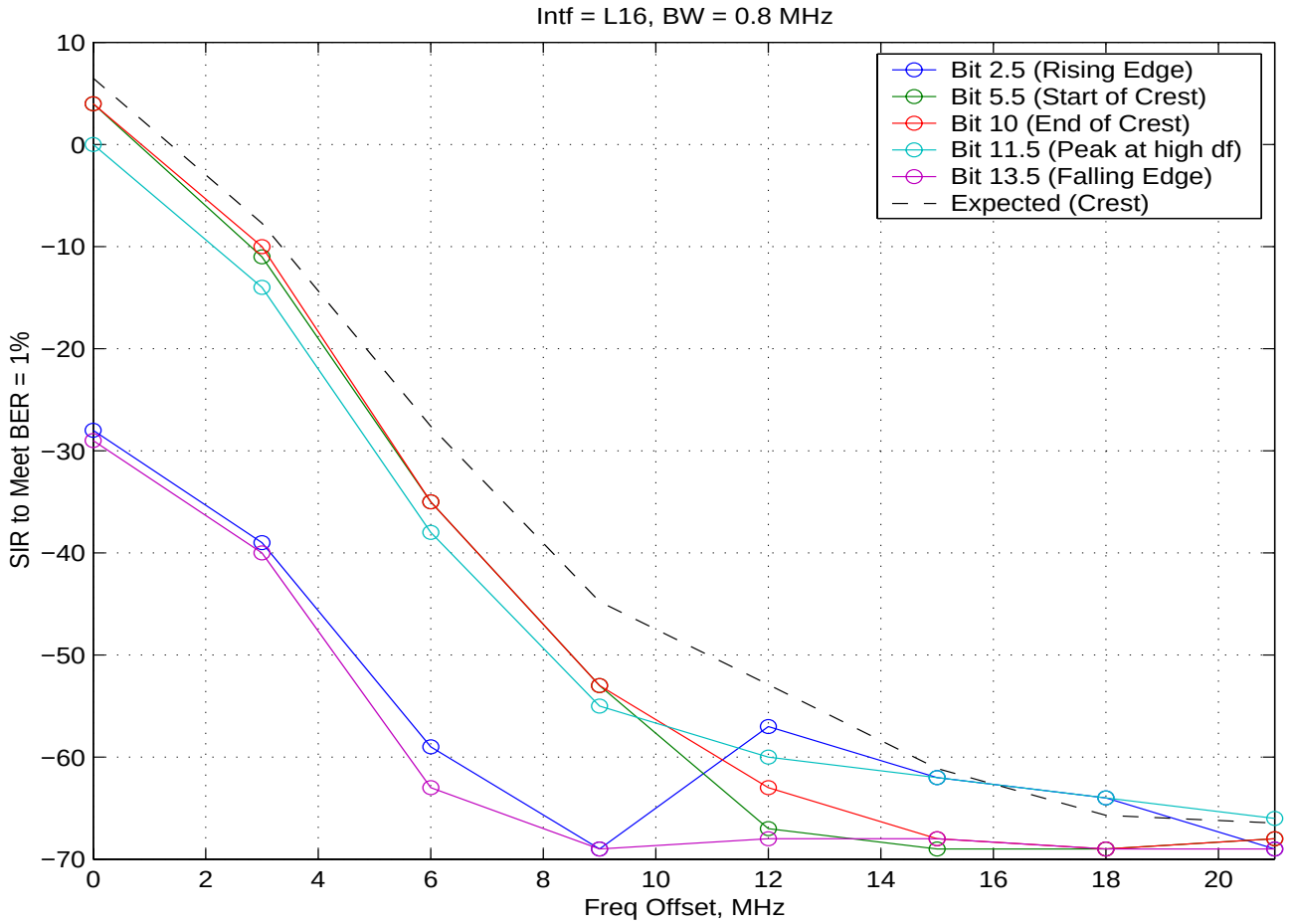
Required SIR Vs. Δfreq Plots for Link 16 Interference

(SIR required to meet BER <=1% at selected time values)

SIR Required to Meet BER <=1%
BW = 1.2 MHz



SIR Required to Meet BER <=1%
BW = 0.8 MHz



BER Observations for Link 16 Interference

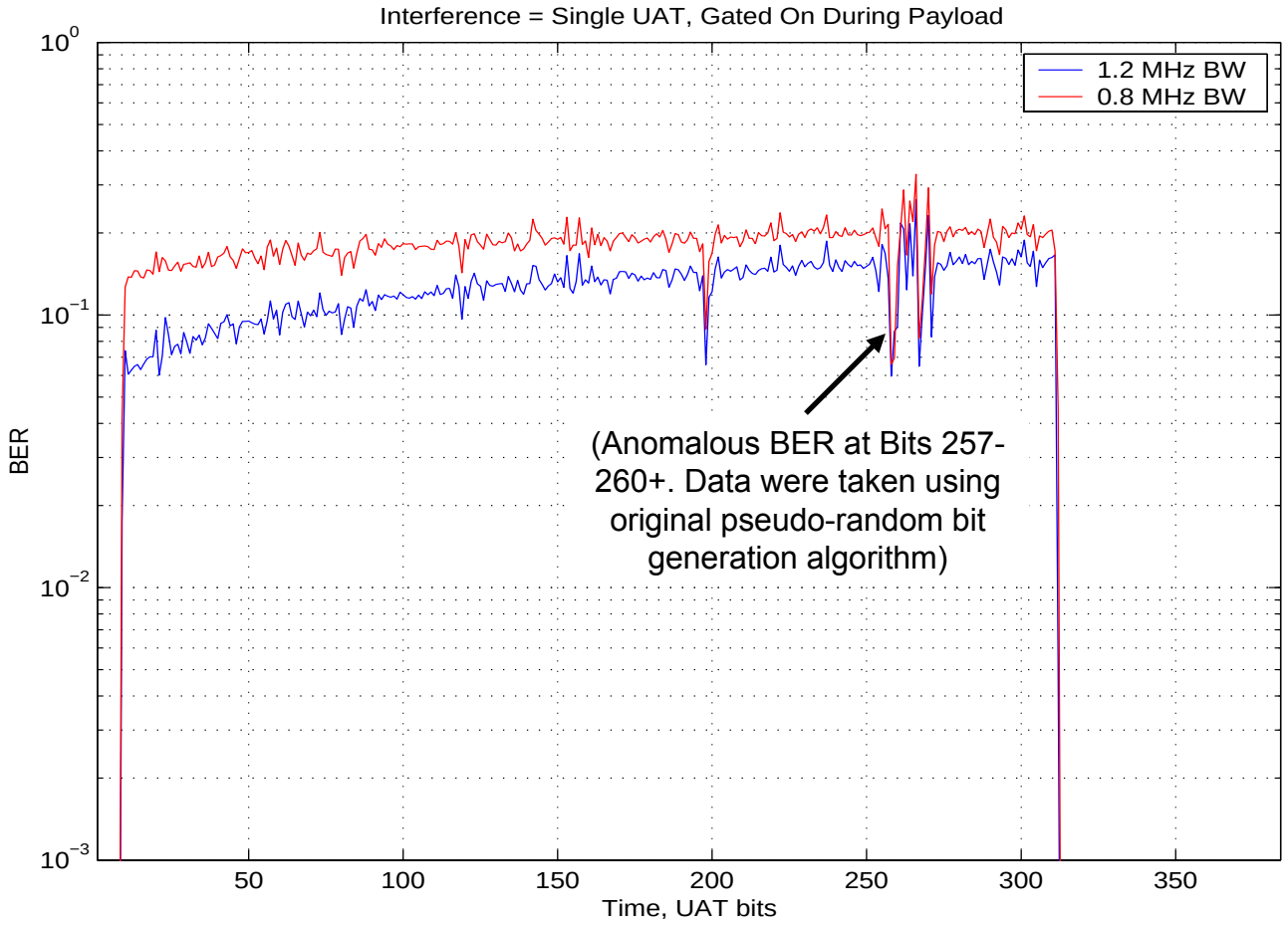
- BER vs. SIR curves are parallel
  - Permits simpler modeling of impact than for DME
- Link 16 pulses are longer but less damaging per bit than assumed
  - Overall impact likely close to that originally modeled
  - "Pulse stretching" of a few μsecs beyond the modeled 7-μsec length occurs for SIRs as high as –20 dB
    - Longer for lower SIRs
    - A ~7.5-usec echo, down 40-45 dB (similar to DME data) can stretch pulses to 17 μsec at SIRs of -50 dB
    - 0.8 MHz BW only very slightly worse than 1.2 MHz BW
  - BER impact during central pulse 2-10 dB less than originally modeled (based on Gaussian noise)
    - Reasonable, given that Link 16 is 5 Mchip/sec MSK, not Gaussian noise
    - Two filter BW's about the same
- BERs above 50% were not observed

Interference =
Single UAT + White Gaussian Noise (WGN)

UAT+WGN Tests—
Differences From DME and Link 16 Tests

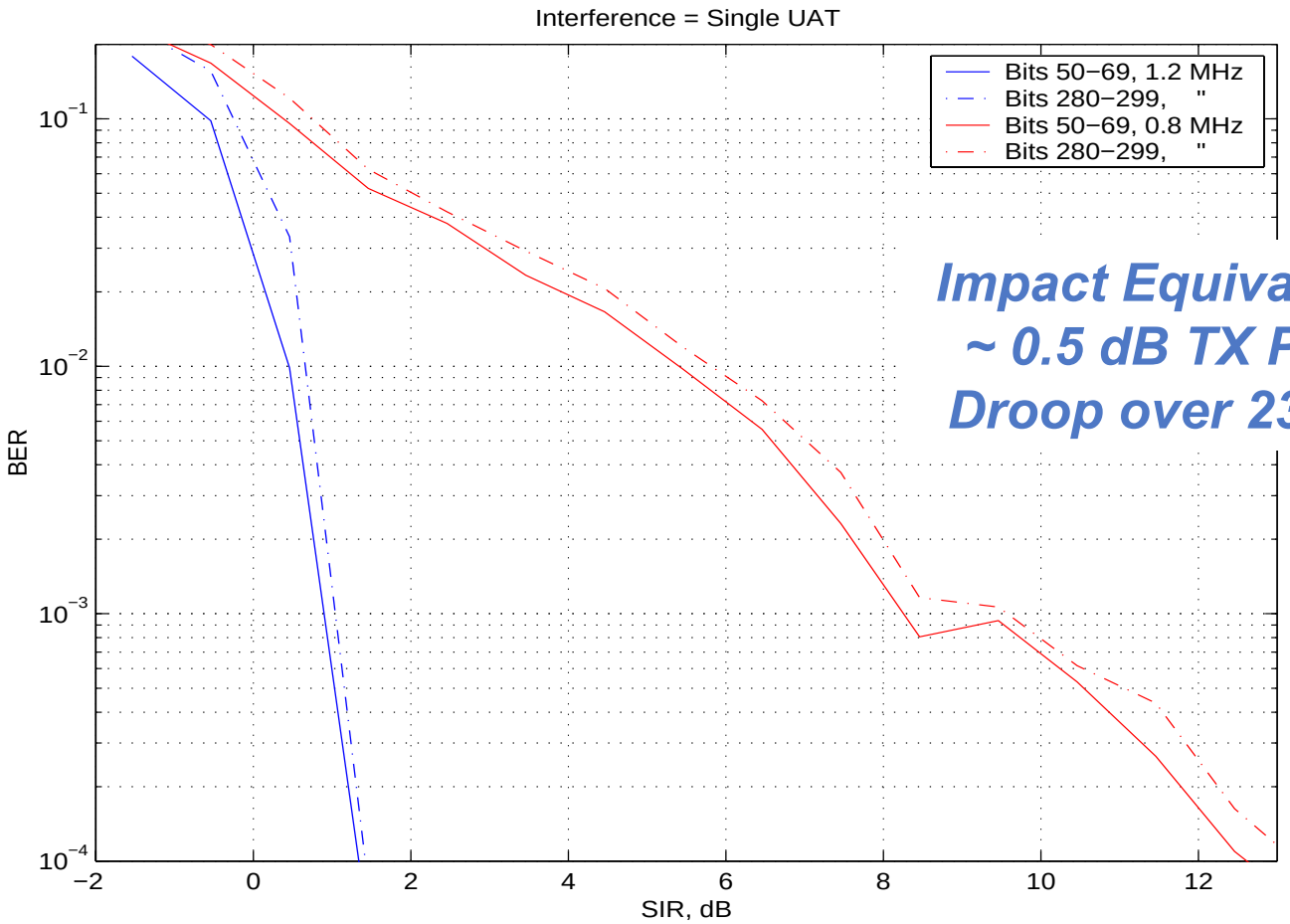
- Need to vary INR = UAT Interference / WGN Ratio for mixed UAT + WGN environments
  - Tested at –inf (no UAT), –6, 0, +6, +8, +18, ~ +70 dB (no added WGN)
- For WGN, SNR values need to include specification of measurement bandwidth
  - Use 1 MHz
- Need to gate interference off at message end to screen out mis-correlated messages
  - Use bit positions #16 through #208 of payload for BER computations
- No time profiles computed
  - BERs at all valid bit positions averaged together
  - Discovered BER isn't time-independent
    - Affected previous data as well, but wasn't as noticeable
    - Impact can be ignored

