September 3, 2014

Via Electronic Filing

Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street SW
Washington, DC 20554

Re: Notice of Ex Parte Communication: *Amendment of the Commission's Rules with Regard to Commercial Operations in the 3550-3650 MHz Band*, GN Docket No. 12-354

Dear Ms. Dortch:

On September 2, 2014, the following individuals and I met with Commission staff: Taeyoung Yang and Randall Nealy of Virginia Polytechnic Institute and State University (Virginia Tech); Austin Schlick and Andrew Clegg of Google Inc.; and John Serafini, Iyad Tarazi, and James Neel from Federated Wireless. Participating in the meeting were John Leibovitz, Brian Regan, Kamran Etemad, and Paul Powell of the Wireless Telecommunications Bureau, and Julius Knapp, Navid Golshahi, and Robert Pavlak of the Office of Engineering and Technology.

During the meeting, we discussed the presentation attached, which summarizes the results of lab and field testing conducted by Virginia Tech, Google, and Federated Wireless (collectively, the presenters). The presentation shows that fixed exclusion zones are not needed in the 3550-3700 MHz band. The presenters' joint lab and field tests demonstrate that LTE and Wi-Fi can operate within close proximity of the incumbent naval radar system without substantial degradation in performance. They also demonstrate that fixed exclusion zones are not needed to protect the radar from interference from commercial operations and that dynamic exclusion zones can be implemented with existing technology.

Pursuant to the Commission's rules, this notice is being filed in the above-referenced docket for inclusion in the public record. Please contact me should you have any questions.

Respectfully submitted,

Prof. Jeff Reed
Willis G. Worcester Professor in
Electrical and Computer Engineering
Virginia Polytechnic Institute and State University

cc: *via electronic mail*
John Leibovitz
Brian Regan
Kamran Etemad
Paul Powell
Julius Knapp
Navid Golshahi
Robert Pavlak

Radar/Small-Cell Compatibility Lab and Field Tests

September 2, 2014

Summary

- Lab tests demonstrate that LTE and Wi-Fi networks can operate in the presence of radar interference when as close as 0.6 km (non-line-of-sight) and 20.7 km (line-of-sight)
- Field tests with an actual 3.5 GHz incumbent radar and an LTE picocell are consistent with the lab tests and confirm non-co-channel operation at a separation of 1.25 km (line-of-sight to the radar) and co-channel operation at a distance of 4 km (non-line-of-sight)
- Field tests with academic radios can detect incumbent radar operations at 70 km. Because of the range of detection, SAS's augmented with Dedicated Listening Devices can detect radar operations and reconfigure the band prior to causing harmful interference to incumbents

Why the difference from the Fast Track Report?

- Technology and assumptions have changed
  - FTR assumed “worst-case” high-site WiMAX, overly stringent interference criteria for wireless networks, peak radar power, and long-distance propagation predictions that did not adequately take into account shadowing and other clutter losses
- Dedicated Listening Devices (DLDs) can detect incumbent radar activities at very large distances, and SASs can configure secondary activities to avoid interference
  - Only ~100 DLDs are needed to monitor all U.S. coastal activity
- Permanent fixed exclusion zones are not needed
  - In small areas where interference may occur, SASs and network management will mitigate interference

Presentation

- Background information on incumbent radar
- Lab tests
  - Results of simulated incumbent radar signals into LTE and Wi-Fi
- Field tests
  - Results of field tests using an actual incumbent radar and a native 3.5 GHz TD-LTE access point
  - Results of detections of radar signal at various distances using cyclostationary techniques
- Discussion

BACKGROUND

Principal incumbent Navy radar: SPN-43

SPN-43 Characteristics

SPN-43 Radar Characteristics

Tuning Range	3500 – 3700 MHz
Pulse Repetition Rate	1,000 Hz
Pulse Width	1 microsecond
Duty Cycle	0.1%
3-dB Bandwidth	~1 MHz
Bandwidth between first spectral nulls	~1.9 MHz
Transmit Power (peak/average)	1 MW/ 1 kW (60/30 dBW)
Antenna Gain	32 dBi
EIRP (peak/average)	1.6 GW/1.6 MW (92/62 dBW)
Antenna Beamwidth (H/V)	1.75/4.4 degrees
Antenna Polarization	Horizontal (typical) or circular
Antenna Rotation Period	I. seconds

Note: Only authorized to operate in 3650-3700 MHz on ships more than 50 miles off-shore and at two land-based sites

There are 22 SPN-43s in operation

- Shipborne SPN-43s installed on:
  - Aircraft carriers
    - Hull classification CVN (10 in existence)
  - Helicopter-carrying amphibious assault ships
    - Hull classification LHD (8)
    - Hull classification LHA (2)
  - Most homeported in Norfolk (9) & San Diego (7)
  - One CVN and one LHD forward deployed in Japan
- Ground-based SPN-43s for training and R&D located at:
  - NAS Pensacola
  - NAS Patuxent River Webster Field Annex, St. Inigoes MD
- Future ships will not use SPN-43

CVN

LHD

LAB TESTS

Lab tests of radar interference into LTE

- Injected simulated SPN-43 radar signal into LTE network and measured impact on download speeds
  - 10 MHz LTE channel (consistent with proposed PAL license)
  - Time Division Duplex (TDD) (uplink and downlink on same frequency, split by time, on 5 or 10 ms timescale)
  - Single-In Single-Out (SISO) mode
    - Multi-In Multi-Out (MIMO) not enabled
    - Expect better LTE performance with MIMO since MIMO includes interference rejection capabilities
- Radar signal characteristics (power, pulse waveform, spectrum) were based off of field measurements
- Did not simulate antenna rotation
  - LTE system was constantly in peak beam of radar
  - Expect better LTE performance if rotation is included, since the main beam has only a 0.5% duty cycle (1.75 deg out of 360)

Radar/Wi-Fi testing

- Interference from radar into Wi-Fi was tested using very similar setup and procedures as for LTE
- We used a consumer-grade Wi-Fi router and an inexpensive USB Wi-Fi adapter
- 20 MHz 802.11n Wi-Fi carrier
- Test conducted using Wi-Fi center frequency of 5825 MHz, but results are directly applicable at 3.6 GHz

Assumptions used in translating lab results

- Converting radar signal strength into distance from radar depends on some propagation assumptions
  - Line-of-sight (LOS), or LOS plus clutter?
    - LOS -> FSL
    - LOS + clutter -> FSL + 17 dB/km
  - Is wireless network outside, in a residential structure, or in a commercial structure?
    - Indoor wireless networks will have additional shielding from radar signals
- Assumptions about propagation/clutter/building loss
  - If clutter loss is used, assume a value of 17 dB/km, which is what we measured in the vicinity of Pax River
  - For indoor residential wireless network, assume radar is attenuated by an additional 10 dB due to building loss (wood structure)
  - If wireless network is indoor commercial, assume 20 dB of building loss (masonry and metal structure)
  - Indoor losses may vary due based on specific scenarios (deep within a building vs. near a window, etc.)
- Wireless network is assumed to operate at 30 dBm EIRP
  - Max non-rural CBSD EIRP allowed under proposed rules

Testing scenarios based on lab parameters

LTE/radar Tested Scenarios

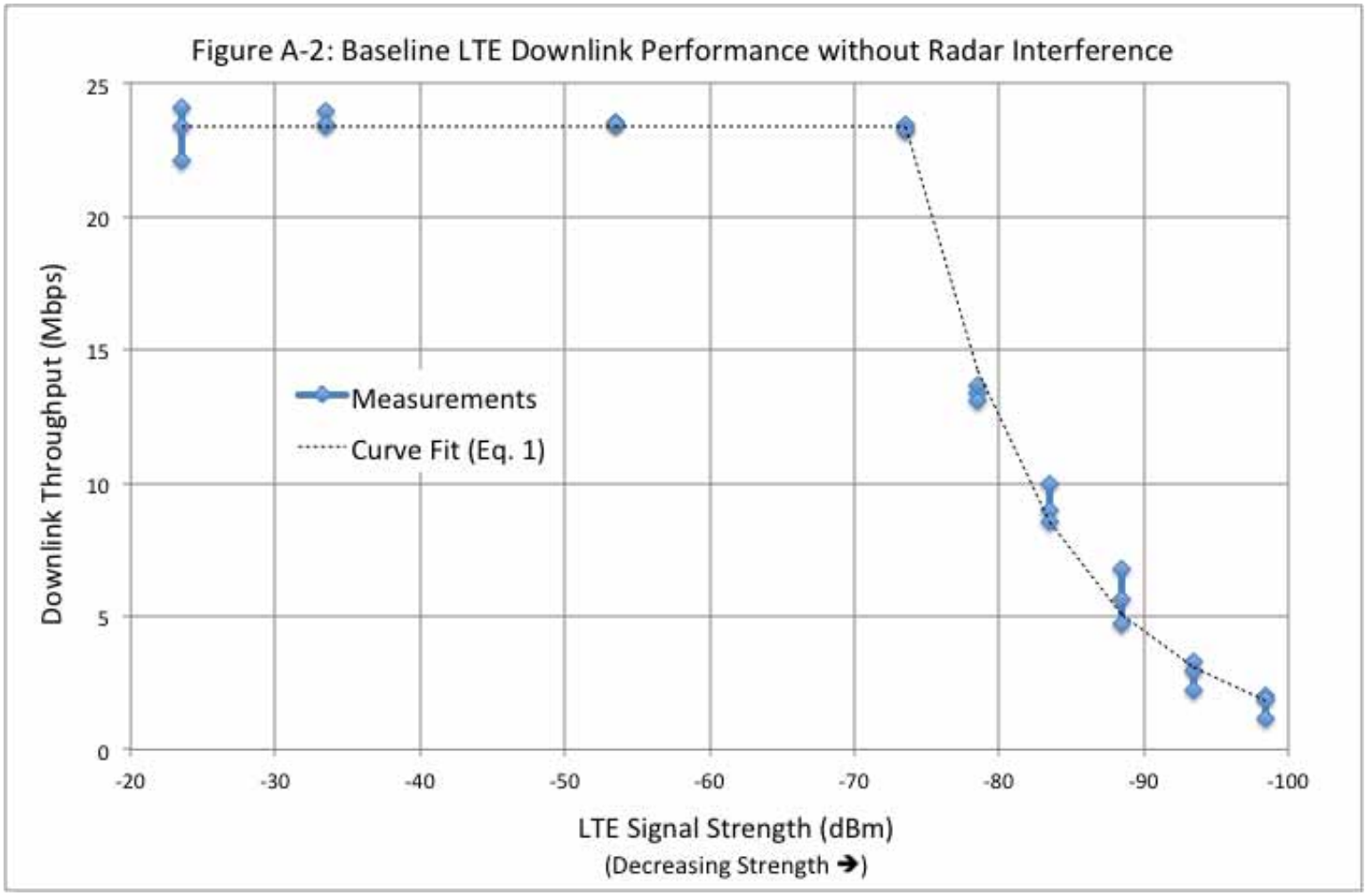
Parameter	Value(s)	Equivalent Separation Distance
Wireless Network Signal Strength (eNB as received by UE)	-24 dBm to -100 dBm	3 m – 21 km (eNB to UE) (Free Space Loss)
Radar Signal Strength (radar as received by UE)	-49 dBm	0.6 – 20.7 km (radar to UE) (Depends on propagation/clutter/building loss assumptions)
I/S Ratio	+51 to -25 dB	N/A