Rising BER Observed During Single UAT Interference



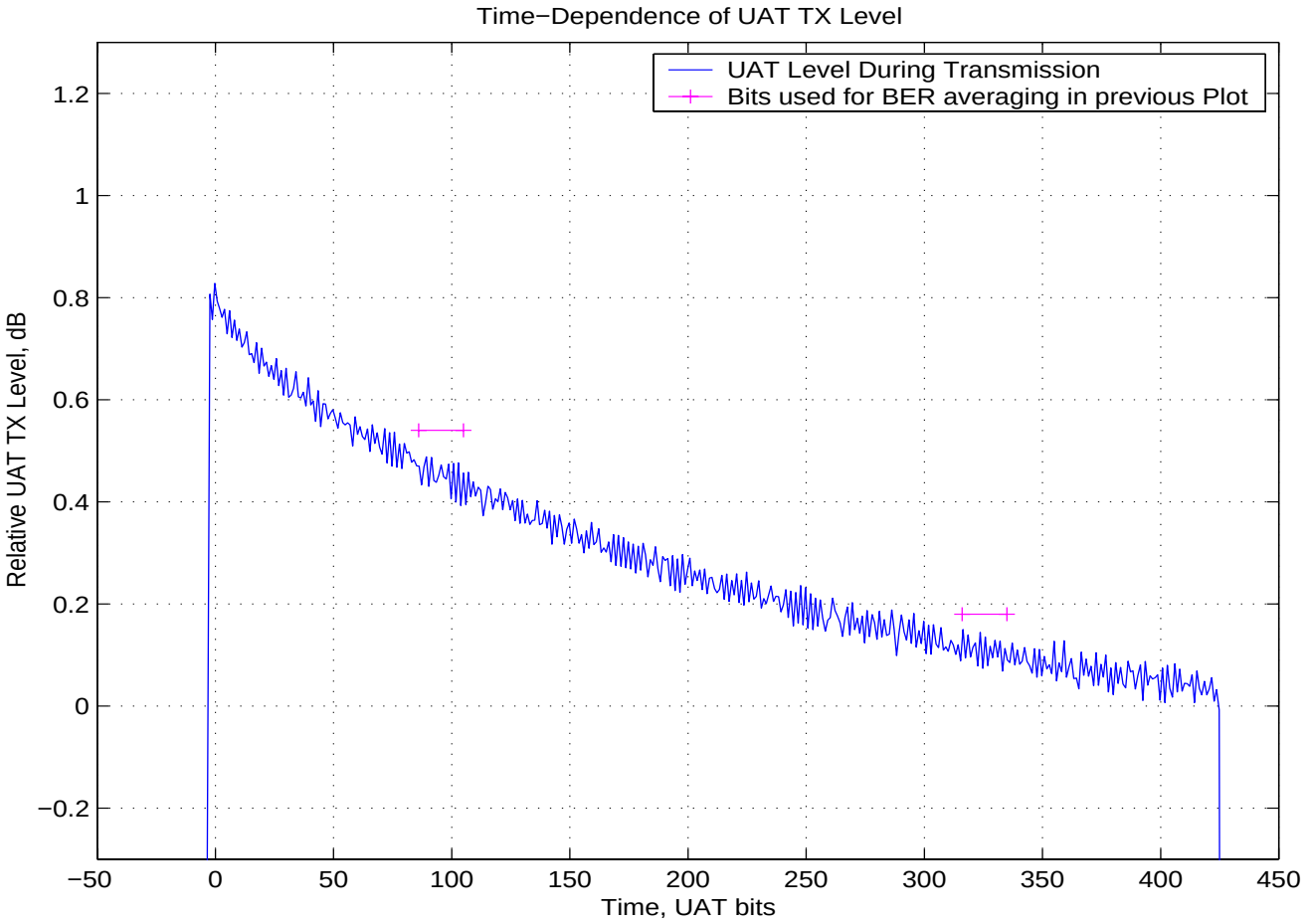
Consistent with Droop in TX Power Over Message

(In hindsight, effect also present for DME & Link 16 Interference & at all SIRs)



Impact Equivalent to ~ 0.5 dB TX Power Droop over 230 bits

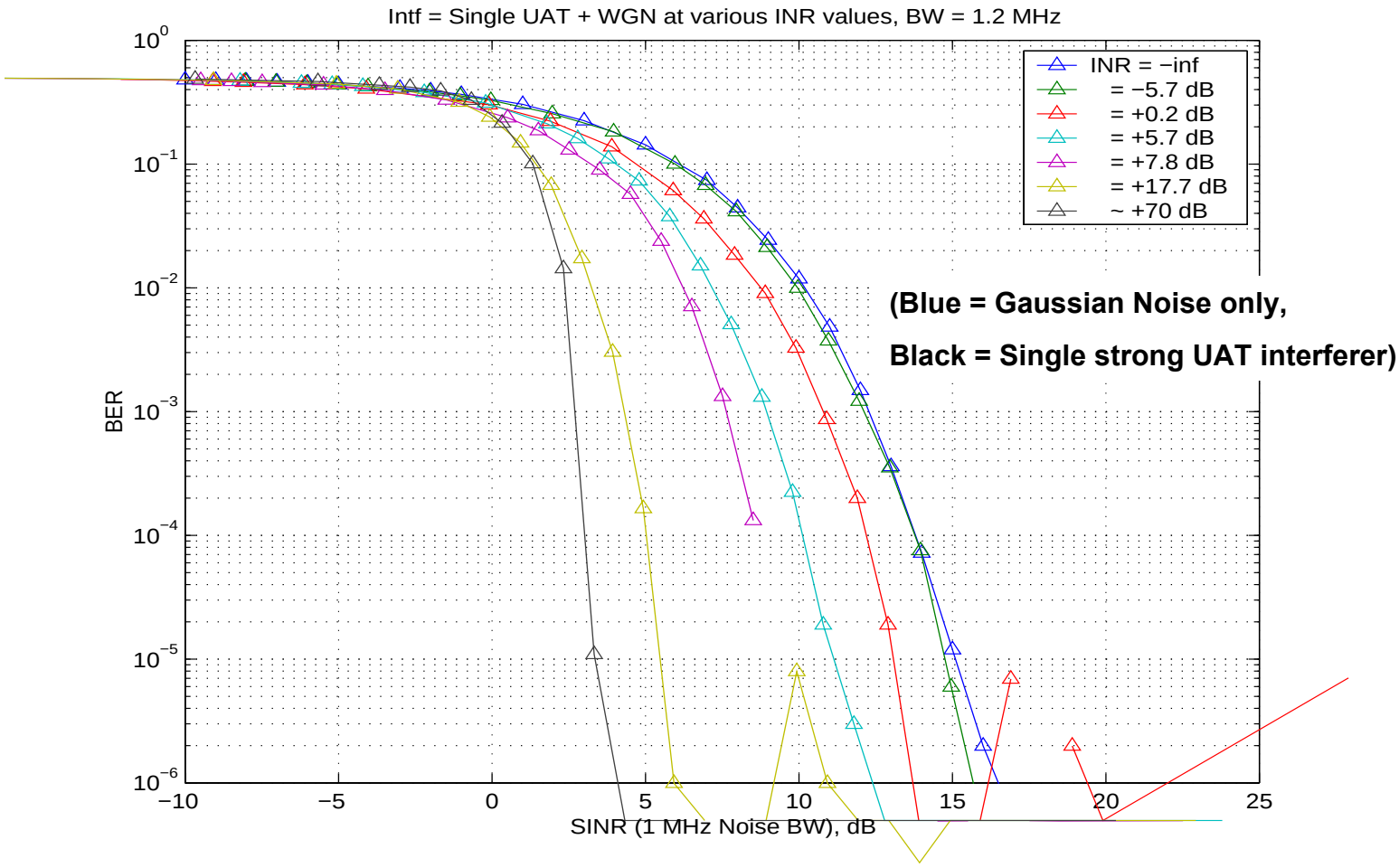
Confirmation of Hypothesized TX Power Droop



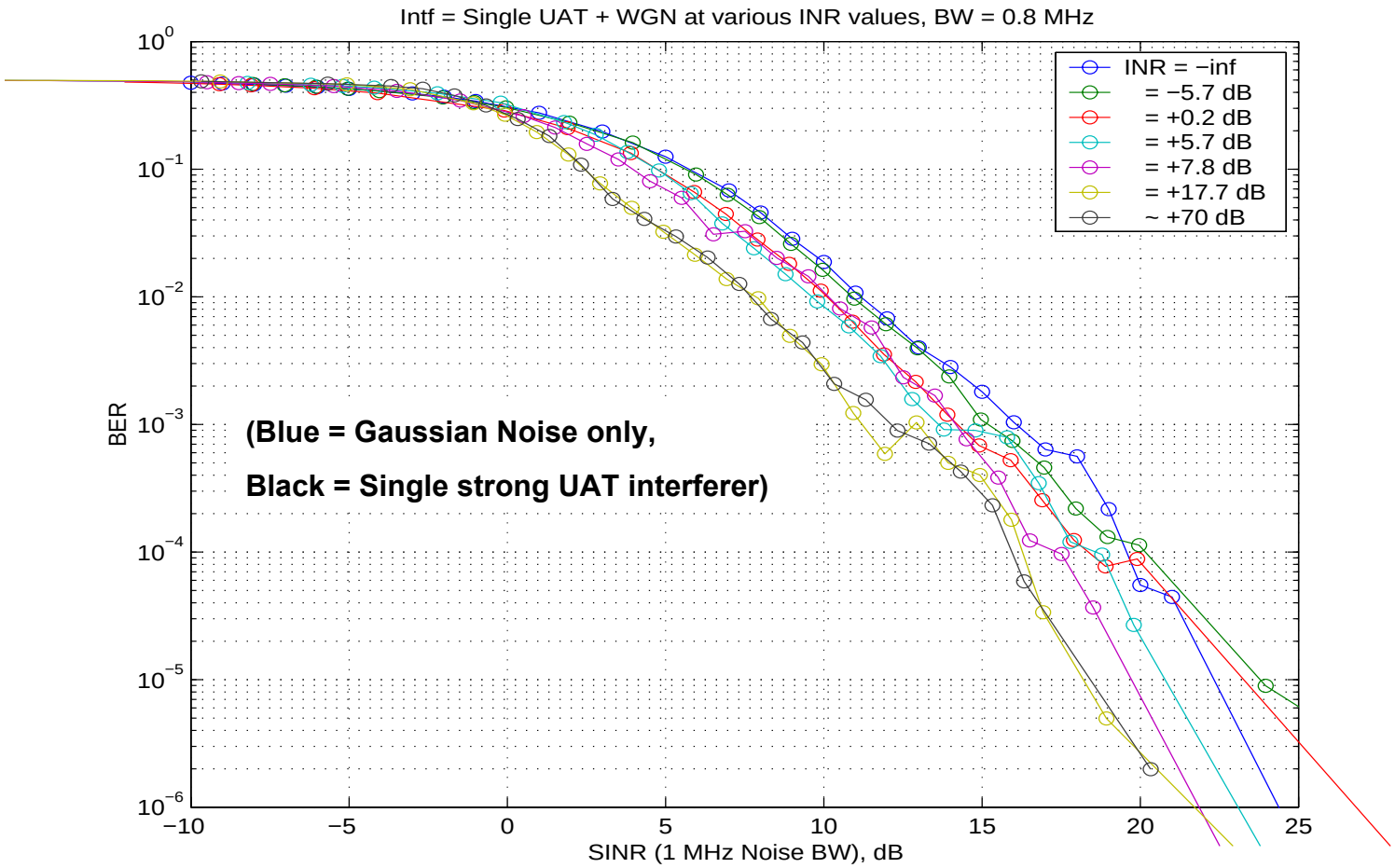
BER Vs. SINR Plots for Interference = Single UAT + WGN

- Summarizes all measured Single-UAT data
  - For each BW (0.8 or 1.2 MHz)
  - Averaged over all interfered bits within a UAT message

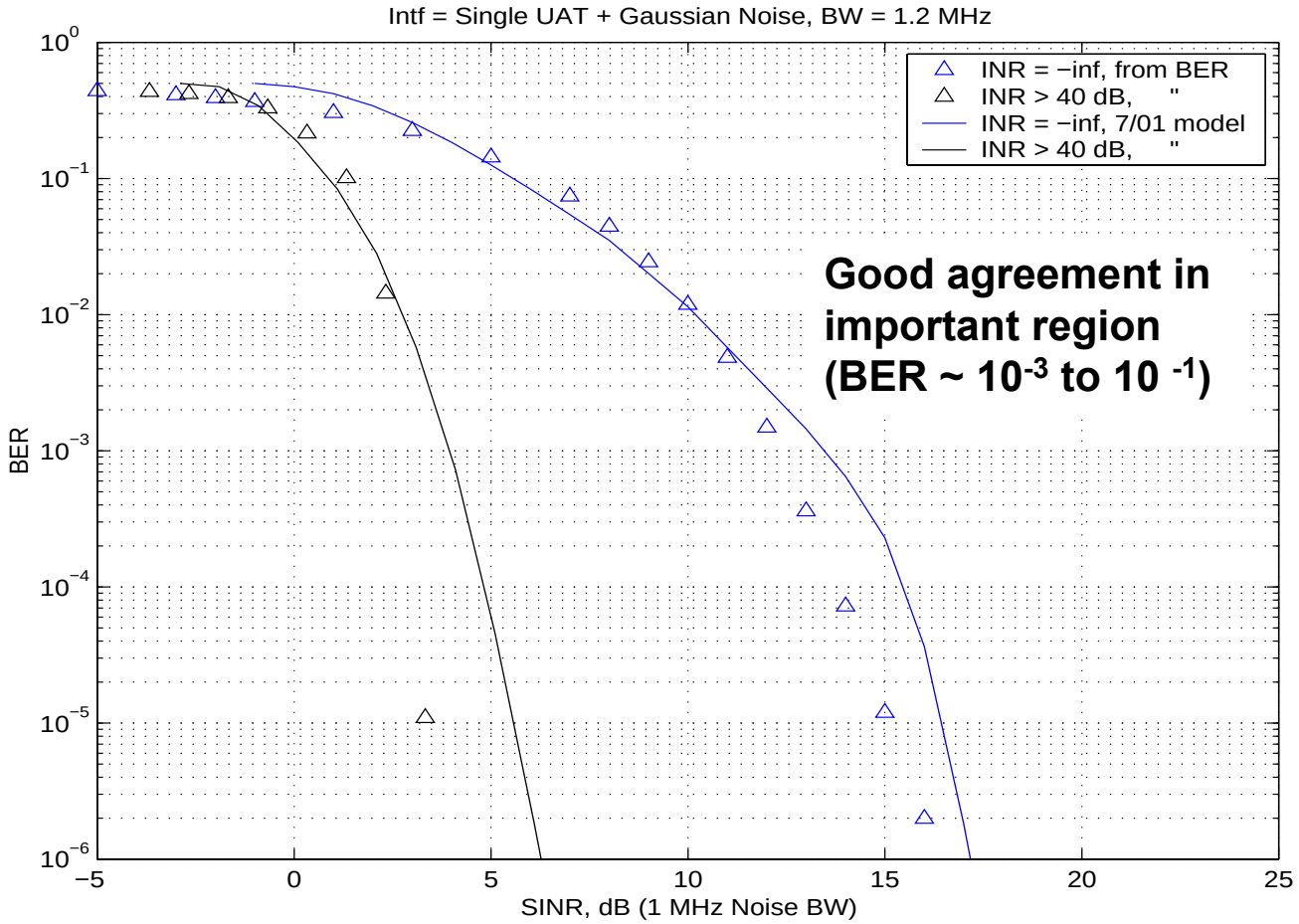
Interference = Single UAT + WGN, BW = 1.2 MHz



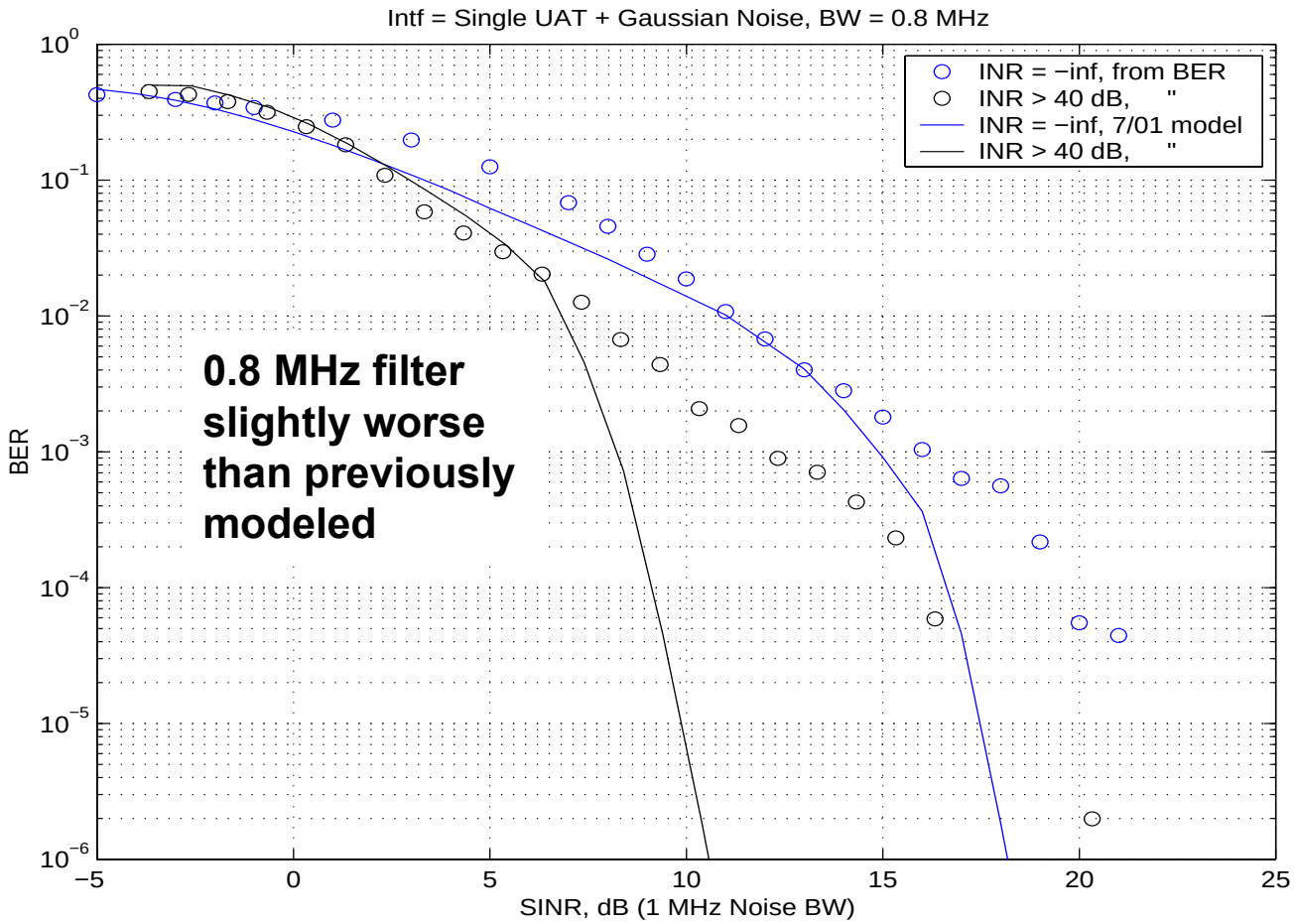
Interference = Single UAT + WGN, BW = 0.8 MHz



Comparison of Measured BER with Previous Model (Based on UPS-AT MER Measurements)– 1.2 MHz BW



Comparison of Measured BER with Previous Model (Based on UPS-AT MER Measurements)– 0.8 MHz BW



BER Observations for Single UAT + WGN Interference

- Measured BER are close to previous model (based on MER measurements)
  - Performance of 0.8 MHz BW slightly worse
- UAT interference has very similar impact on 0.8 MHz filter as WGN
  - Nearly the same for the same power in a 2 MHz BW
  - Expected for heavy Inter-Symbol Interference

Status

Performance Modeling With Collected BER Data

- Collected BER data can be inserted directly into the multi-aircraft network simulation
  - For every DME or Link 16 reception event (SIR and start time), a time profile of BERs for the following bits is provided
  - For single UAT interference, the BER is assumed constant during interference duration
  - For multiple simultaneous interferers at comparable levels:
    - Measured data is used for common situations (receiver noise and several UAT interferers)
    - Current approach is to assume independent bit errors for less likely situations (DME+UAT, Link 16+UAT, DME+Link 16, etc.):

$$BER_{12} = BER_1 + BER_2 - 2*BER_1*BER_2$$

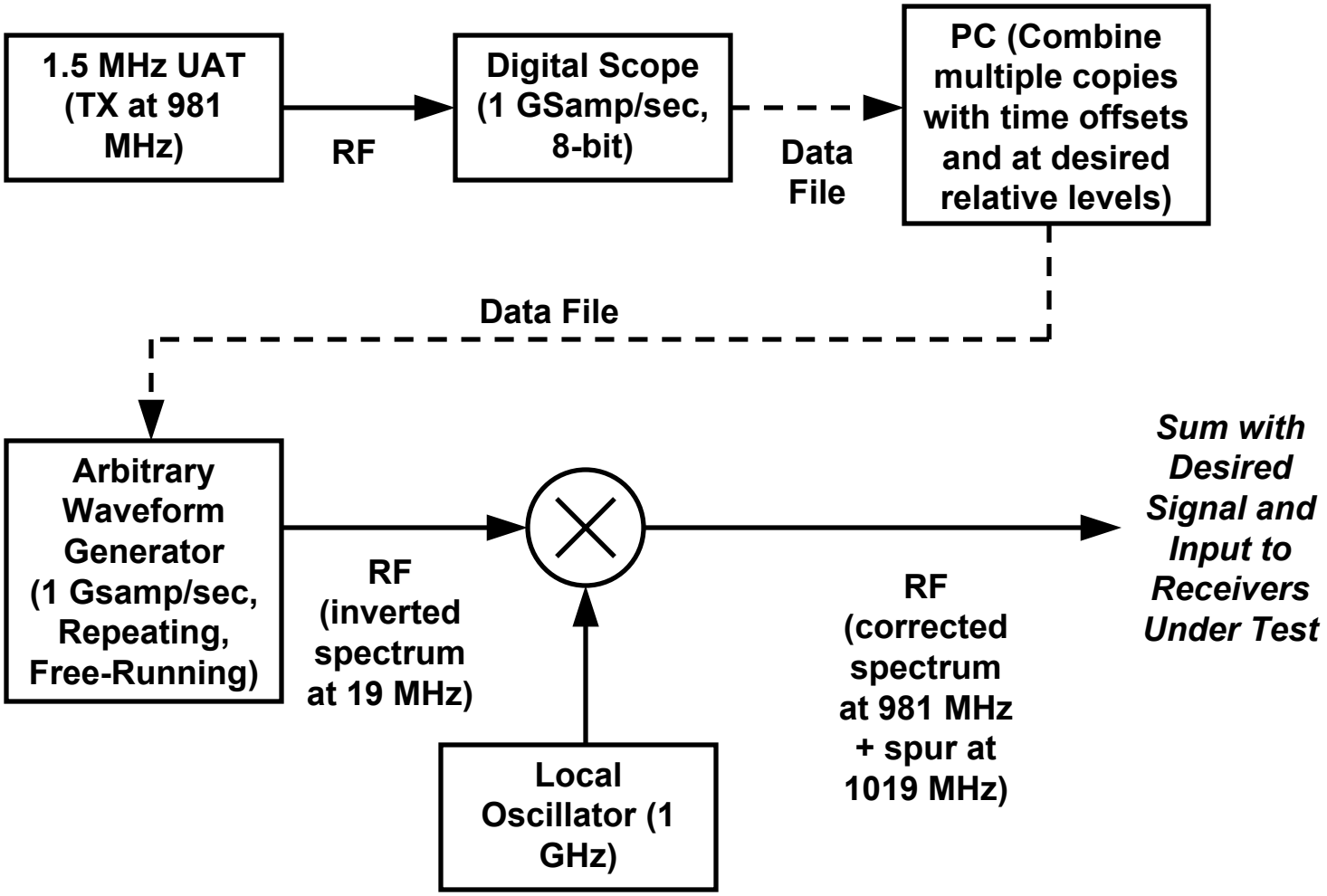
–This approach can be expected to slightly underestimate errors in these infrequent cases

BER Test Status

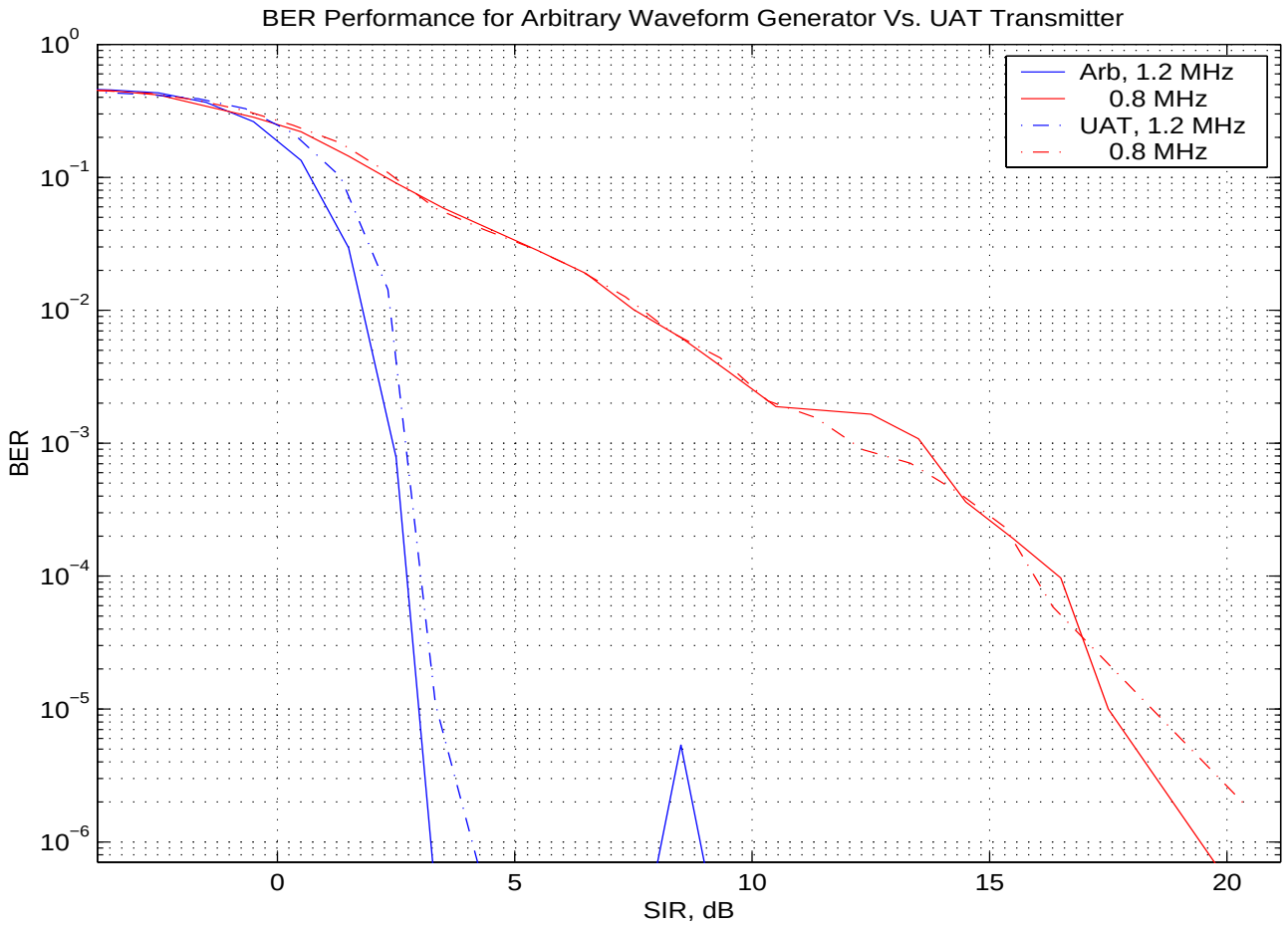
- DME
  - Tests completed
  - Receiver model completed
  - Included in latest multi-aircraft network simulation results
- Link 16
  - Tests completed
  - Receiver model completed
- Single UAT and/or Gaussian Noise
  - Tests completed
- Multi-UAT + Gaussian Noise
  - Initial tests planned for completion by 10 December