Wi-Fi/radar Tested Scenarios

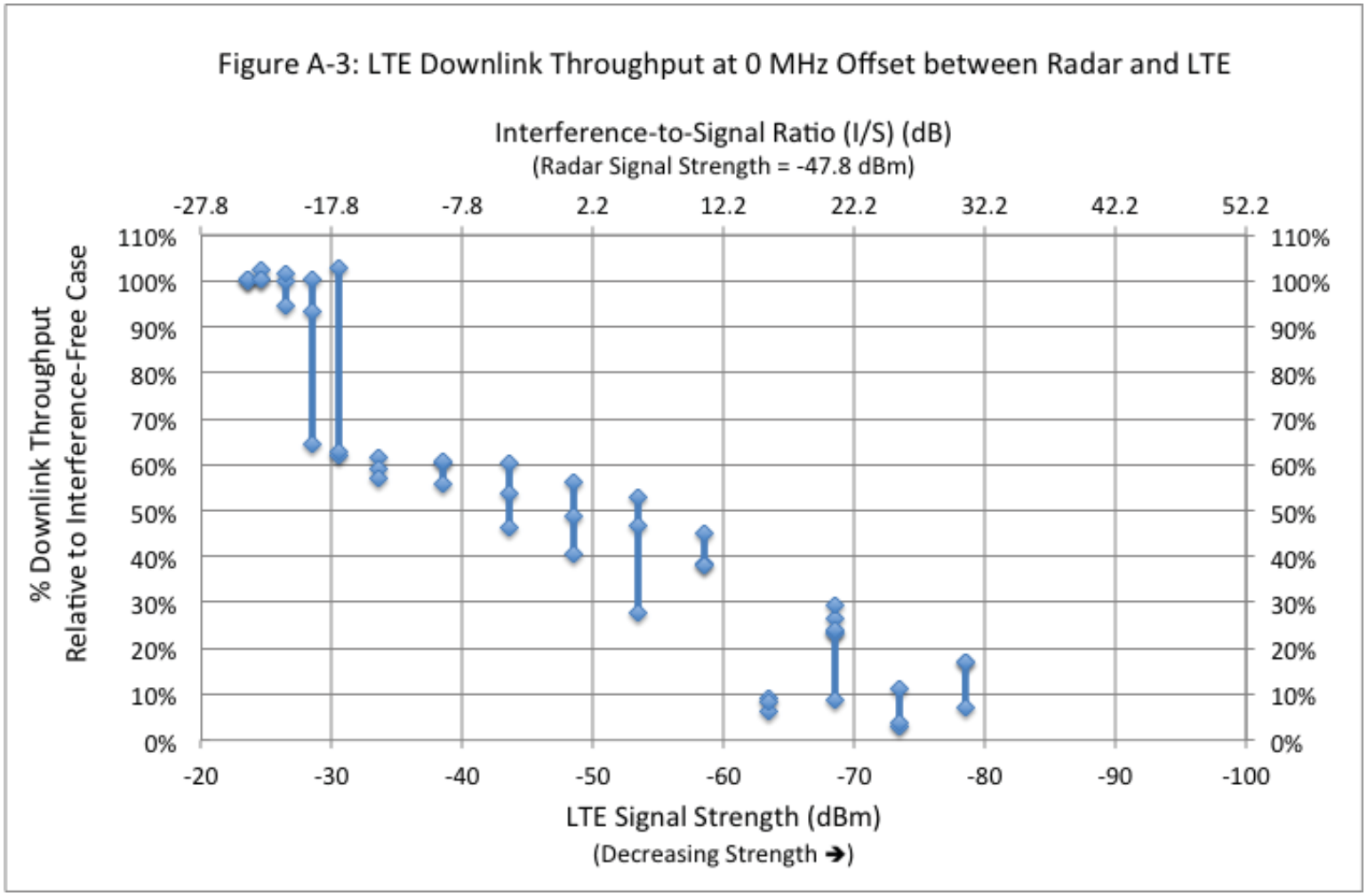
Parameter	Value(s)	Equivalent Separation Distance
Wireless Network Signal Strength (router as received by adapter)	-25 dBm to -89 dBm	4 m – 5.9 km (router to adapter) (Free Space Loss)
Radar Signal Strength (radar as received by adapter)	-49 dBm	0.6 – 20.7 km (radar to adapter) (Depends on propagation/clutter/building loss assumptions)
I/S Ratio	+40 to -24 dB	N/A

Simulated radar distance remains the same for all lab tests since simulated radar power was always the same

Baseline LTE downlink throughput (no interference)



LTE/radar, 0 MHz offset (co-channel)

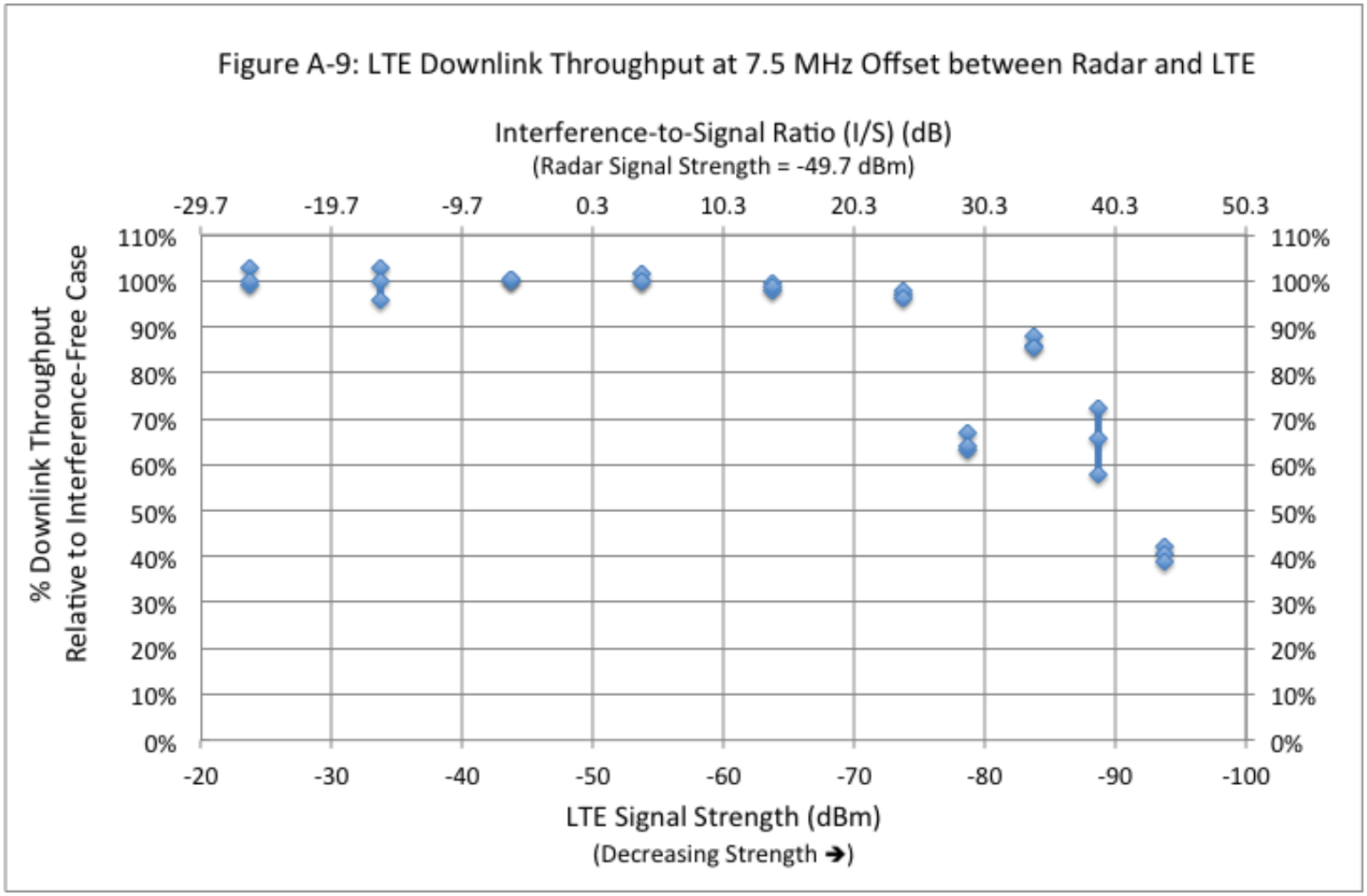


Interpretation of co-channel LTE/radar result

- Assuming:
  - Radar signal strength of -49 dBm
  - I/S = -20 dB (from previous plot, LTE performance is near 100% for I/S of this value or less)
  - LTE signal strength (eNB as received by UE) of -29 dBm, corresponding to separation distance of ~5.1 m (free space loss)

Co-channel LTE Deployment (5.1 m separation between eNB and UE):	Outdoor	Indoor Residential	Indoor Commercial
Required Separation Distance from LTE to Radar (Free Space Loss)	20.7 km	6.6 km	2.1 km
Required Separation Distance from LTE to Radar (Free Space + Clutter)	1.4 km	1.0 km	0.6 km

LTE/radar, 7.5 MHz offset (non-co-channel)



Interpretation of non-co-channel LTE/radar result

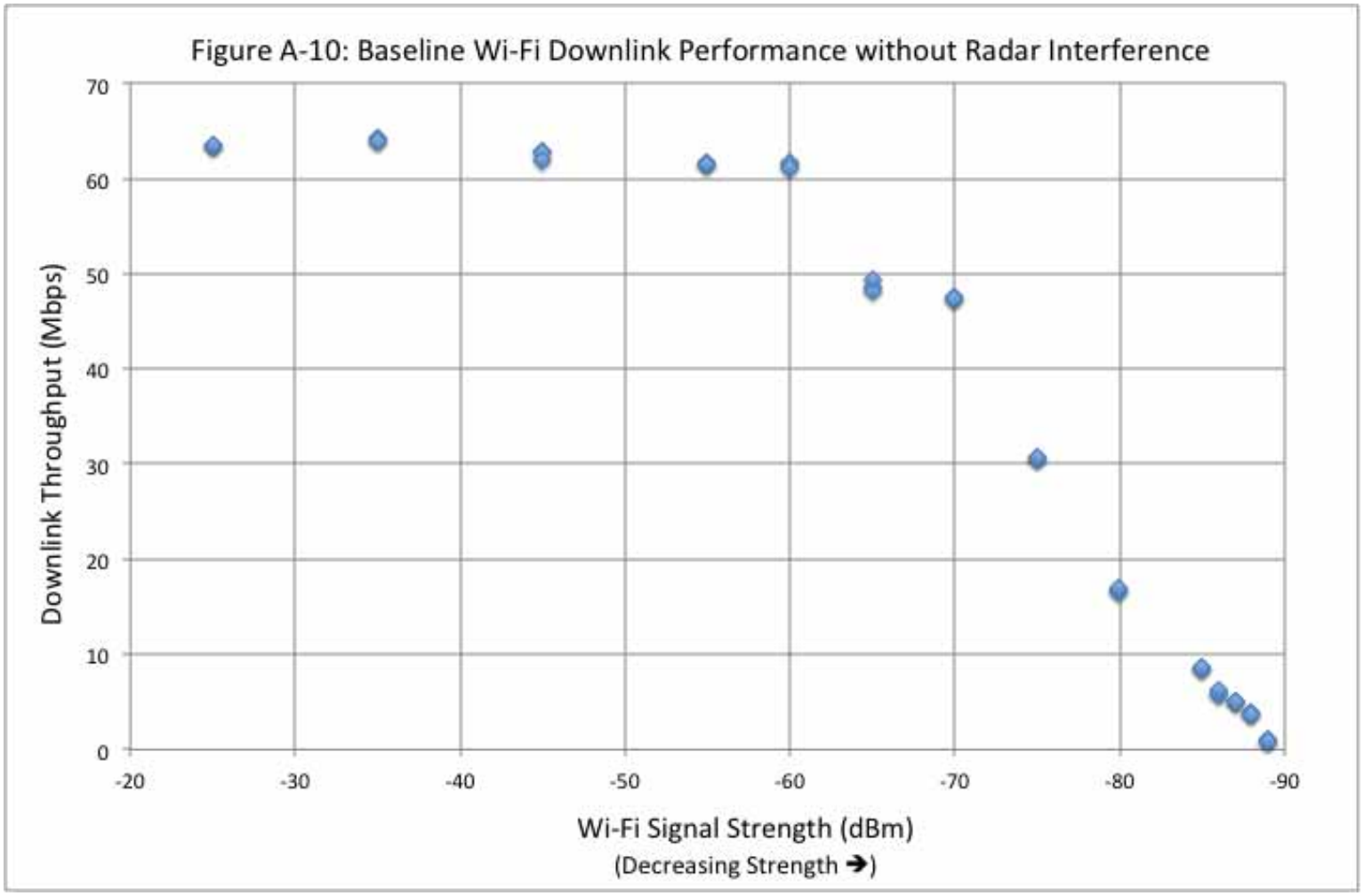
- Same separation from radar as co-channel case (since radar signal strength remains the same), but now UE can be up to 1.1 km from eNB
- Under case of indoor commercial use, and LOS plus clutter loss, the LTE system could perform virtually unaffected by interference when the UE is physically closer to the radar than to its own base station