Near-Term Multi-UAT Test Approach

Alternative to multiple TX units or FAA-TC RF UAT Msg. Generator

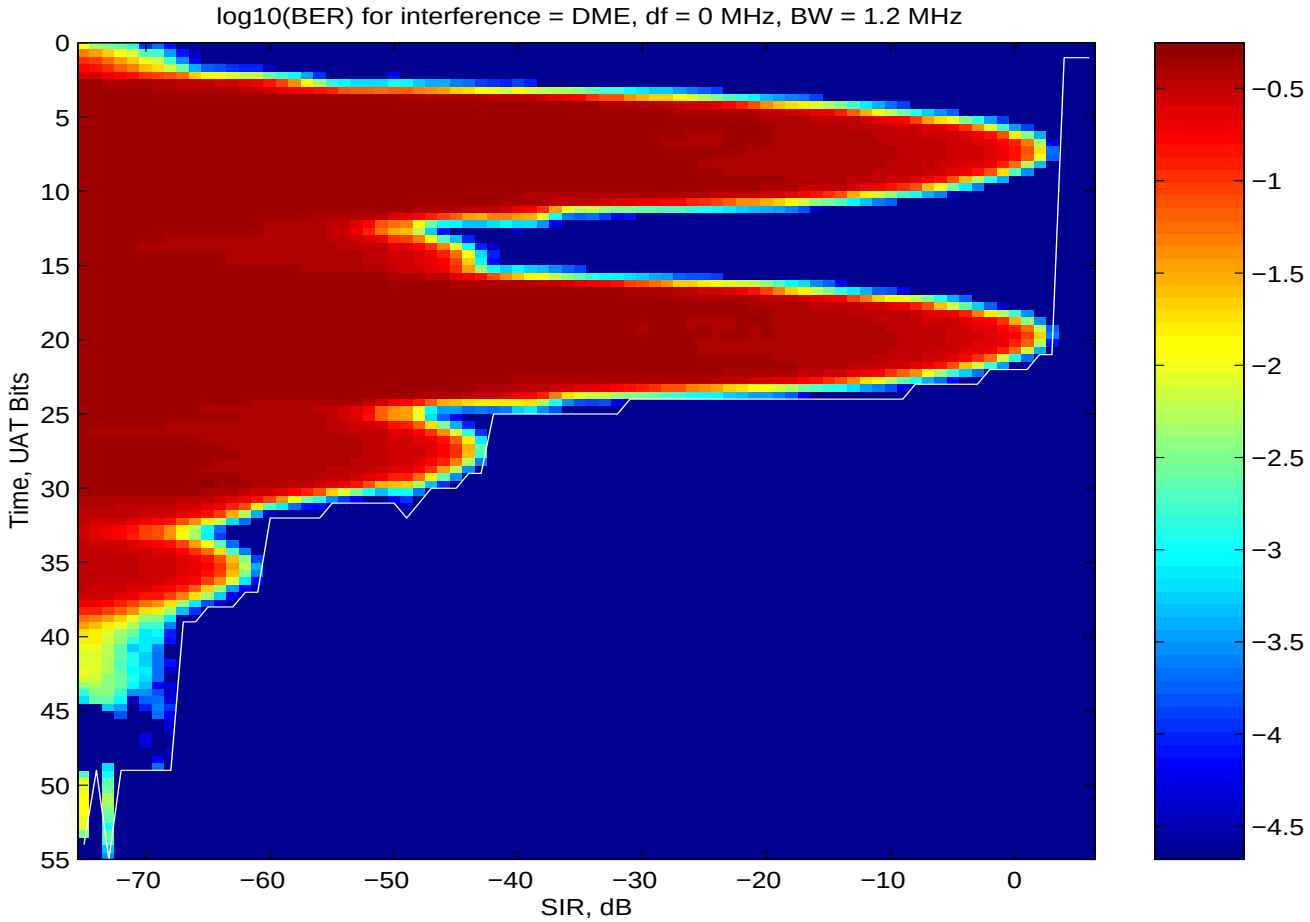


Comparison of BER Impact of Interference From Arbitrary Waveform Generator Vs. From UAT

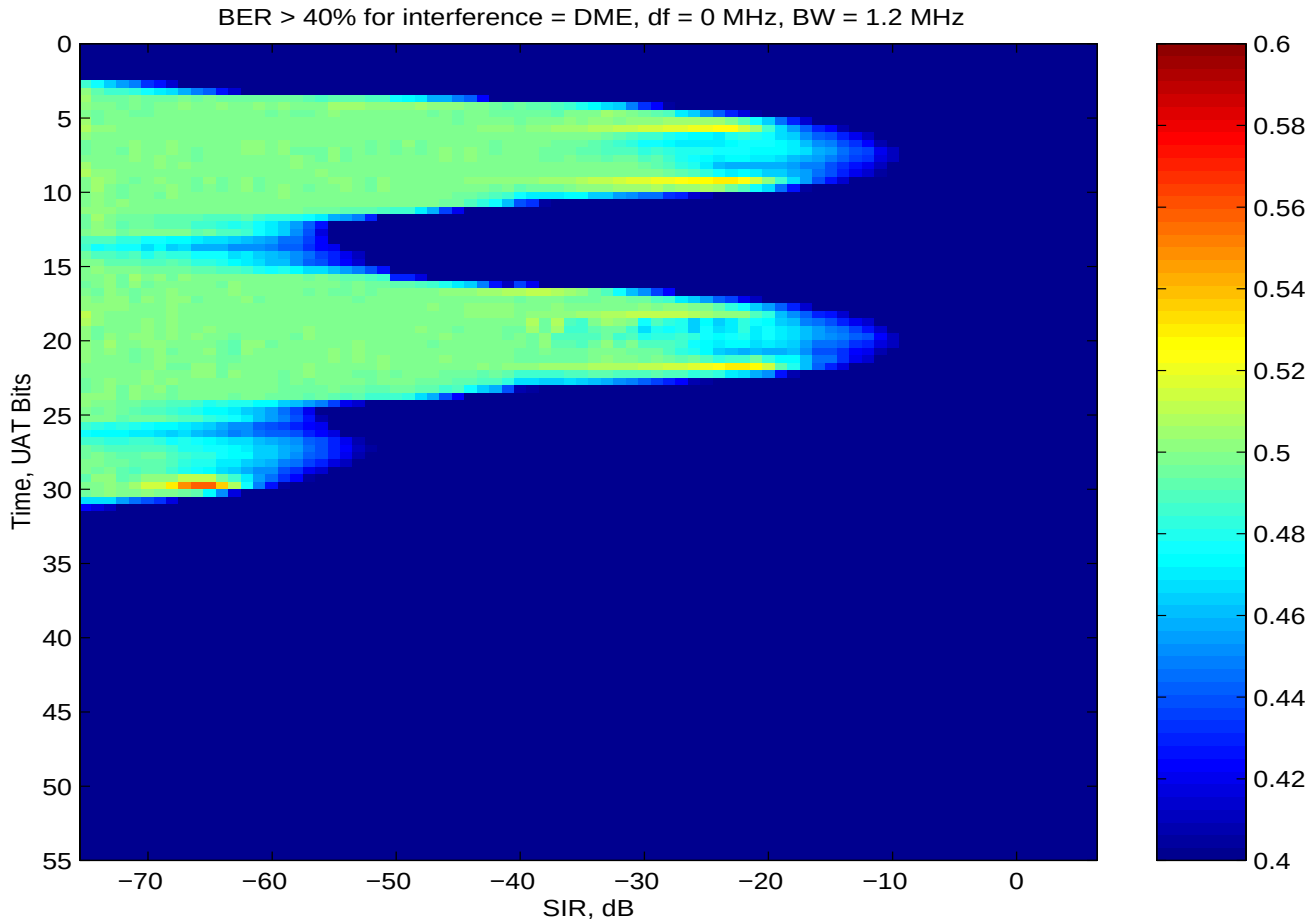


Backup Material

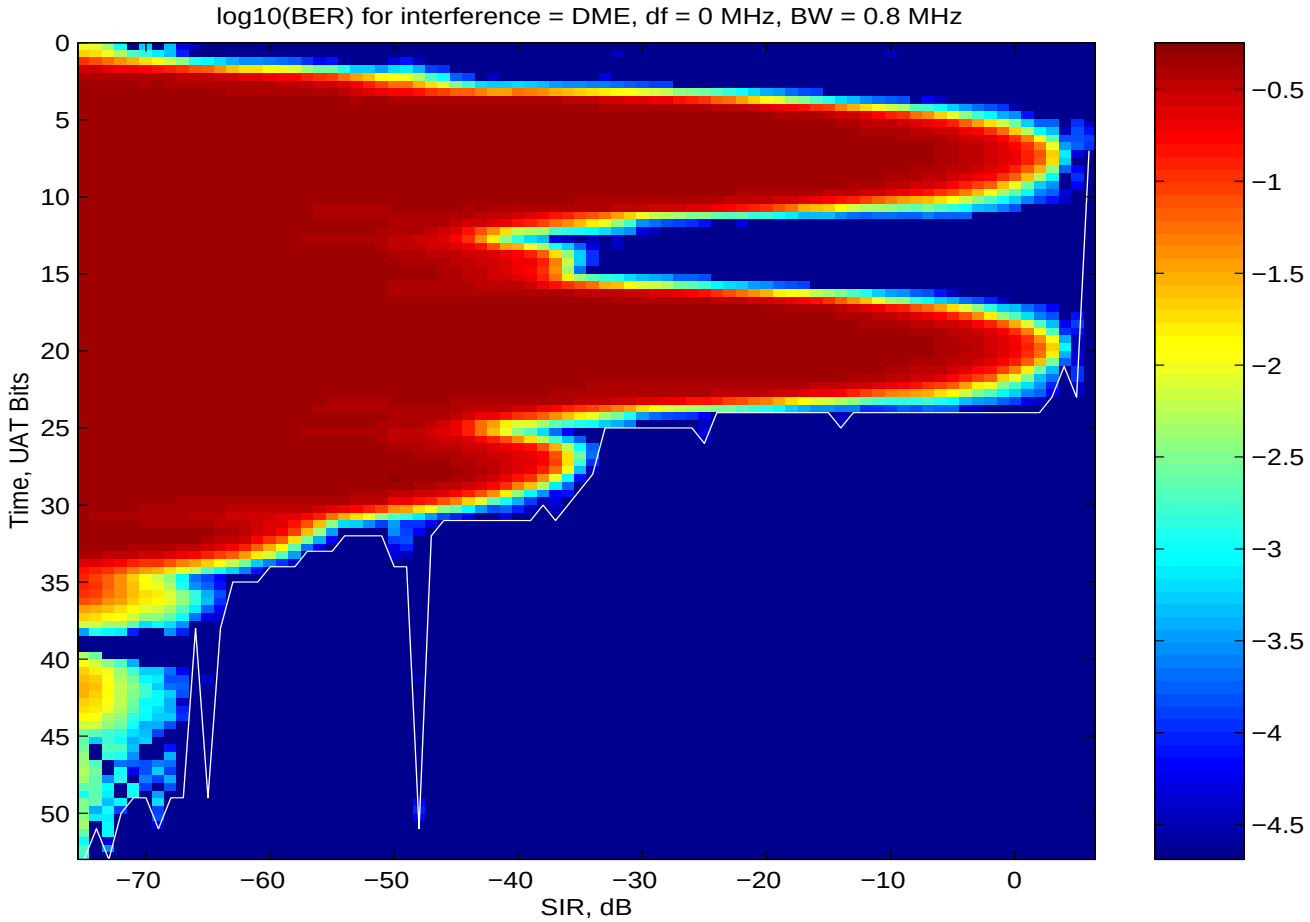
DME Interference, Δfreq = 0 MHz
Bw = 1.2 MHz



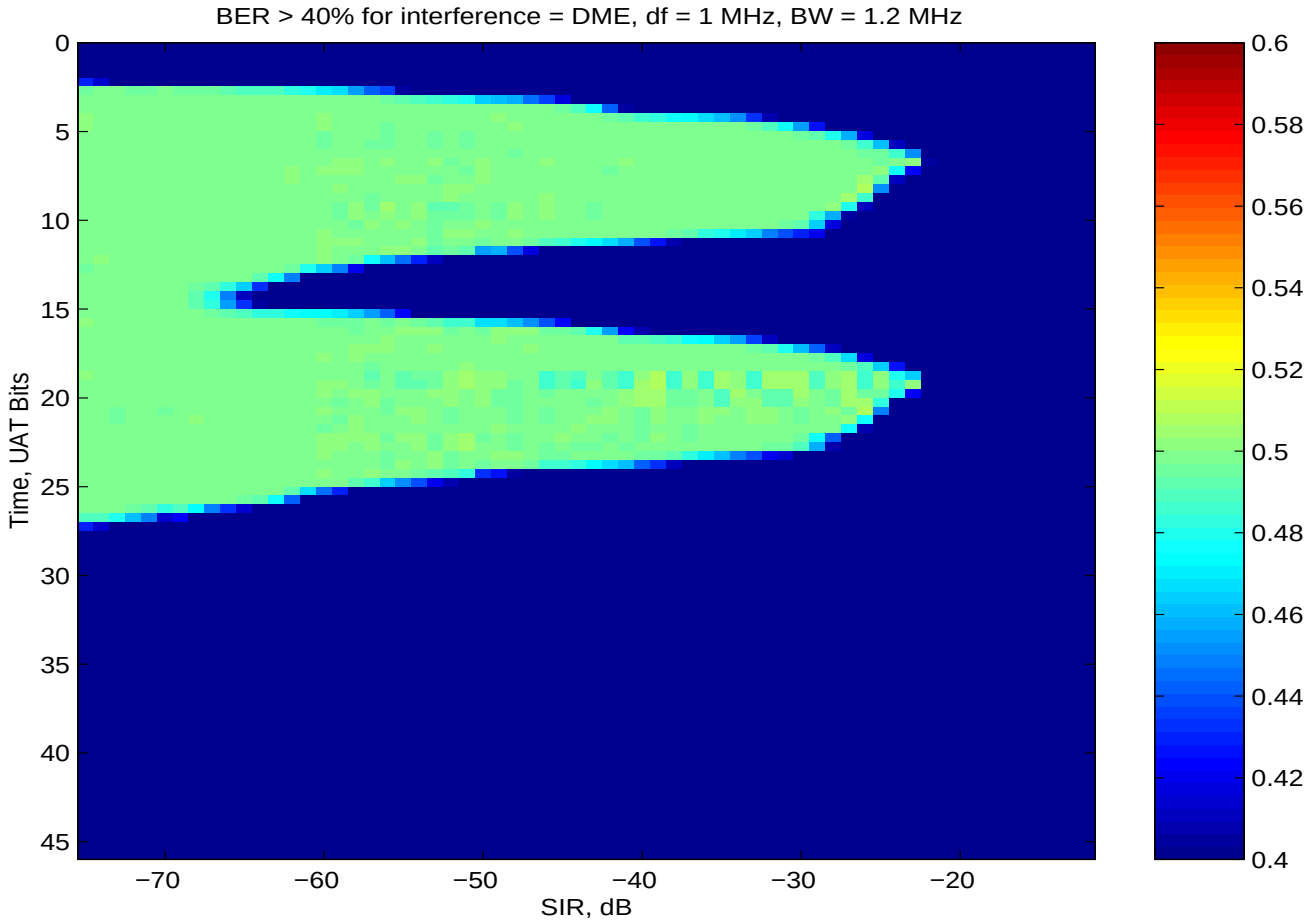
DME Interference, Δfreq = 0 MHz
Bw = 1.2 MHz



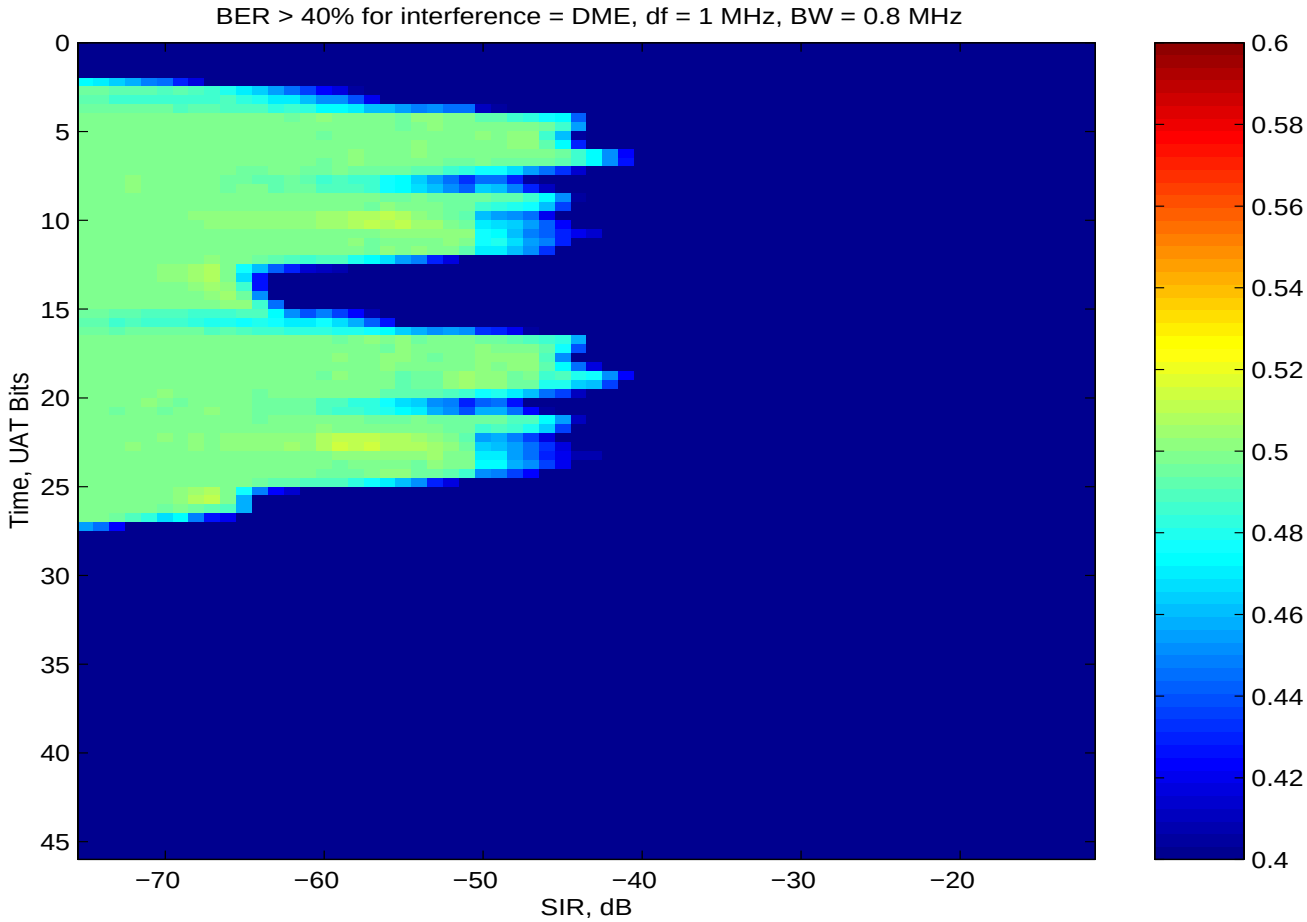
DME Interference, Δfreq = 0 MHz
Bw = 0.8 MHz



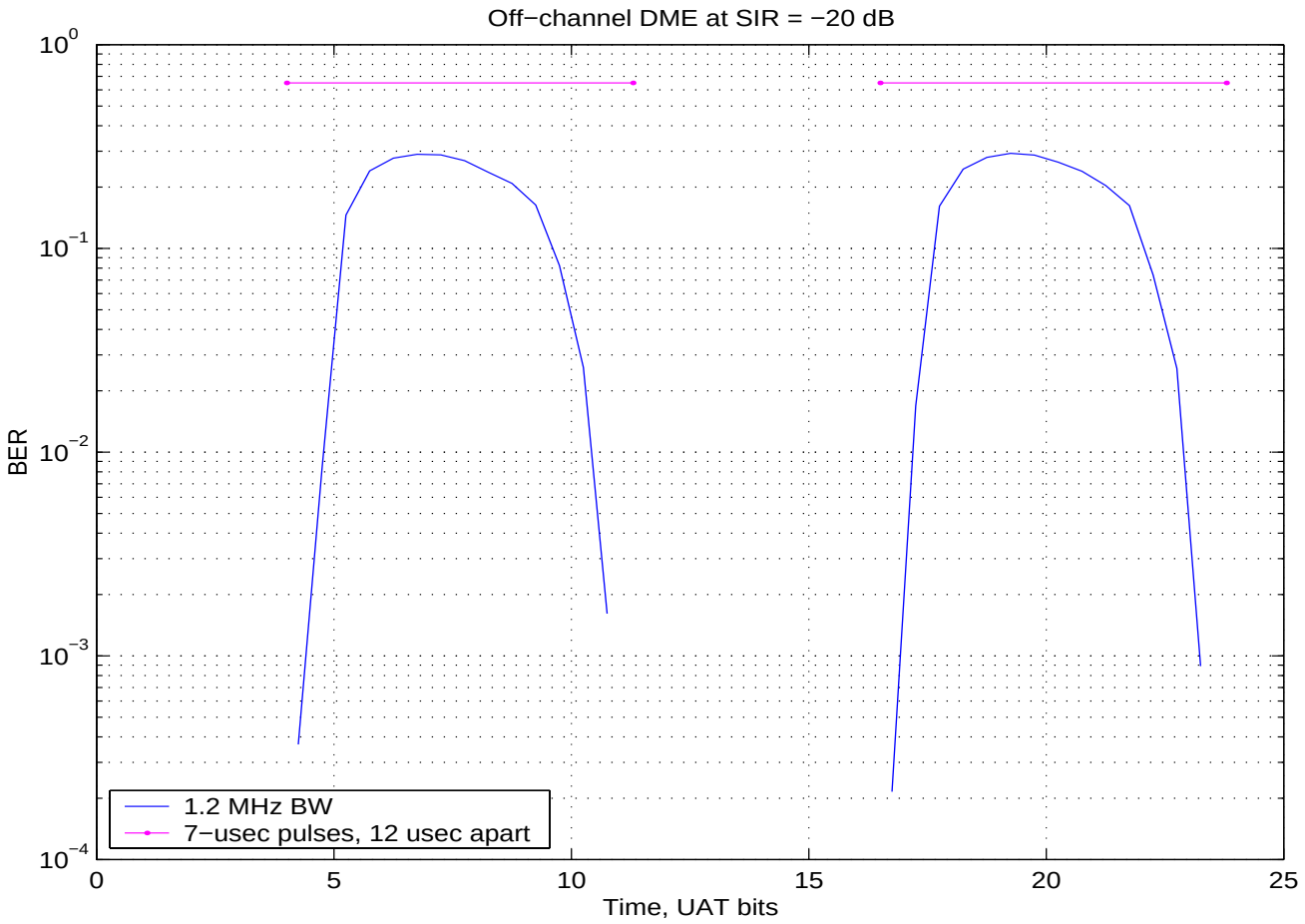
DME Interference, Δfreq = 1 MHz
Bw = 1.2 MHz



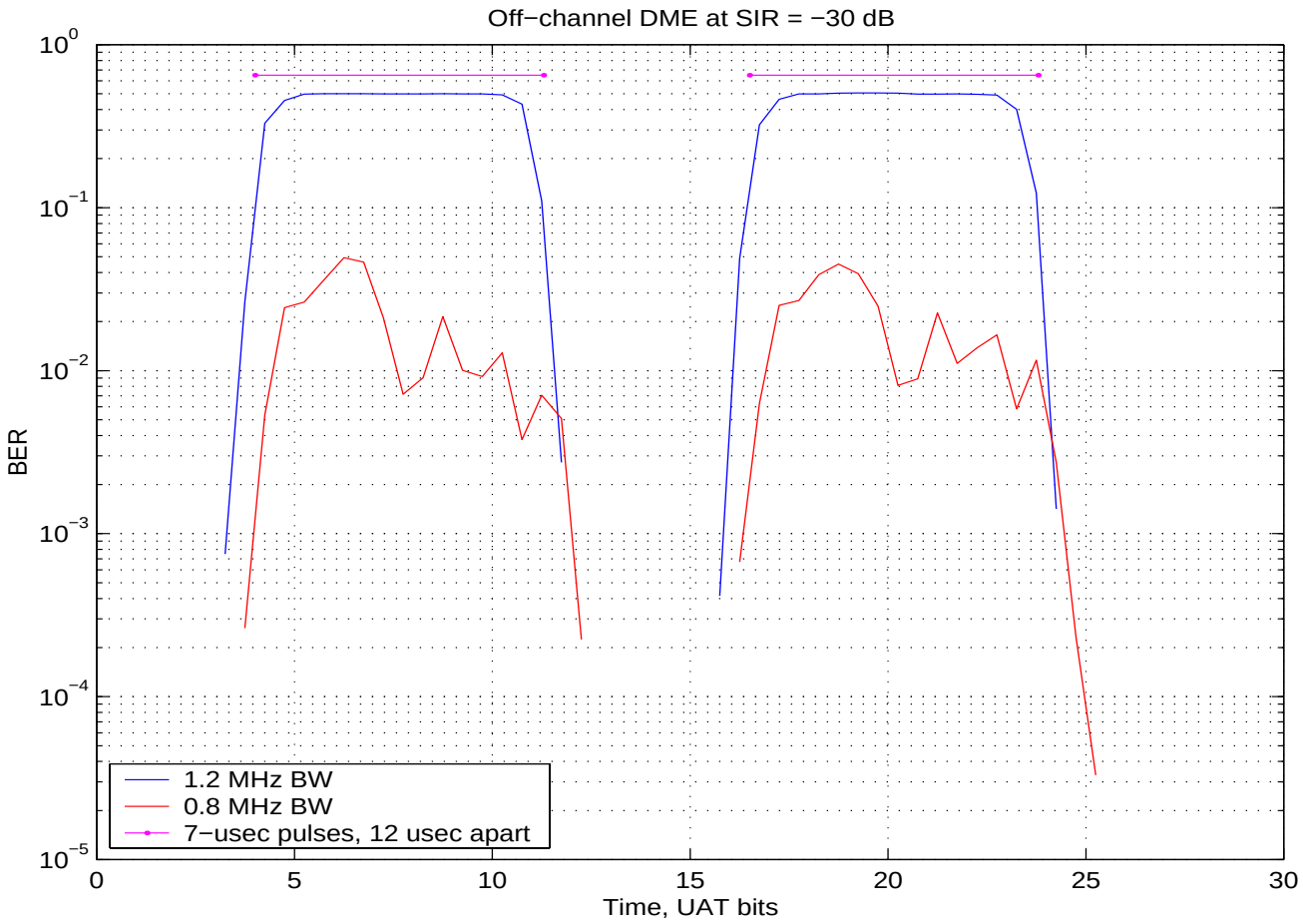
DME Interference, Δfreq = 1 MHz
Bw = 0.8 MHz