Non-co-channel LTE Deployment (1.1 km separation between eNB and UE):	Outdoor	Indoor Residential	Indoor Commercial
Required Separation Distance from LTE to Radar (Free Space Loss)	20.7 km	6.6 km	2.1 km
Required Separation Distance from LTE to Radar (Free Space + Clutter)	1.4 km	1.0 km	0.6 km

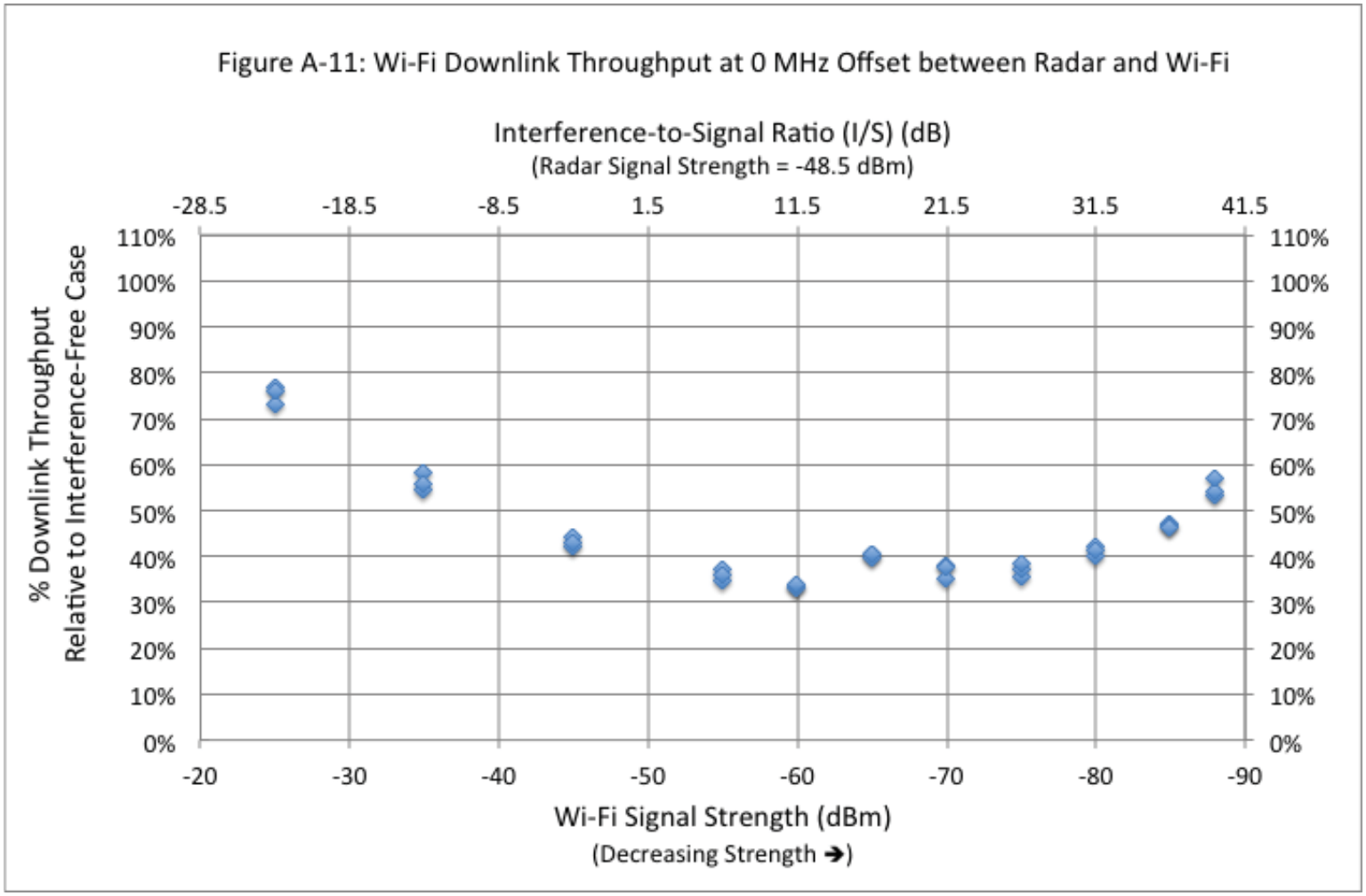
Summary of LTE/radar lab results

- Non-co-channel operation of LTE is possible when the base station and user terminal are 1.1 km apart and:
  - Best-case propagation assumptions, the radar is as close as 0.6 km
  - Worst case propagation assumptions, the radar is 20.7 km away
  - Unlikely LTE picocell would be operated over 1.1 km
- Co-channel operation of LTE is possible when the base station and user terminal are 5.1 m apart and:
  - Best-case propagation assumptions, the radar is as close as 0.6 km
  - Worst case propagation assumptions, the radar is 20.7 km away

Baseline Wi-Fi downlink throughput (no interference)



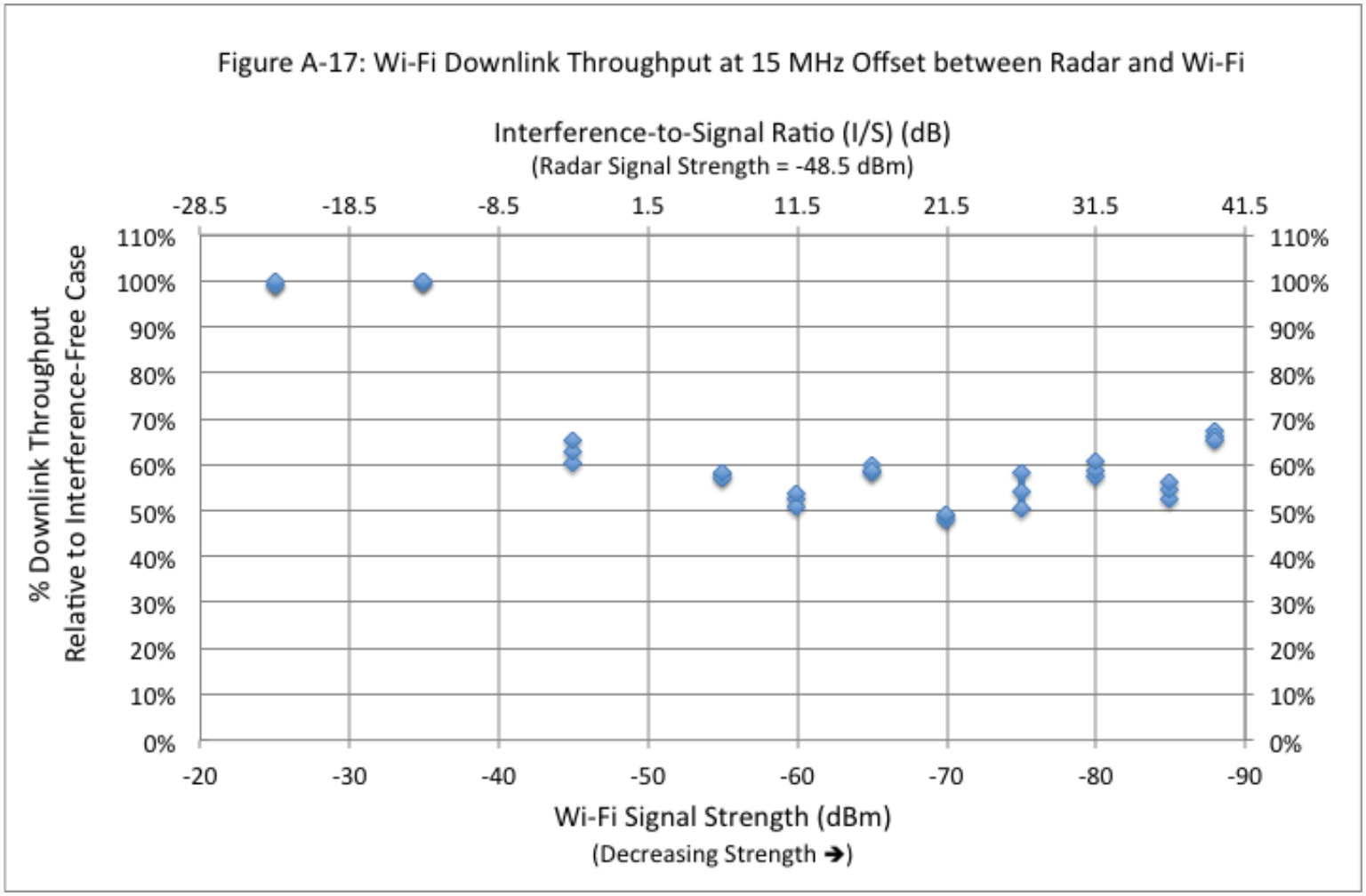
Wi-Fi/radar, 0 MHz offset (co-channel)



Interpretation of co-channel Wi-Fi/radar result

- Wi-Fi is more susceptible to co-channel radar interference than LTE
- Our results show:
  - Worst-case, that a radar 20.7 km away could reduce Wi-Fi throughput by ~40% for a router/adapter separation as close as 4 m
  - Best-case, that a radar 0.6 km away would cause the same degradation at the same 4 m separation

Wi-Fi/radar, 15 MHz offset (non-co-channel)



Interpretation of non-co-channel Wi-Fi/radar result

- Good performance is achieved in the non-co-channel Wi-Fi case for I/S ratios of less than about -10 dB
- This corresponds to a Wi-Fi signal strength of about -39 dBm, or a free-space separation of about 18 m between router and adapter

Non Co-channel Wi-Fi Deployment (18 m separation between router and adapter):	Outdoor	Indoor Residential	Indoor Commercial
Required Separation Distance from Wi-Fi to Radar (Free Space Loss)	20.7 km	6.6 km	2.1 km
Required Separation Distance from Wi-Fi to Radar (Free Space + Clutter)	1.4 km	1.0 km	0.6 km

Summary of Wi-Fi/radar lab results

- The Wi-Fi equipment we tested is more susceptible to interference than the LTE equipment
- Co-channel Wi-Fi operation, with a separation of 4 m from router to adapter, will see a 40% throughput degradation for radar separation of 0.6 – 20.7 km, depending on propagation assumptions
- Non-co-channel Wi-Fi operation, assuming 18 m separation of router and adapter, will be unaffected for radar separations of 0.6 – 20.7 km, depending on propagation assumptions

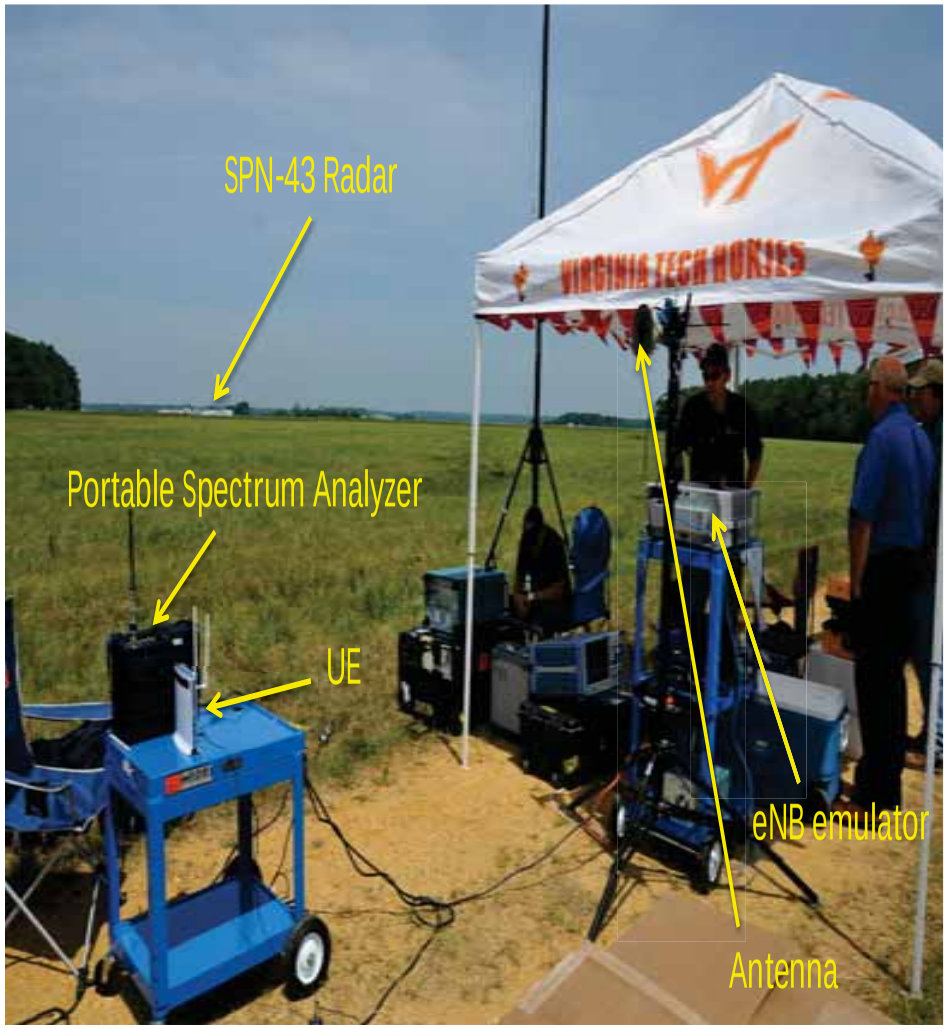
FIELD TESTS

Summary

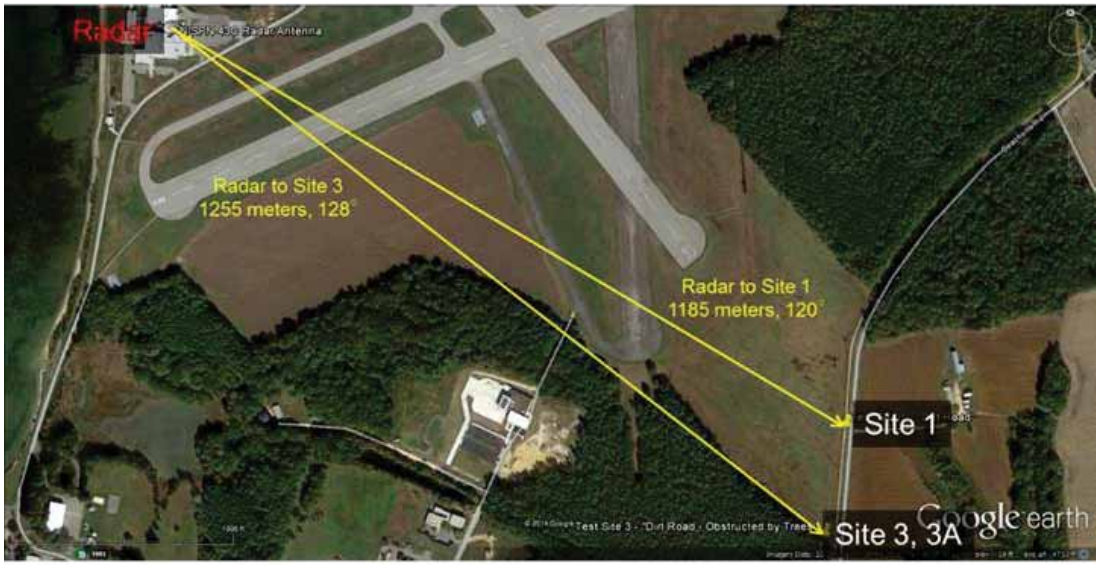
- **Experiments on operation of commercial 4G TD-LTE systems** in the presence of pulsed interfering signals in the 3550-3650 MHz band
- **Conclusion**: **Permanent fixed exclusion zones** as proposed in the FCC's Further Notice of Proposed Rulemaking (FNPRM) **are unnecessary**

Experiment

- 7 working days in field (7/7 – 7/15)
- TD-LTE system operating with interference from in-band radar in 3550-3650 MHz band
- Figures of merit for LTE performance:
  - Block Error Rate (BLER)
  - Throughput
- Measurements at varying frequency offsets from radar operating frequency (3571 MHz)
- Approximately 100 data records in the set



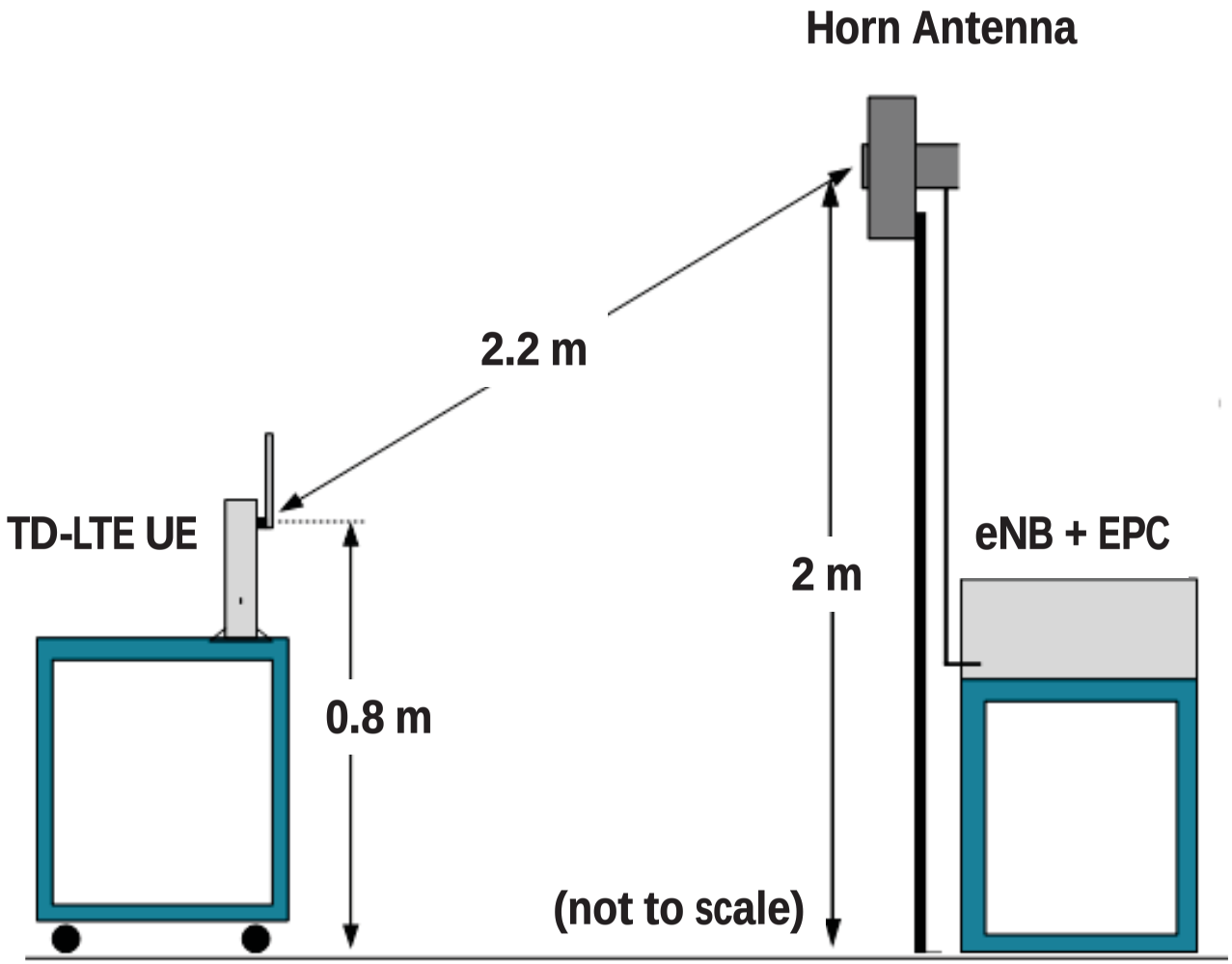
Measurement Sites



Site Location	Distance from Radar (km)	Azimuth to Radar (deg.)	Direction of eNB to UE Path (deg.)	Obstruction in Radar Path	Radar Antenna Elevation (deg.)	Radar Power Density (dBm/cm2)
1	1.185	300	190	unobstructed	+3	-17.1*
2	3.980	337	170	forest	+3	-84.6
3	1.255	308	70	forest	+3	-57.4
3A	1.255	308	70	forest	0	-30.0

*Estimated from measured H-Pol value.

Measurement Configuration

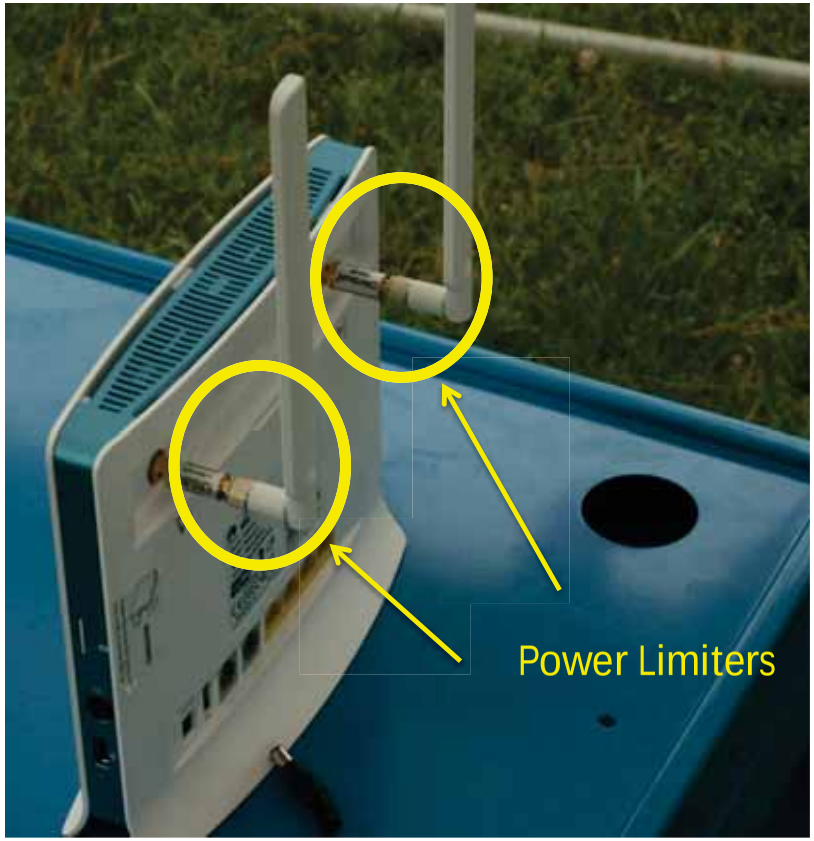


Typical test configuration

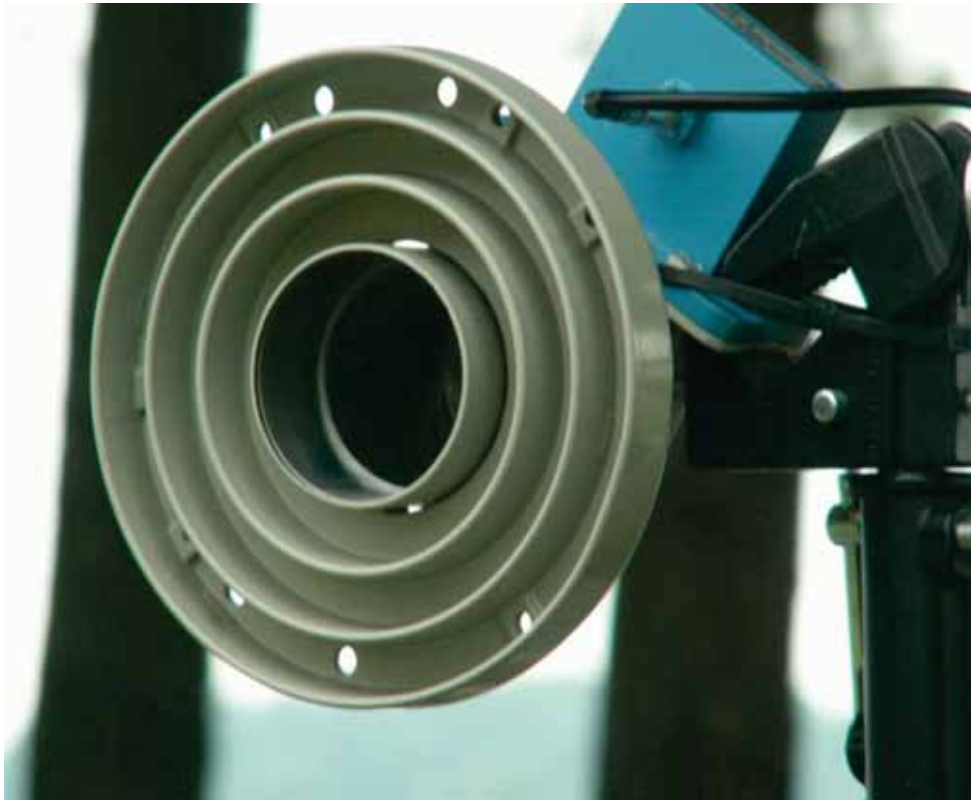
Test configuration at Site 2

Antennas

- Power limiters for UE were removed for the test at Site 3A



UE Antennas (Gain ~ 0 dBi)