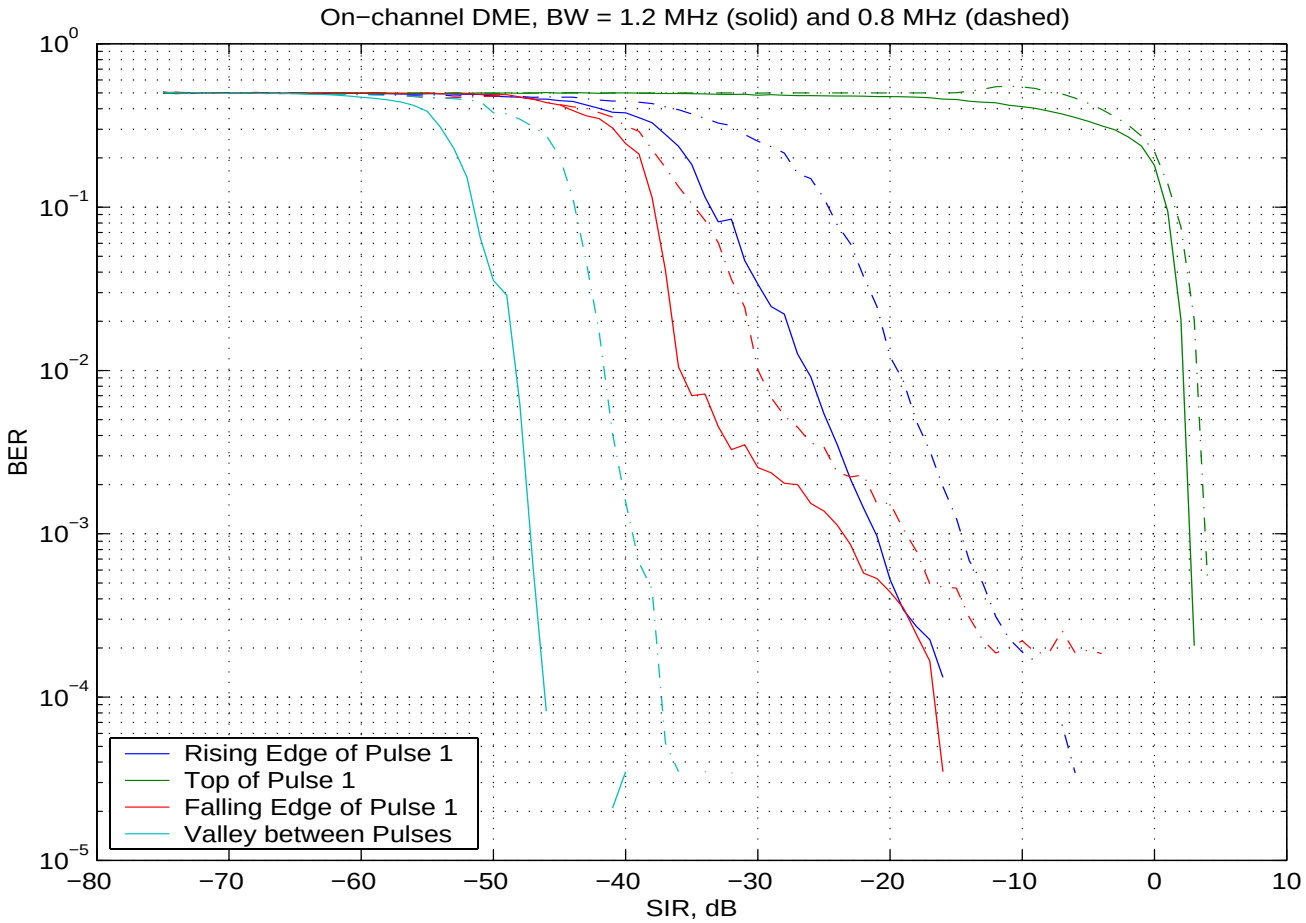
SIR = -20 dB


Off−channel DME at SIR = −20 dB
BER
Time, UAT bits
1.2 MHz BW
7−usec pulses, 12 usec apart

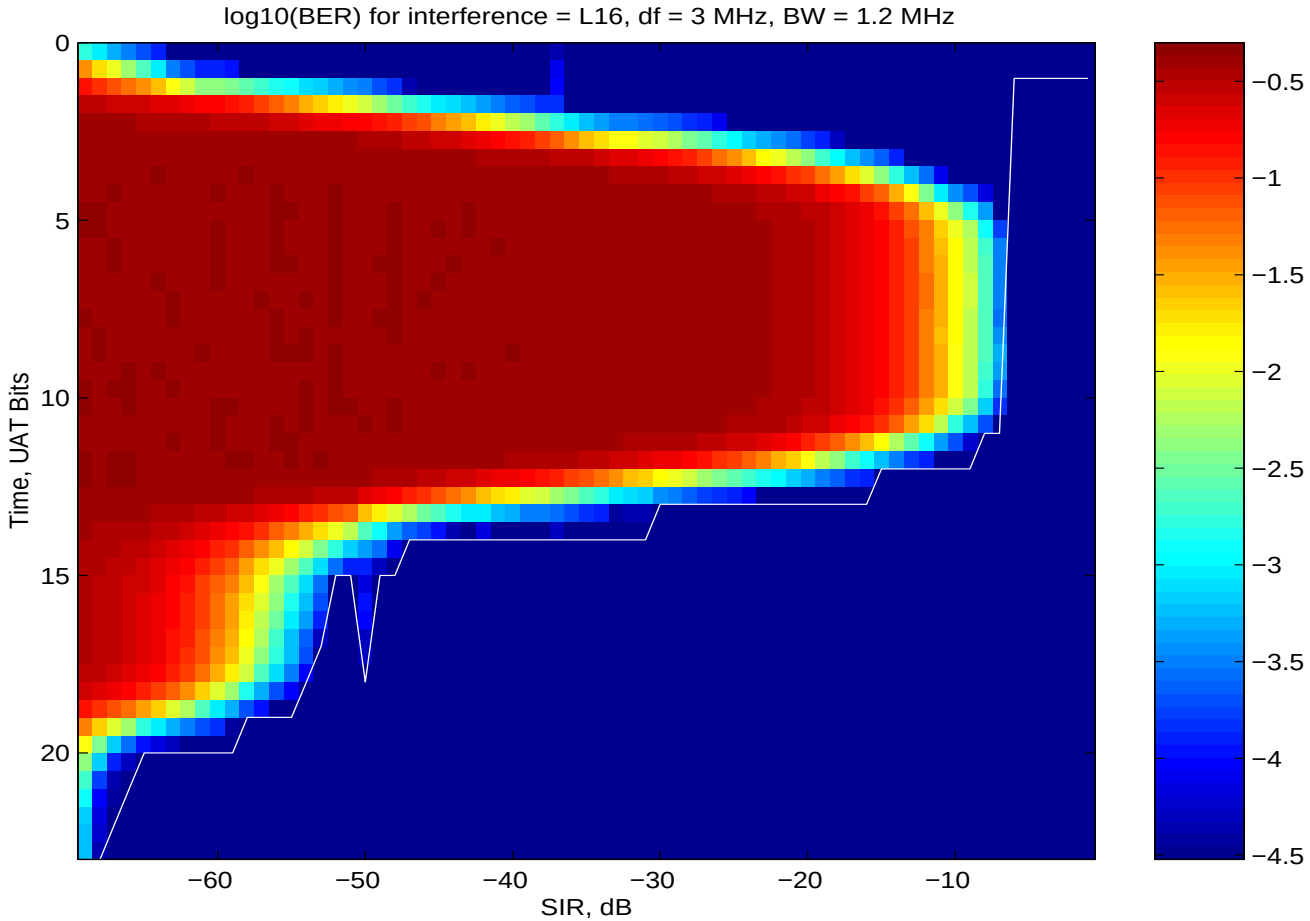
SIR = -30 dB


Off−channel DME at SIR = −30 dB
BER
Time, UAT bits
1.2 MHz BW
0.8 MHz BW
7−usec pulses, 12 usec apart