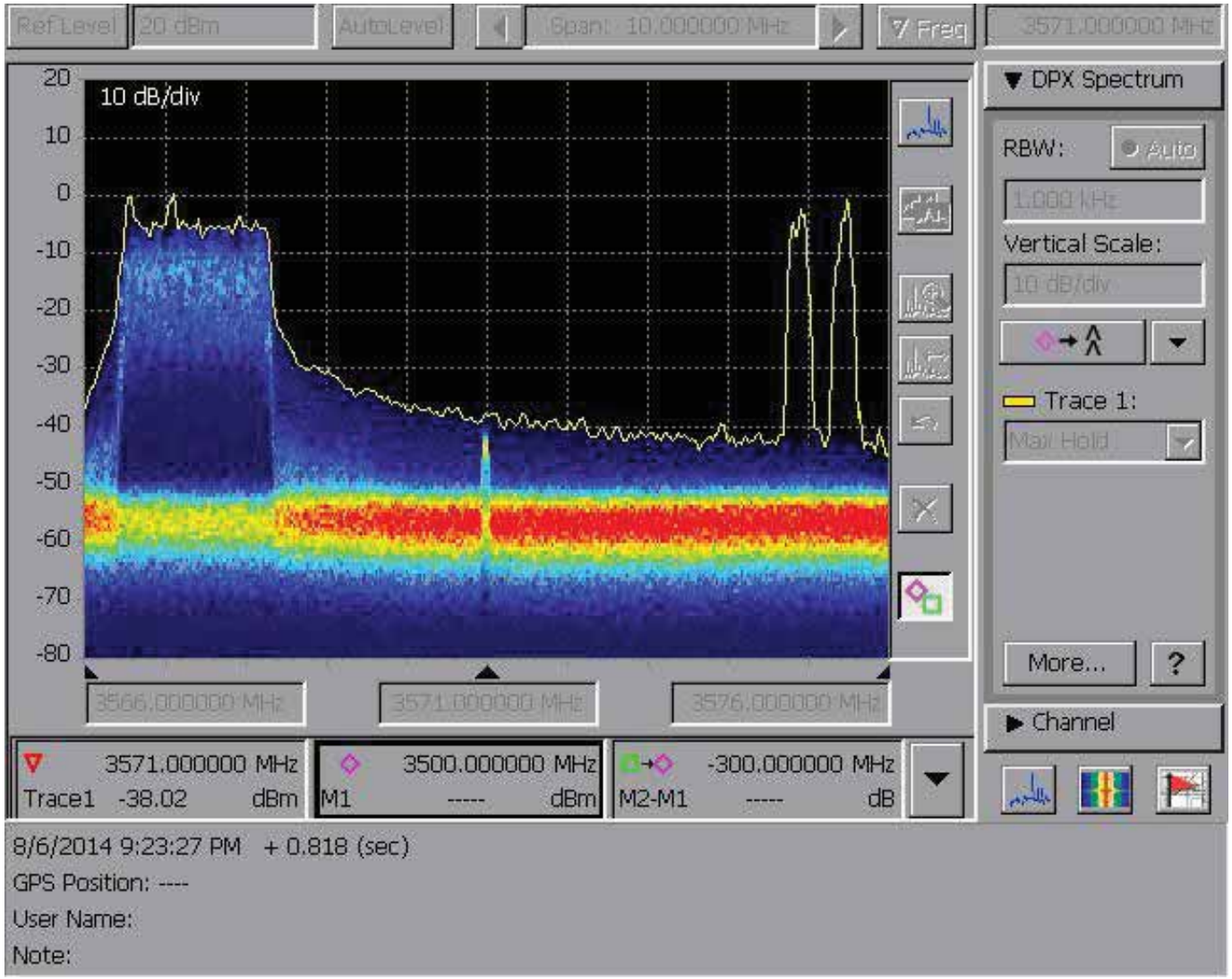


eNB Antenna (Gain ~ 10 dBi)

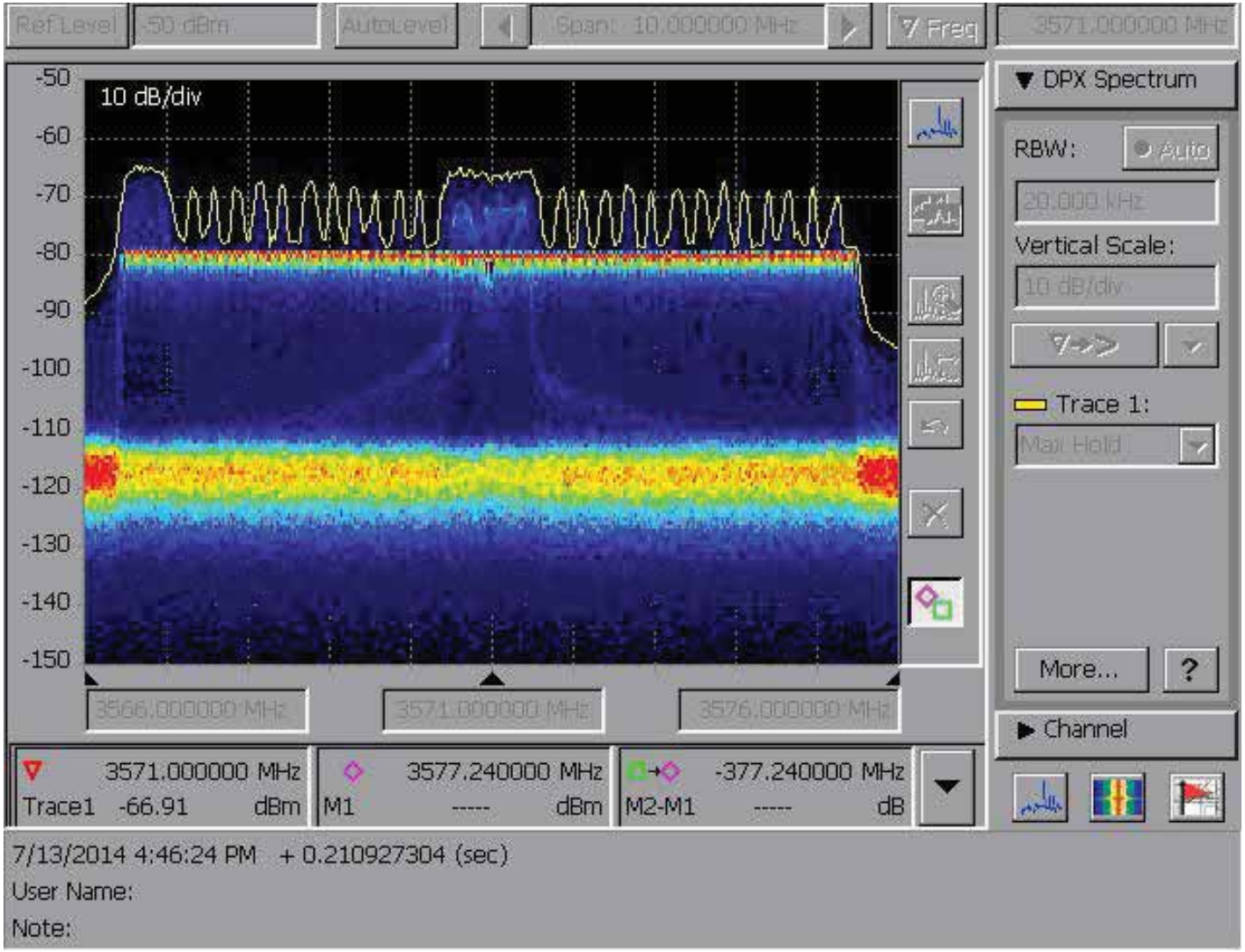
Communication Link Details

	Downlink (all sites)	Uplink (site 1)	Uplink (sites 2 and 3)	Uplink (site 3A)
Mode	TD-LTE	TD-LTE	TD-LTE	TD-LTE
Modulation	16 QAM	QPSK	QPSK	QPSK
LTE Cell Bandwidth (MHz)	10	10	10	10
# Resource Blocks	50	50	10	10
Transmitter Power per Resource Element (dBm/15 kHz)	-42.8	-35.8	-29	-1
Total Transmitter Power in Bandwidth (dBm)	-15	-8	-8	+20
Receiver Noise Floor (dBm in 15 kHz BW)	-126	-81	-81	-81
Path Loss (dB)	40.5	40.5	40.5	40.5

Example TD-LTE UL (10 Resource blocks used, upper peaks are RACH, w/peak hold)



Example TD-LTE DL
(50 resource blocks, -80 dBm/15 kHz)



Calculated S/N and S/I

Site	Downlink		Uplink	
	S/N (dB)	S/I (dB)	S/N (dB)	S/I (dB)
1	43	-50.8	45	-48.4
2	43	+16.7	52	+19.1
3	43	-10.5	52	-8.1
3A	43	-38.0	80	-7.5

CMW500 Screen Capture

Throughput

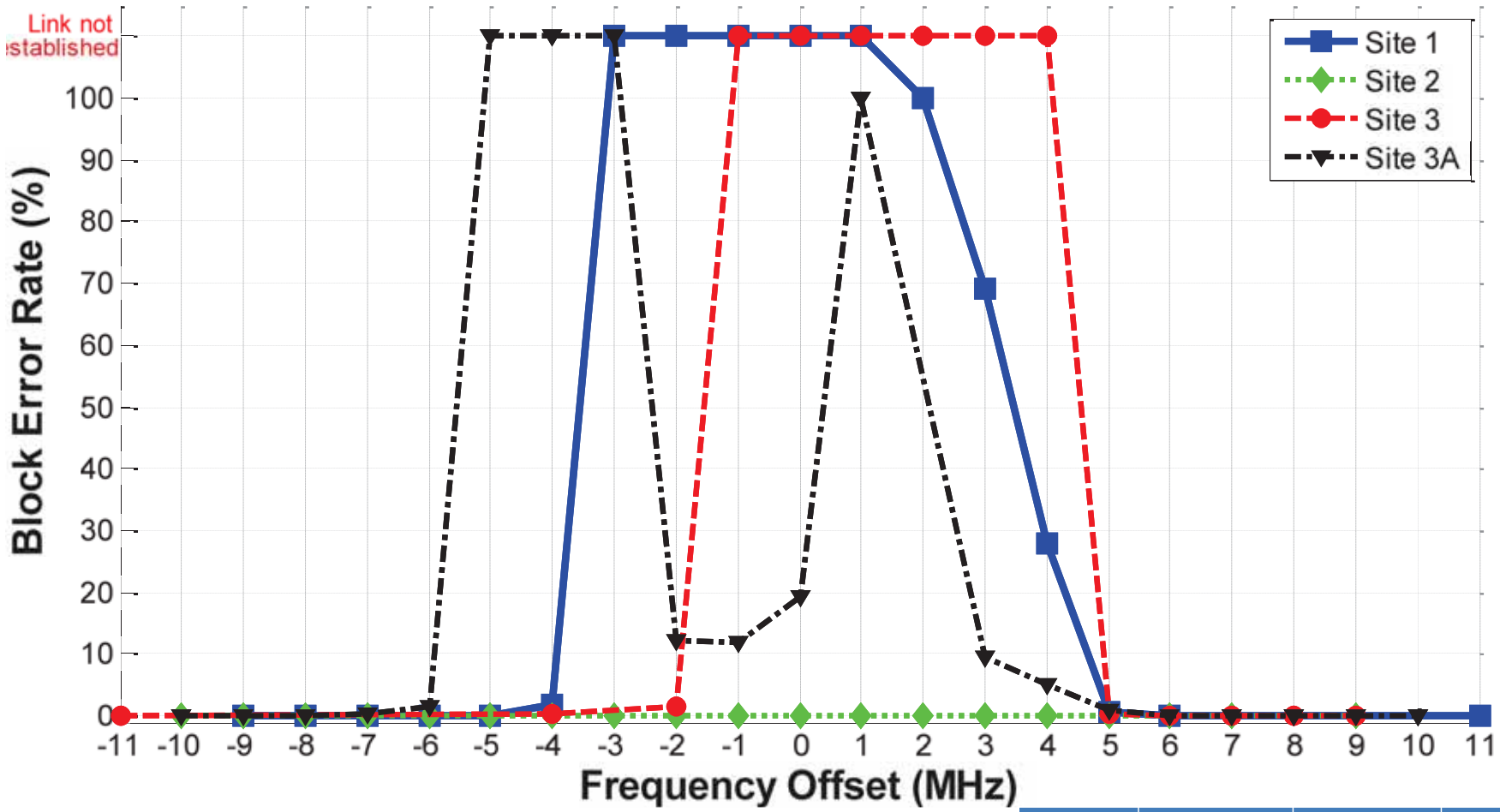
CQI

ACK / NACK

BLER

- Throughput dipped when in radar main beam

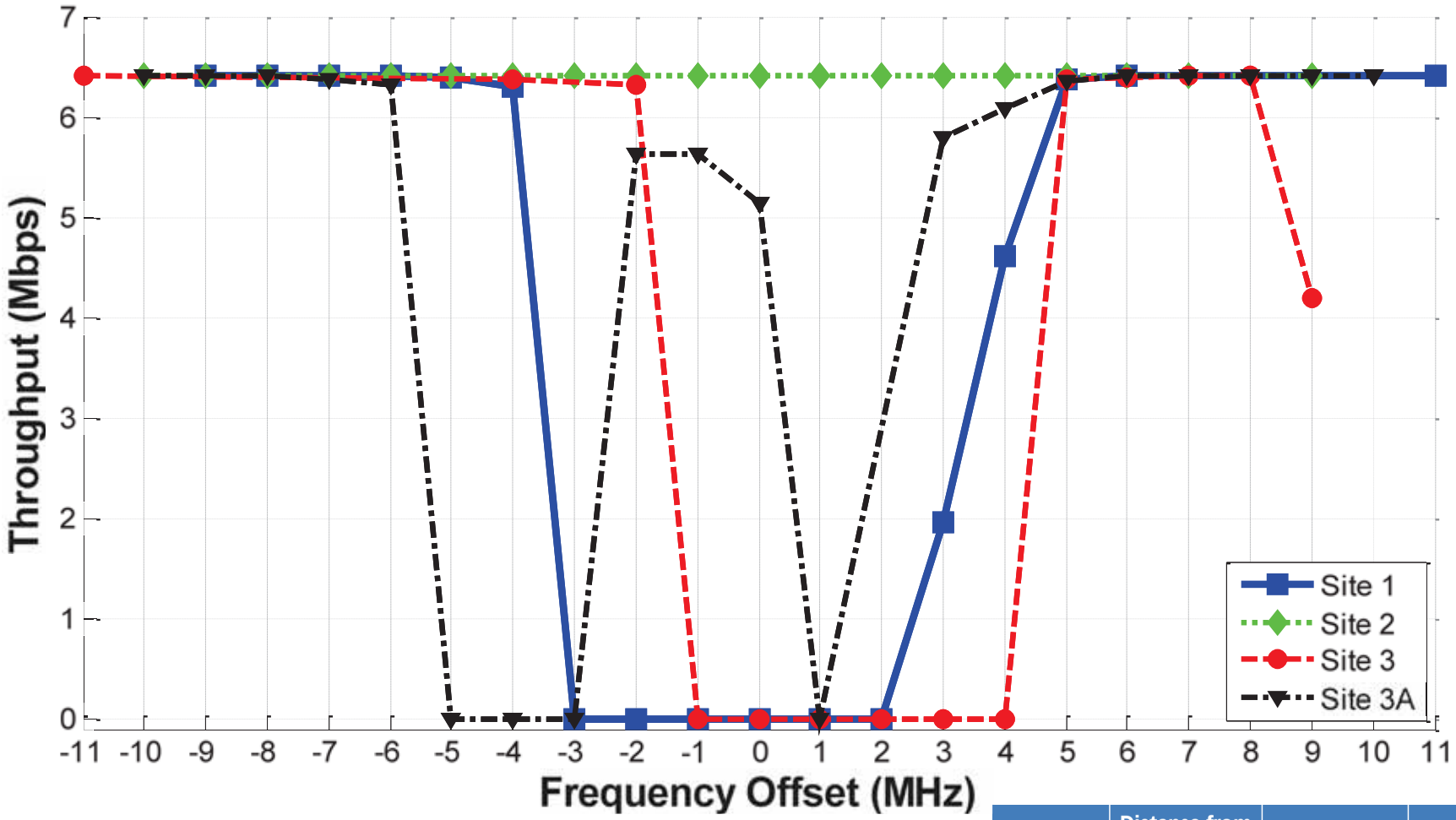
Downlink Performance: **Block Error Rate** vs. f_{offset}



- At Site 2, where the downlink S/I was +17 dB, zero errors were measured at any offset frequency

Site Location	Distance from Radar (km)	Obstruction in Radar Path	Downlink S/I (dB)
1	1.185	unobstructed	-50.8
2	3.980	forest	+16.7
3	1.255	forest	-10.5
3A	1.255	forest	-38.0

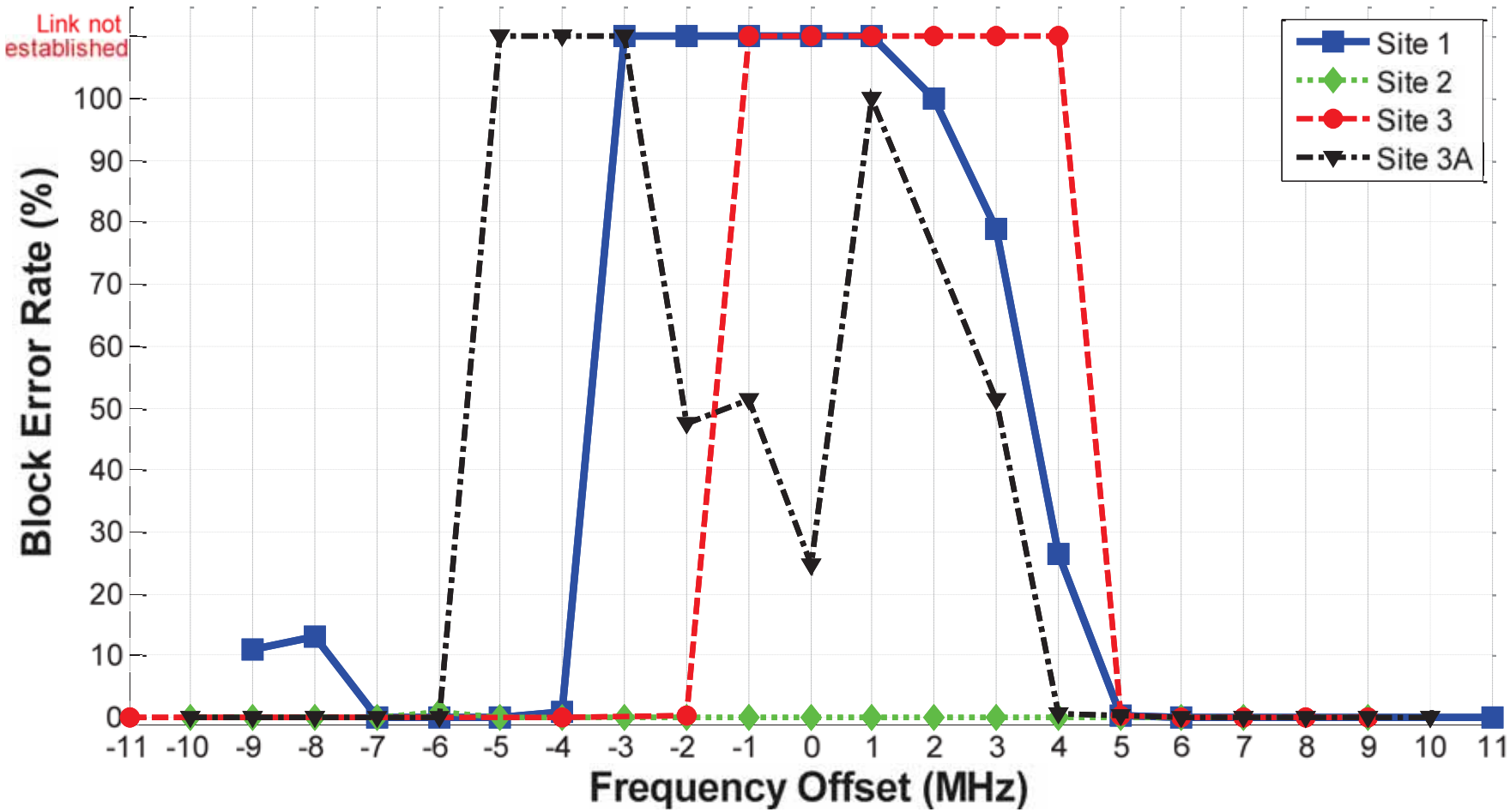
Downlink Performance: **Throughput** vs. f_{offset}



- In all cases, except Site 2, there was either a reduction of throughput or a loss of connection where the radar overlapped the LTE band

Site Location	Distance from Radar (km)	Obstruction in Radar Path	Downlink S/I (dB)
1	1.185	unobstructed	-50.8
2	3.980	forest	+16.7
3	1.255	forest	-10.5
3A	1.255	forest	-38.0

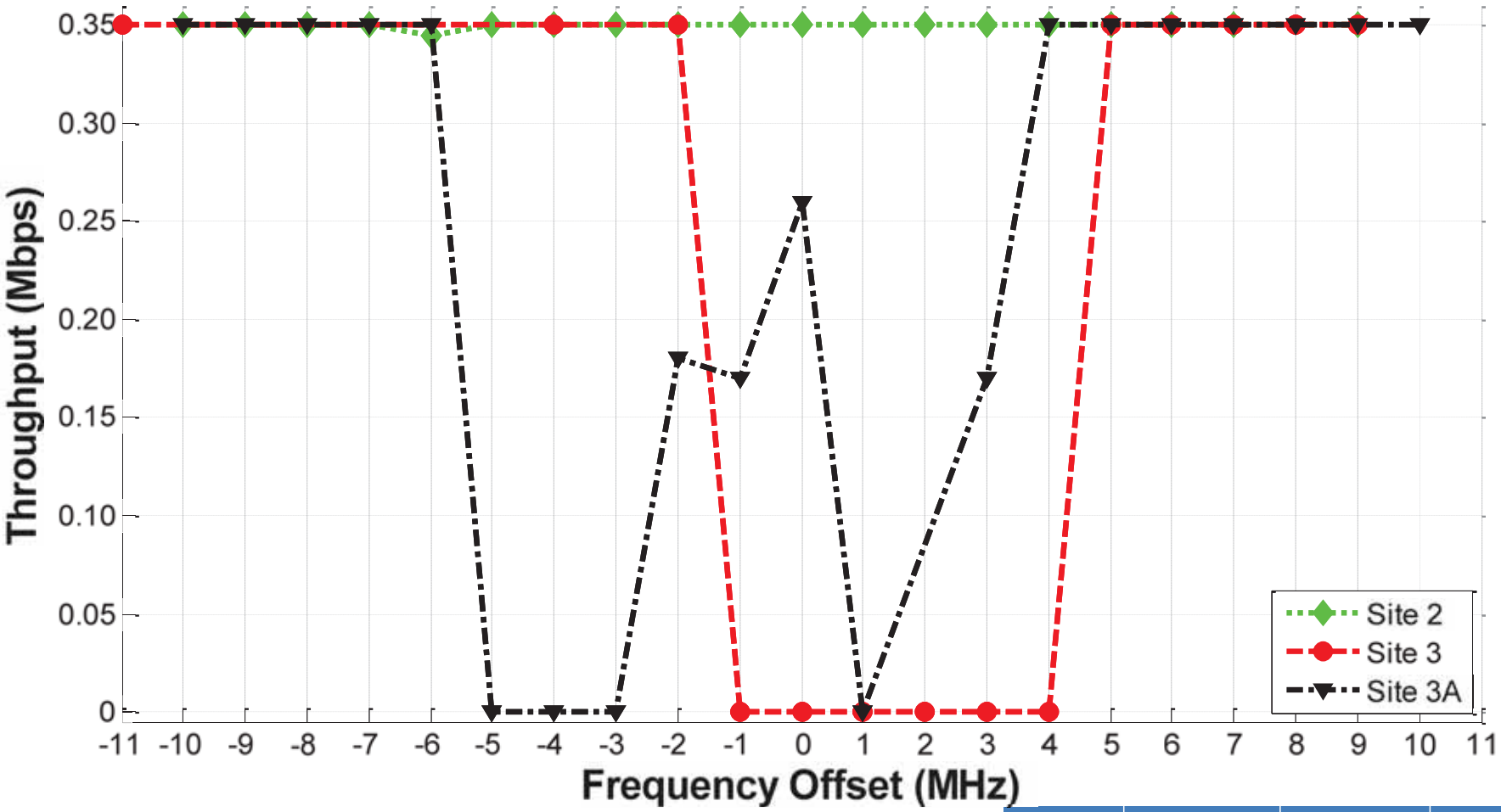
Uplink Performance: **Block Error Rate** vs. f_{offset}