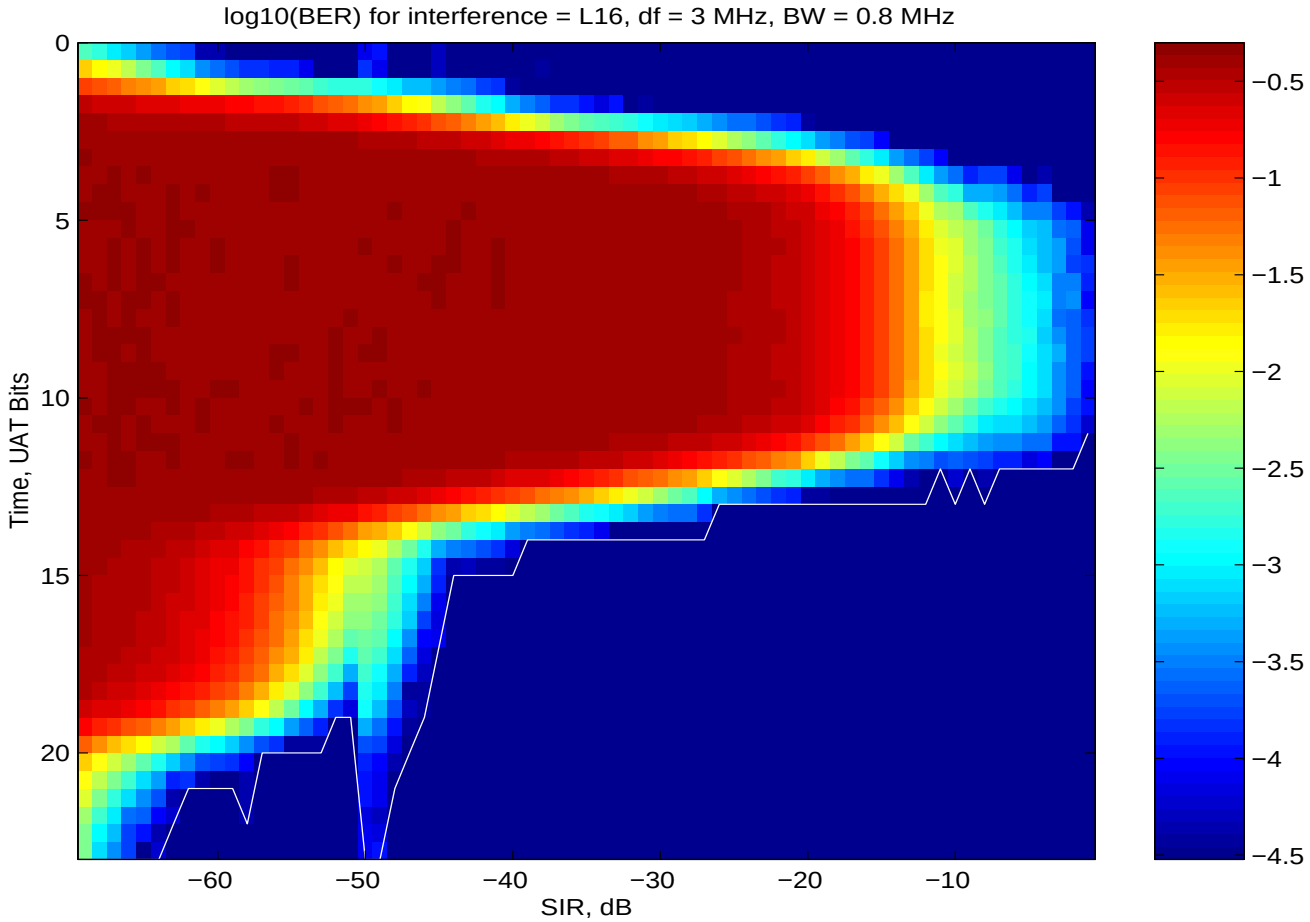
On-Channel DME



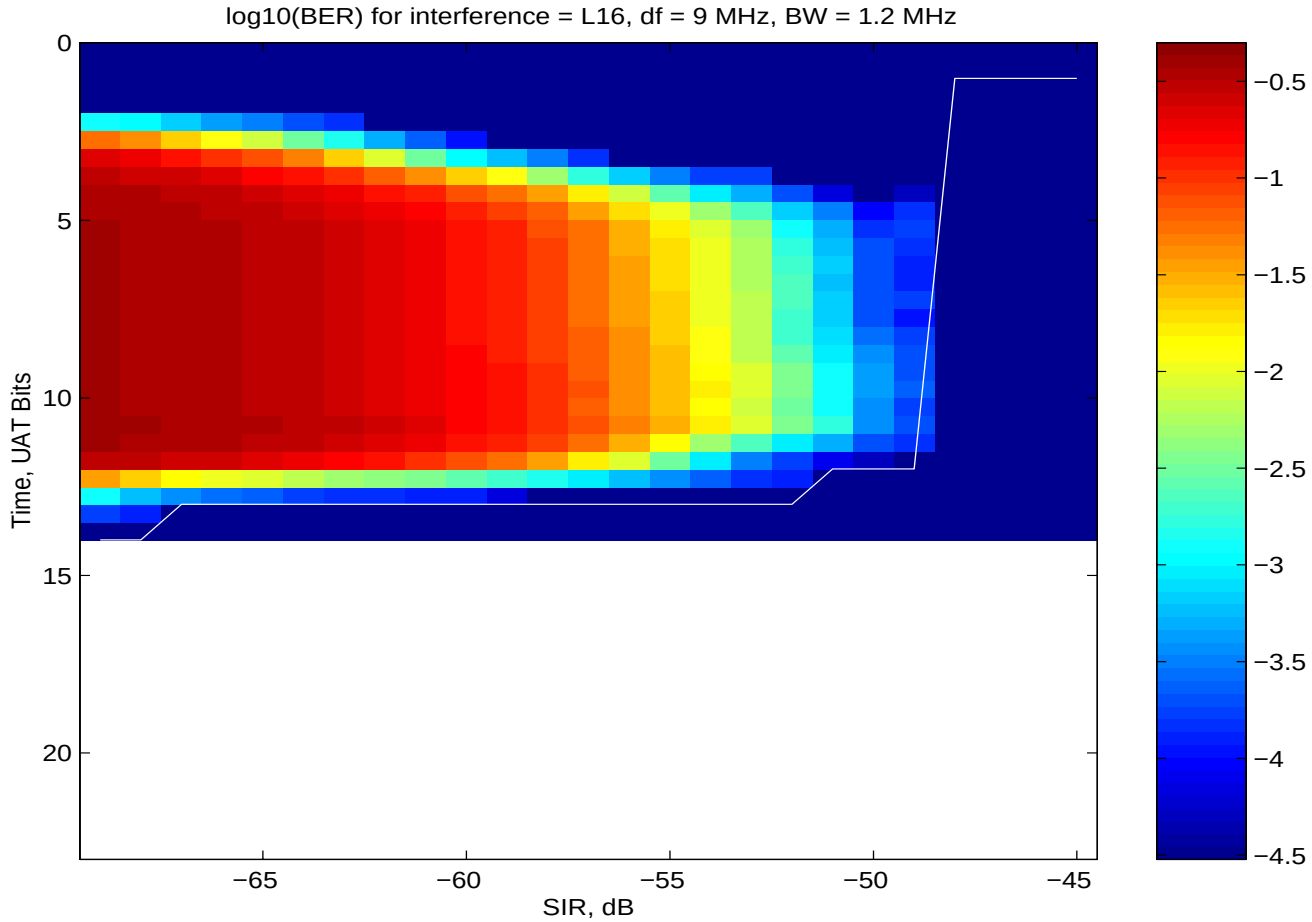
Link 16 Interference, Δfreq = 3 MHz
Bw = 1.2 MHz



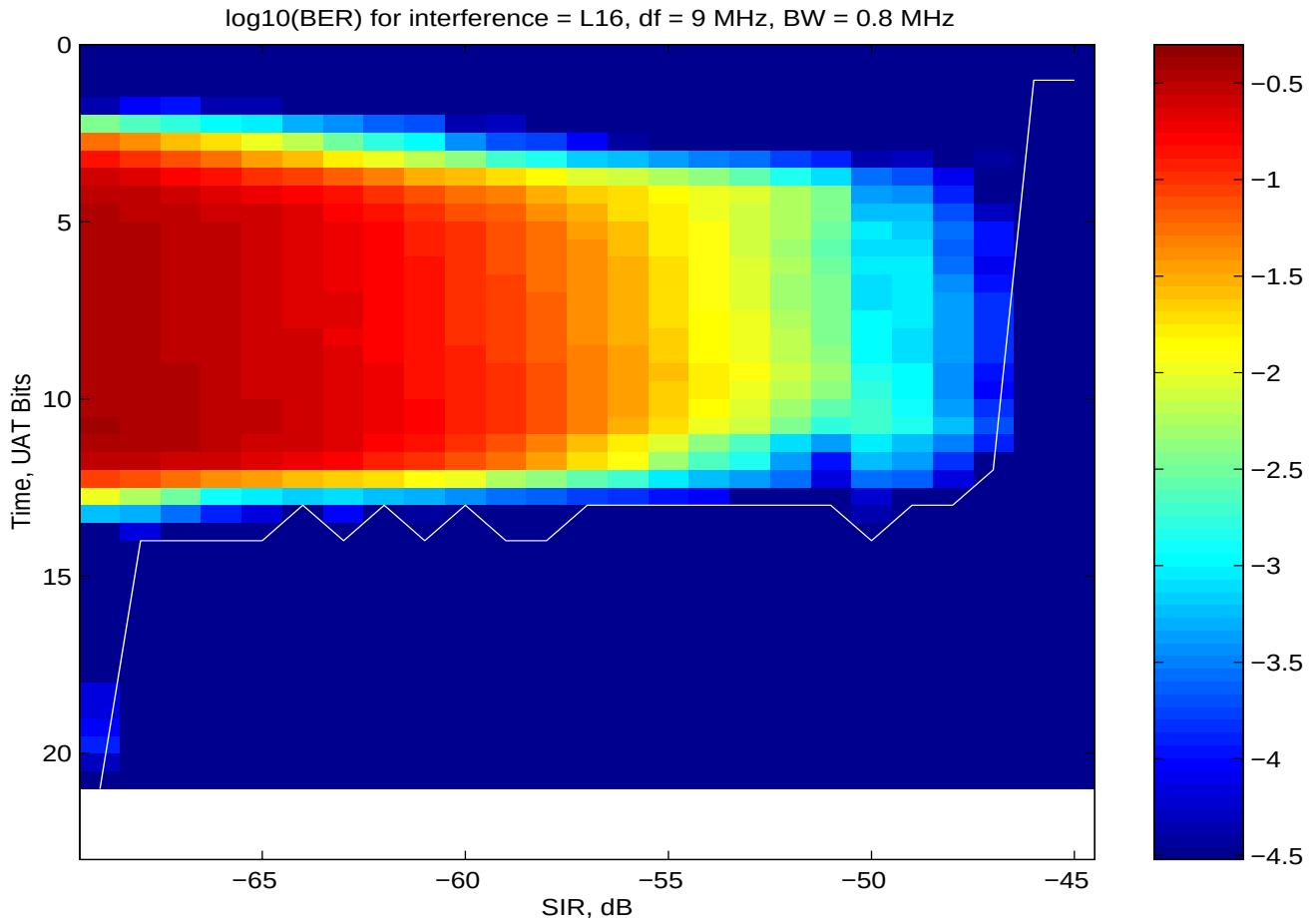
Link 16 Interference, Δfreq = 3 MHz
Bw = 0.8 MHz



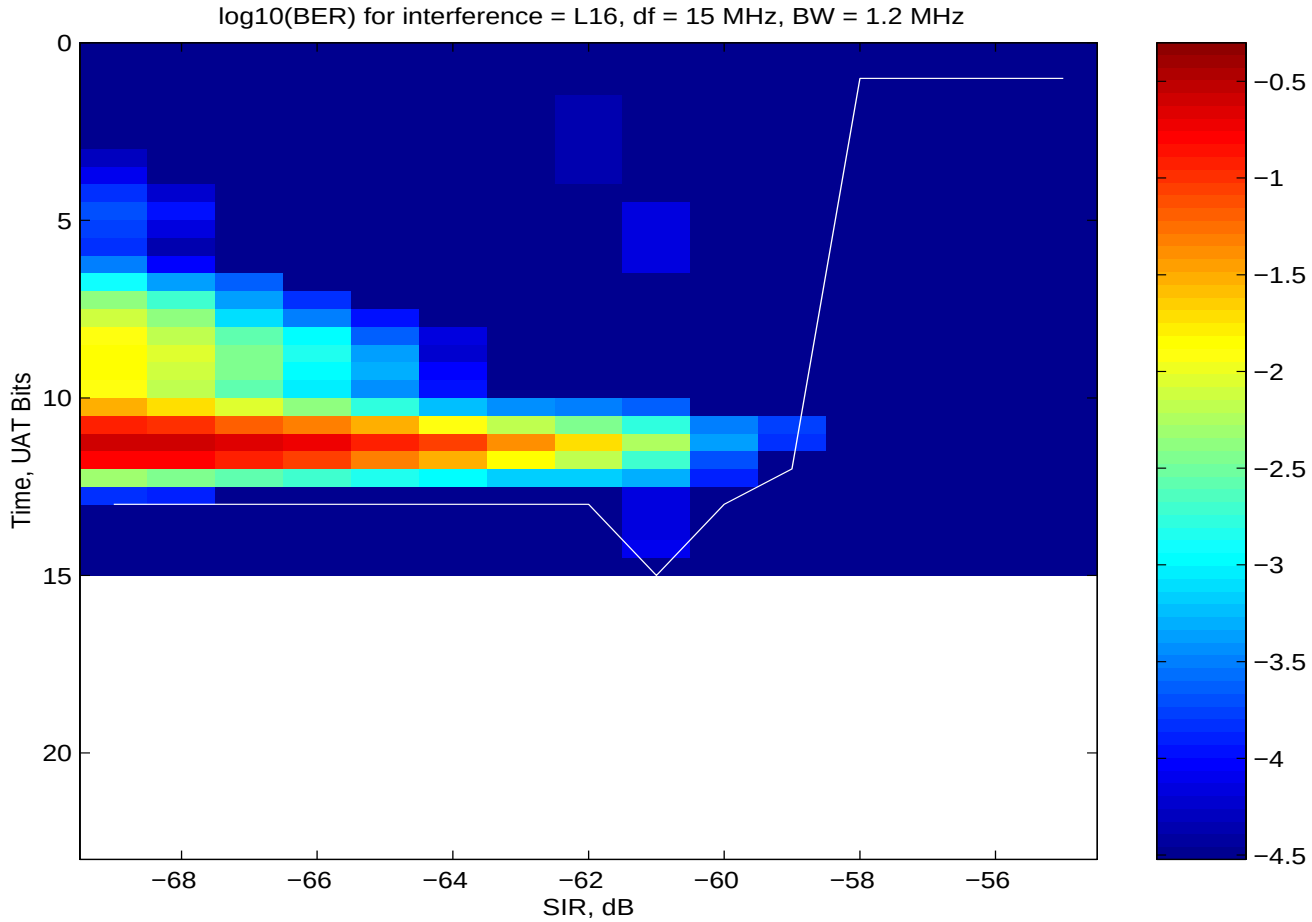
Link 16 Interference, Δfreq = 9 MHz
Bw = 1.2 MHz



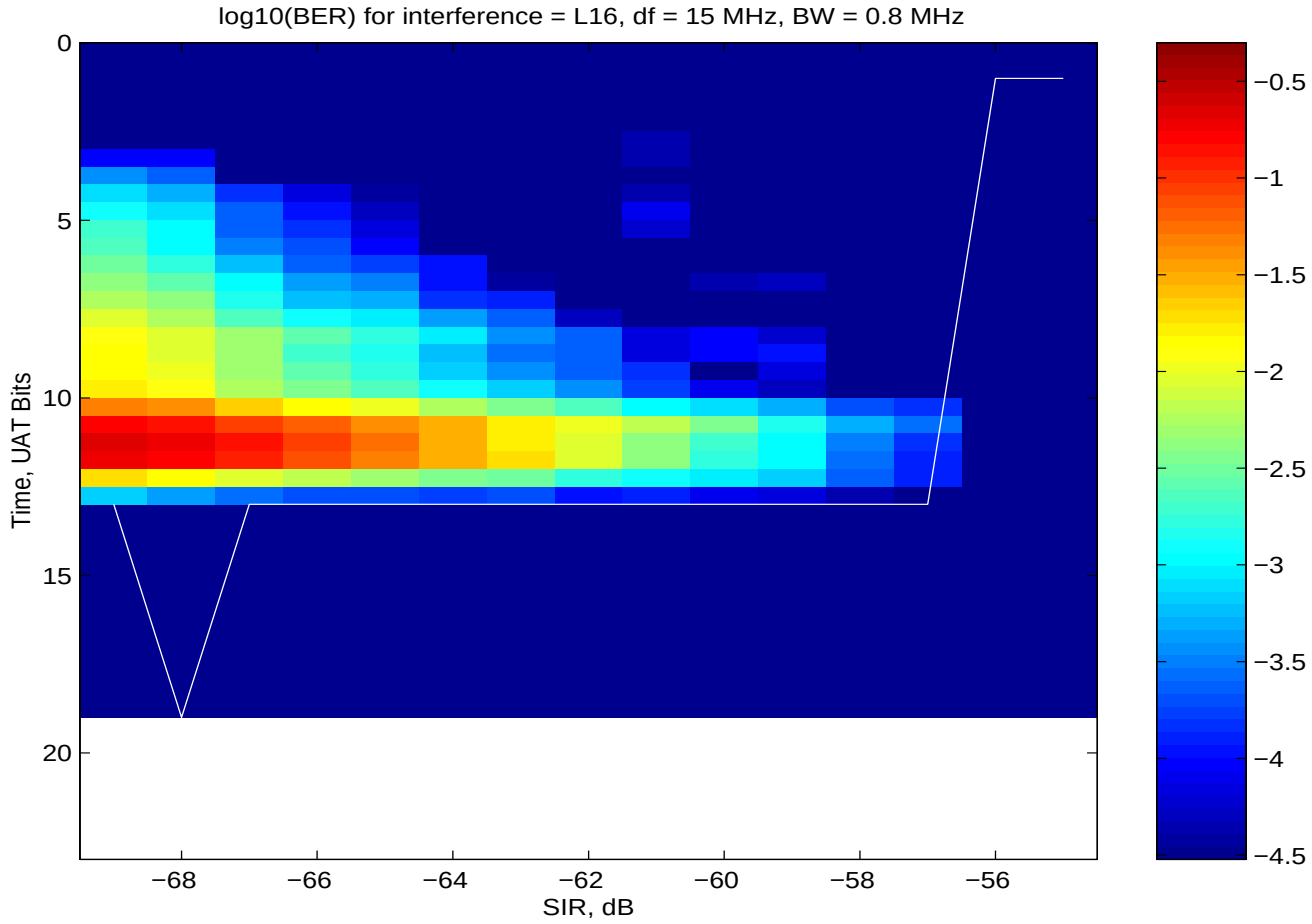
Link 16 Interference, Δfreq = 9 MHz
Bw = 0.8 MHz