- Similar to the DL case, Site 2, at a distance of about 4 km from the radar, had a nearly zero uplink BLER at any frequency

Site Location	Distance from Radar (km)	Obstruction in Radar Path	Uplink S/I (dB)
1	1.185	unobstructed	-48.4
2	3.980	forest	+19.1
3	1.255	forest	-8.1
3A	1.255	forest	-7.5

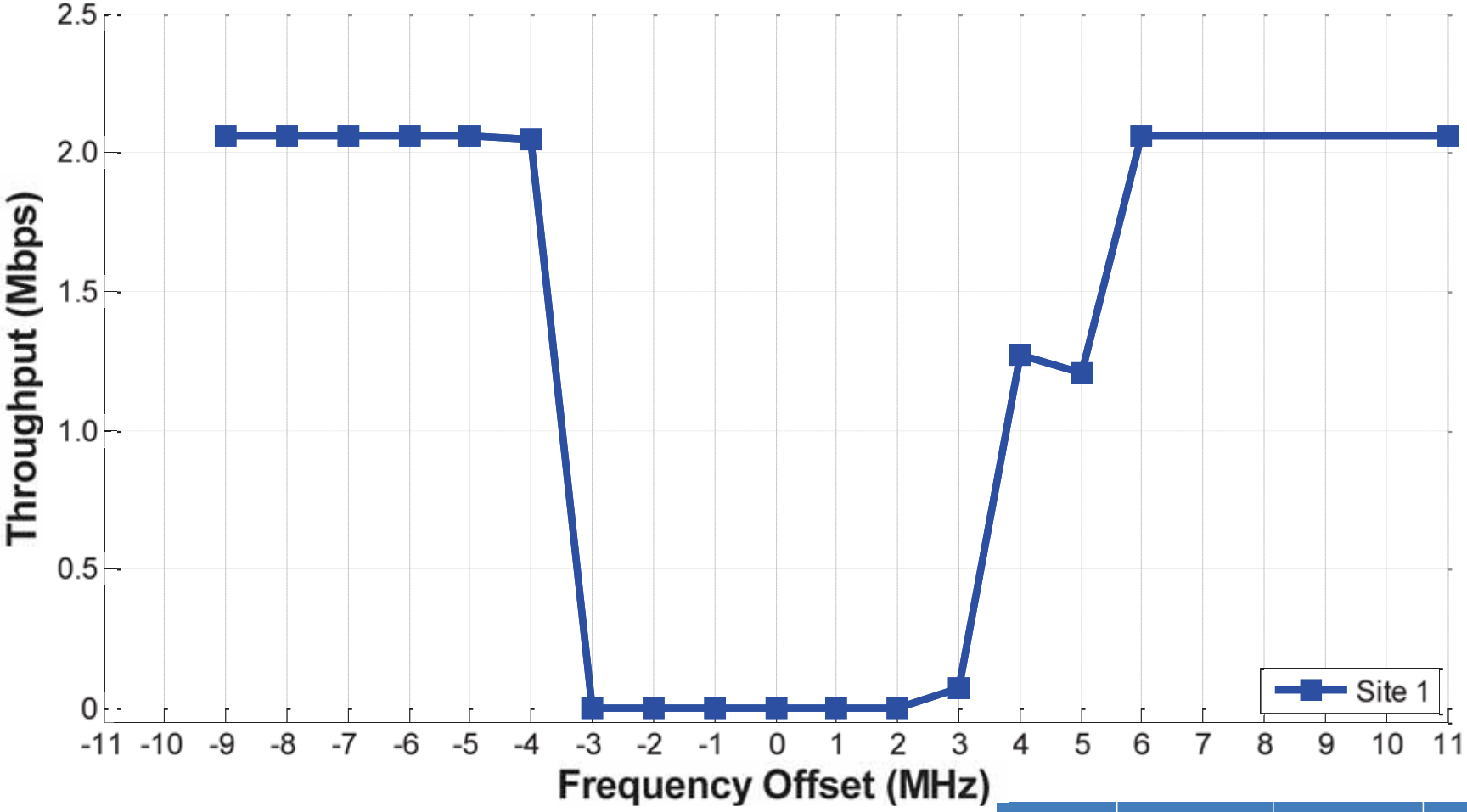
Uplink Performance: **Throughput** vs. f_{offset} - I



- Asymmetry of the throughput near the center might be due to the use of only 10 RBs

Site Location	Distance from Radar (km)	Obstruction in Radar Path	Uplink S/I (dB)
1	1.185	unobstructed	-48.4
2	3.980	forest	+19.1
3	1.255	forest	-8.1
3A	1.255	forest	-7.5

Uplink Performance: **Throughput** vs. f_{offset} - II



- # of RBs increased from 10 to 50

Site Location	Distance from Radar (km)	Obstruction in Radar Path	Uplink S/I (dB)
1	1.185	unobstructed	-48.4
2	3.980	forest	+19.1
3	1.255	forest	-8.1
3A	1.255	forest	-7.5

Conclusions

- **Results favorable for spectrum sharing**
  - **LTE could operate in close proximity to radar**
  - In worst case LTE passband could not overlap radar signal
  - At Site 2 **(less than 4km from radar)**, **no errors were measured** even when LTE signal was centered on radar frequency
- In practice LTE system would typically be much farther from radar
- **Exclusion zones are not necessary to protect LTE from incumbent radar signals**

Federated Wireless measurements

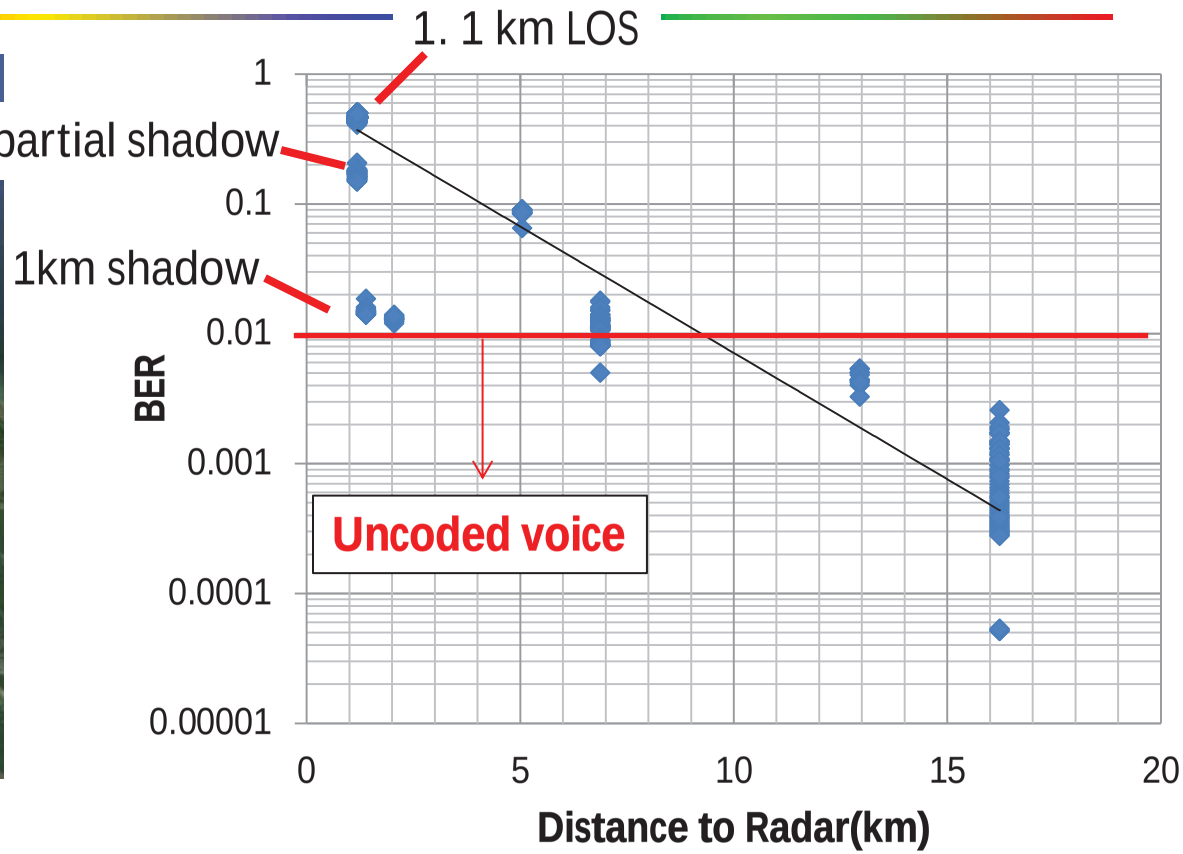
- Measurements made independently by Federated Wireless with different equipment, waveforms, and locations confirm VT and Google's results that LTE-like systems are able to successfully communicate in close proximity to radar
  - Even with academic-grade radios
- No need to protect CBSDs from radar

Bit Error Rate Experiment Setup

- Experiment Radios
  - 2 Universal Software Radio Peripherals (USRPs)
    - Low cost academic radios
  - Analog Devices AD9361 RFICs tuned to 3.5 GHz connected to varying antennas.
  - 6dB omni antenna
  - 10-20 dB Noise Figure
- Setup
  - Measured at radar center frequency
- Waveform software
  - LTE-Like OFDM signal from GNU Radio Library
  - 5 MHz LTE, 1024 pt FFT & 600 data subcarriers
  - Uncoded
  - 0.5 ms Frames

Impact of Radar on “LTE” Bit Error Rate

- Yellow radar site
- Red = measurement sites



- Strong dependence on propagation conditions
  - Under normal conditions, BER < 1% at 10 km
  - Low BER achievable at close range with shadowing

INCUMBENT SIGNAL DETECTION

FNPRM proposed coexistence scheme

- NTIA analysis excludes entire coast with fixed exclusion zones
- Problems
  - Excludes highly populated areas of the US even when no ship is present and radar is not in use
  - Ships, unlike TV towers, move
    - Frequently overseas and not enough systems to come close to blanketing the coasts

From Figure D-7 in NTIA Fast Track Report

Sensing-Based Temporal Coexistence

- Goal: only exclude regions where radar is in use
- Steps:
  - Detect radar activity via dedicated sensors
  - Determine affected regions
  - Leverage FNPRM proposed mechanisms to change CBSD assignments in affected regions
- Advantages
  - Builds on FNPRM proposed control mechanisms, only adding sensing
  - Significant improvement in spectrum use and efficiency

Modified From Figure D-7 in NTIA Fast Track Report

Detection Based Coexistence with Shipborne Radar is Much Easier than Signal Detection Problems Considered in TVWS

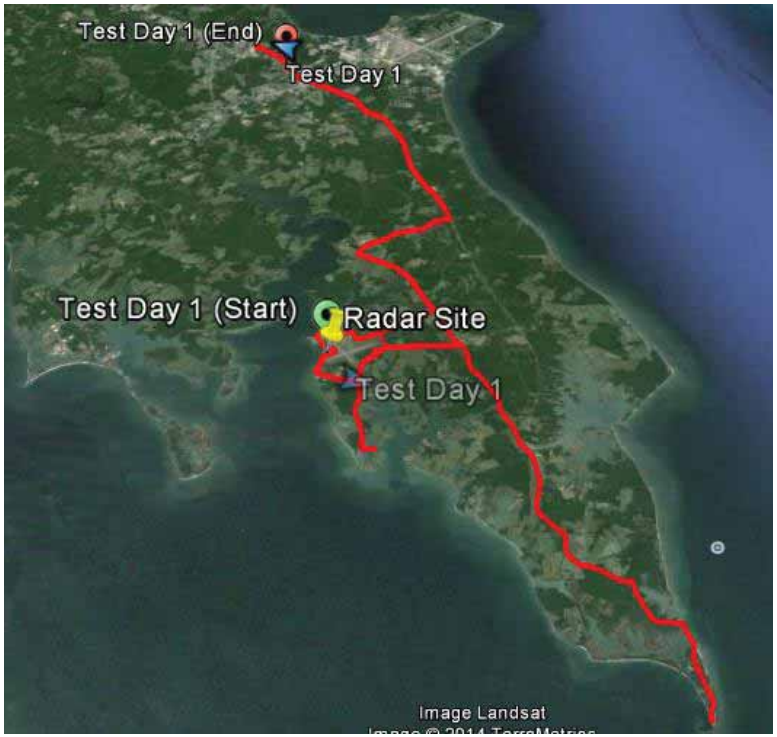
- Power Asymmetry
  - Detect radar transmissions well before CBSD interference with radar could occur
  - Radar receiver is co-located with transmitter
  - Bounds on location (sea) allow for use of directional antennas
- Long detection range makes deployment of dedicated sensors feasible
  - 20,000 km US coastline
  - 200 km spacing = 100 detectors
  - No need for consumer devices to incorporate sensing to protect shipborne radar systems

Detection Feasibility Experiment Setup

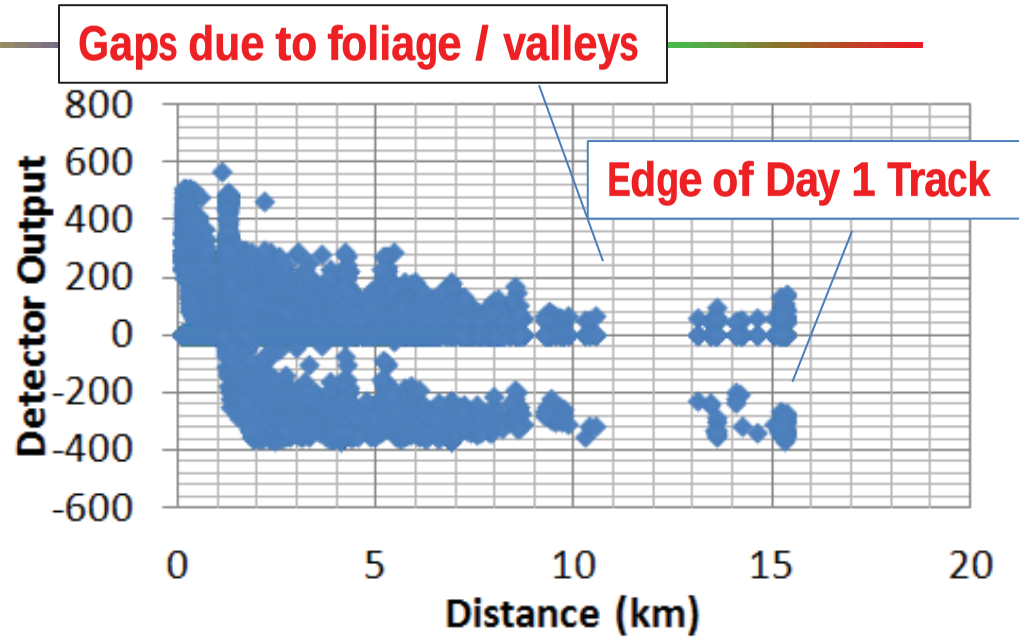
- Experiment Radios
  - Universal Software Radio Peripherals (USRPs)
    - Low cost academic radios
  - Analog Devices AD9361 RFICs tuned to 3.5 GHz connected to varying antennas.
  - 6 dB omni antenna for drive tests
- Setup
  - Measured at radar center frequency
  - Antenna mounted on car
  - No correction for radar rotation in data
  - Continual measurement/ logging while driving
- Radar detector algorithm:
  - Proprietary FW Algorithm

Day 1 Detector Outputs

Measurement Path



- Yellow = radar site
- Red = drive path
- Terrain: low hills, mix of foliage and open areas

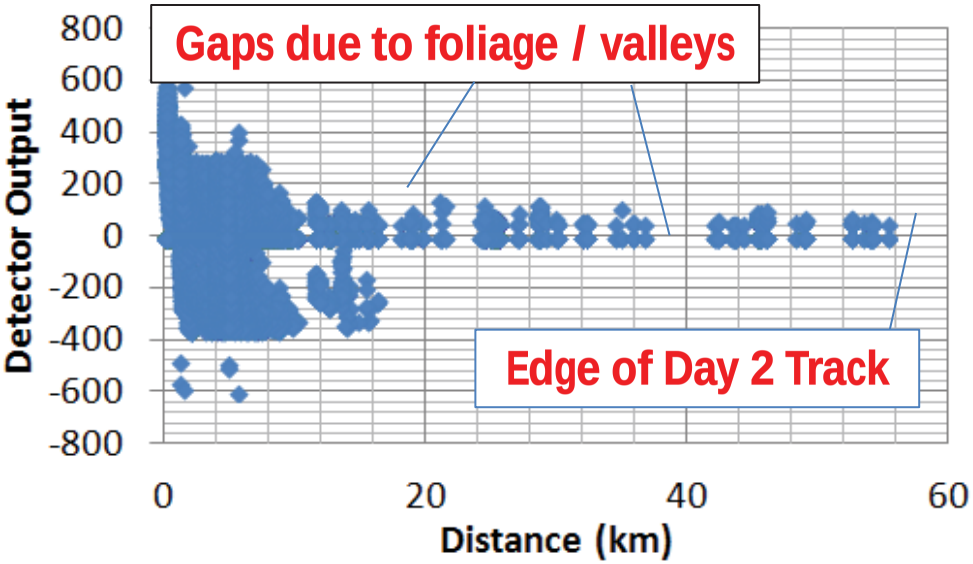


- Blue dot = detection
  - Value related to strength
  - Sign is side effect of matched filter (e.g., detect as inverted pulse)
- Detectable at all distances considered on Day 1 drive
- Strong dependence on specific propagation conditions
  - Proper siting matters
- Almost exclusively NLOS after 5 km

Day 2 Detector Outputs

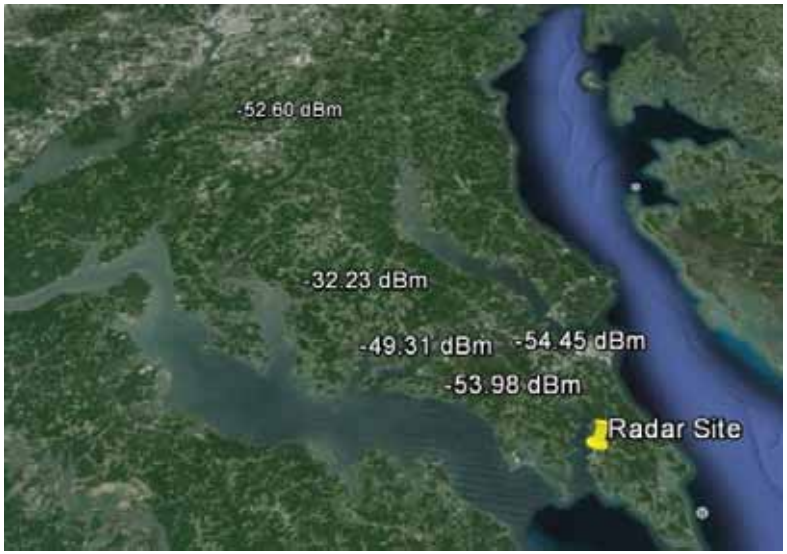
Measurement Path

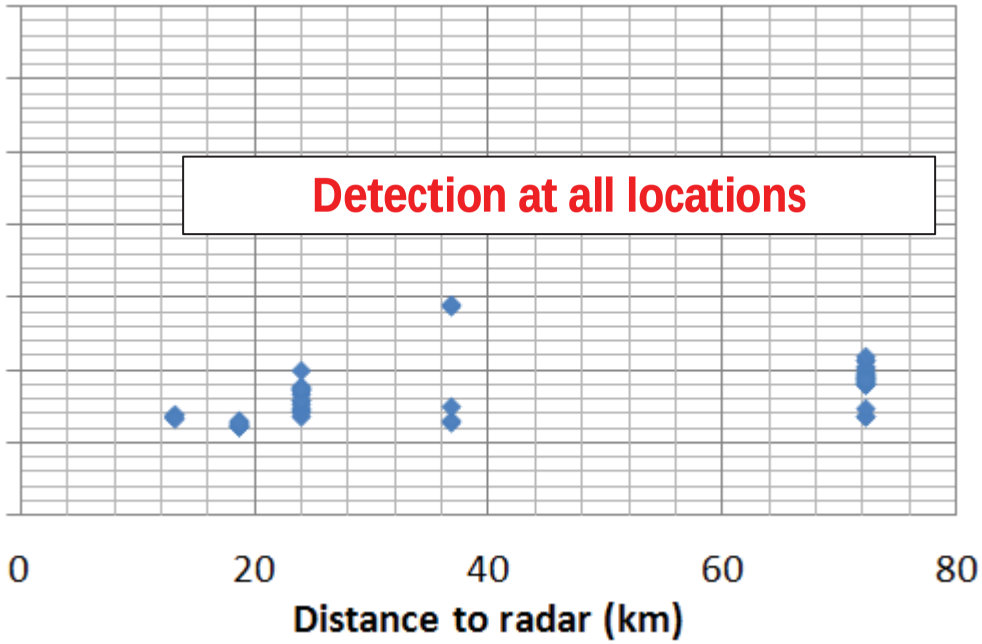
- Yellow = radar site
- Red = drive path
- Terrain: hills, mix of foliage and open areas



- Blue dot = detection
  - Value related to strength
  - Sign is side effect of matched filter (e.g., detect as inverted pulse)
- Strong dependence on specific propagation conditions
- Almost exclusively NLOS after 5 km (drive test)
- Detectable by CBSDs at distances > 55 km

Day 2 RSS Backfire Measurements





- Change in setup
  - Measurement at selected fixed locations
  - Directional antenna
    - 20 dB
    - Approximately pointed towards site
  - 6 foot mast

- Blue dot = detection
  - Value related to strength
- Detectable by well-sited dedicated sensors at distances > 70 km using academic-grade equipment

Incumbent Signal Detection Experiment Summary

- Radar detection is feasible well beyond the range where CBSDs will interfere with radar
  - Demonstrated a 70 km range with low cost equipment without site or equipment advantages
  - Expected fielded detection range greater than 100 km
  - Consistent with Google's previously filed comments showing detection of carrier strike group return when still over-the-horizon
- The use of dedicated sensors for incumbents is a feasible means to protect shipborne radar systems without using fixed exclusion zones
  - No changes required to CBSDs
  - Relatively few (~100) dedicated sensors needed
  - Can still be database driven (but informed by dedicated sensors)
    - Greater efficiencies if databases (SAS) account for terrain

SUMMARY

Conclusions

- Lab tests show, and field tests verify, that LTE and Wi-Fi networks can operate very close to incumbent radars, as close as 0.6 km under favorable scenarios and as far as 20.7 km under worst-case conditions
  - Given these results, fixed permanent exclusion zones are not needed to protect secondary operations
- Dedicated Listening Devices can detect incumbent radar operations to great distances, allowing SASs to reconfigure the band prior to secondary users causing harmful interference
  - Given this result, fixed permanent exclusion zones are not needed to protect primary operations

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- PCAST, "Report to the President: Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth," White house, Washington DC, 2012.
- Federal Communications Commission, “Amendment of the Commission’s Rules with Regard to Commercial Operations in the 3550–3650 MHz Band,” (NPRM), FCC 12-148, Dec. 2012.
- Federal Communications Commission, “Amendment of the Commission’s Rules with Regard to Commercial Operations in the 3550–3650 MHz Band,” (FNPRM), FCC 14-49, April 2014.
- Michael Cotton and Roger Dalke, “Spectrum Occupancy Measurements of the 3550–3650 Megahertz Maritime Radar Band near San Diego, California,” NTIA Report TR-14-500, January 2014.
- Mike Mearns, “AN/SPN-43C and LTE Spectrum Sharing Tests at 3.55-3.65 GHz,” (slide presentation),NSWCDD/Q51, 2014.