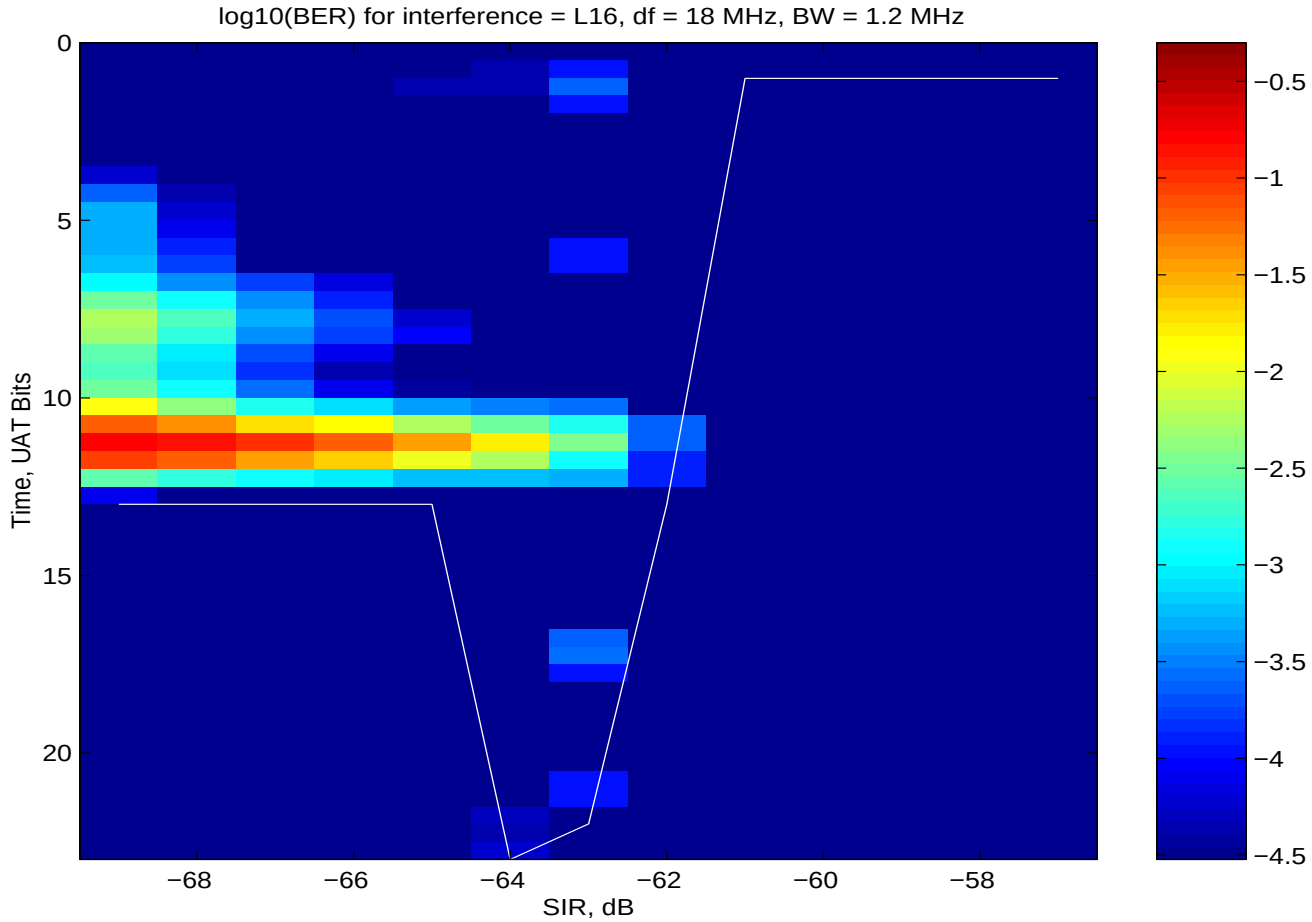
Link 16 Interference, Δfreq = 15 MHz
Bw = 1.2 MHz



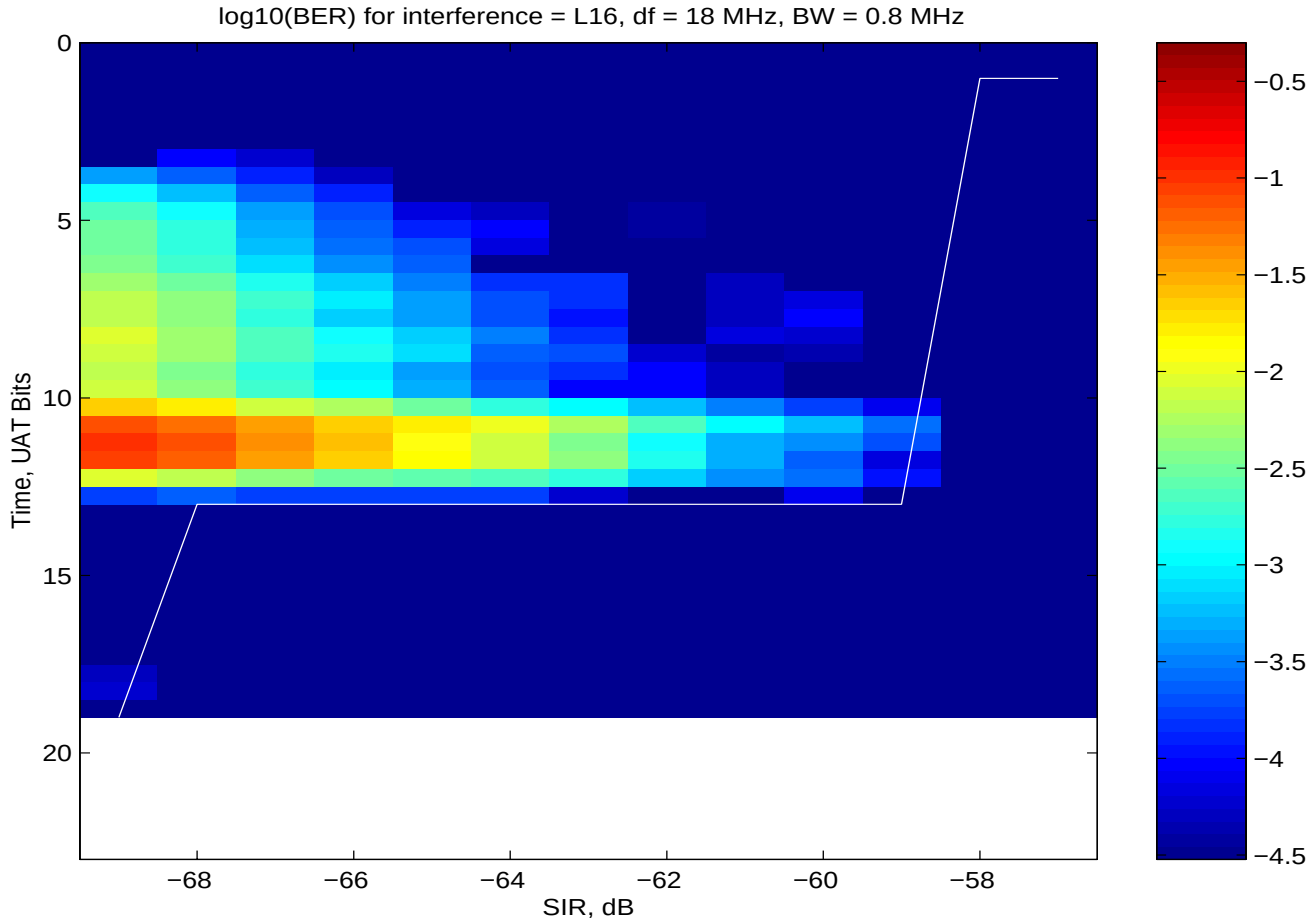
Link 16 Interference, Δfreq = 15 MHz
Bw = 0.8 MHz



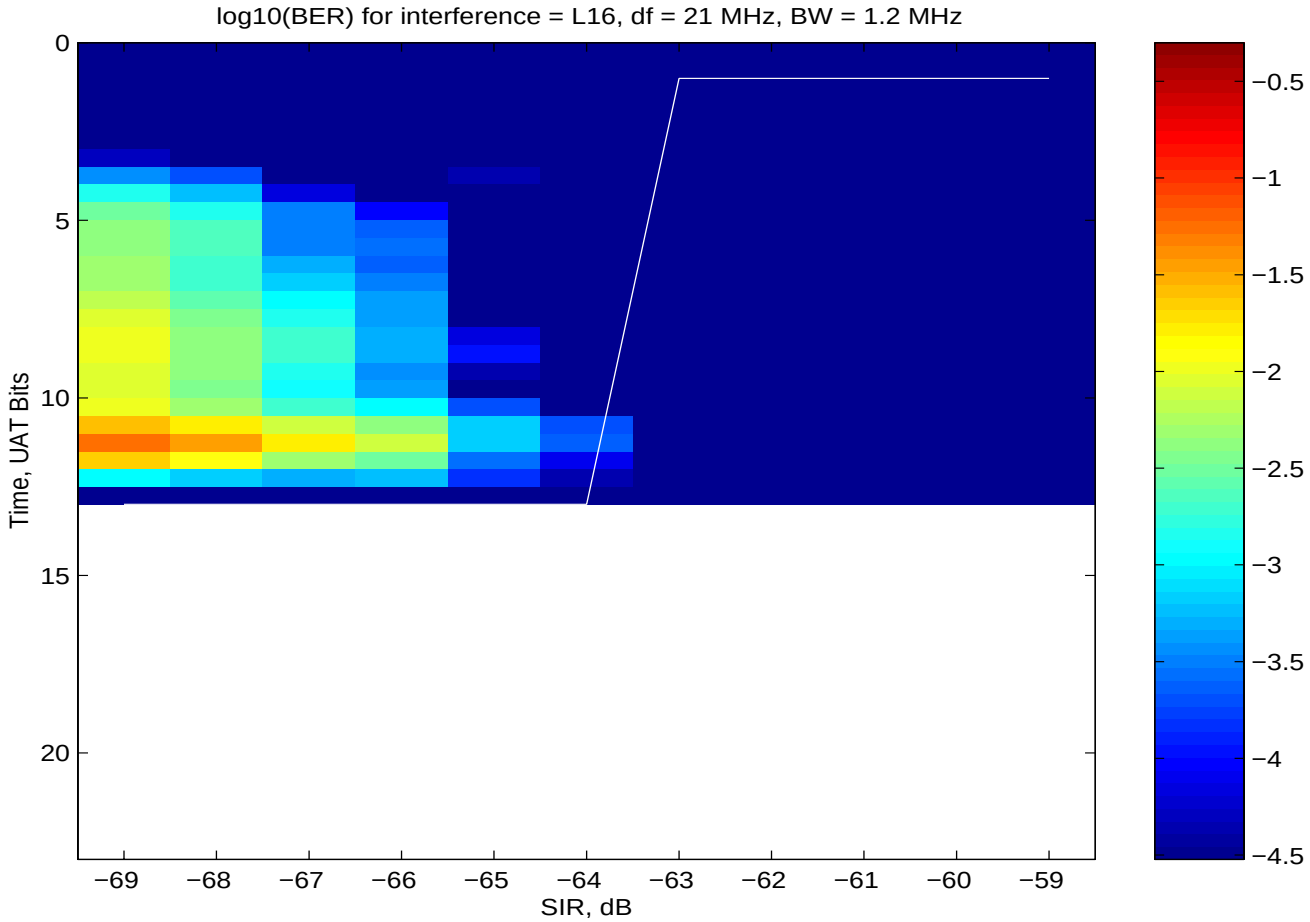
Link 16 Interference, Δfreq = 18 MHz
Bw = 1.2 MHz



Link 16 Interference, Δfreq = 18 MHz
Bw = 0.8 MHz



Link 16 Interference, Δfreq = 21 MHz
Bw = 1.2 MHz



Link 16 Interference, Δfreq = 21 MHz
Bw = 0.8 MHz