FM Harmonic Interference to LTE Wireless Systems

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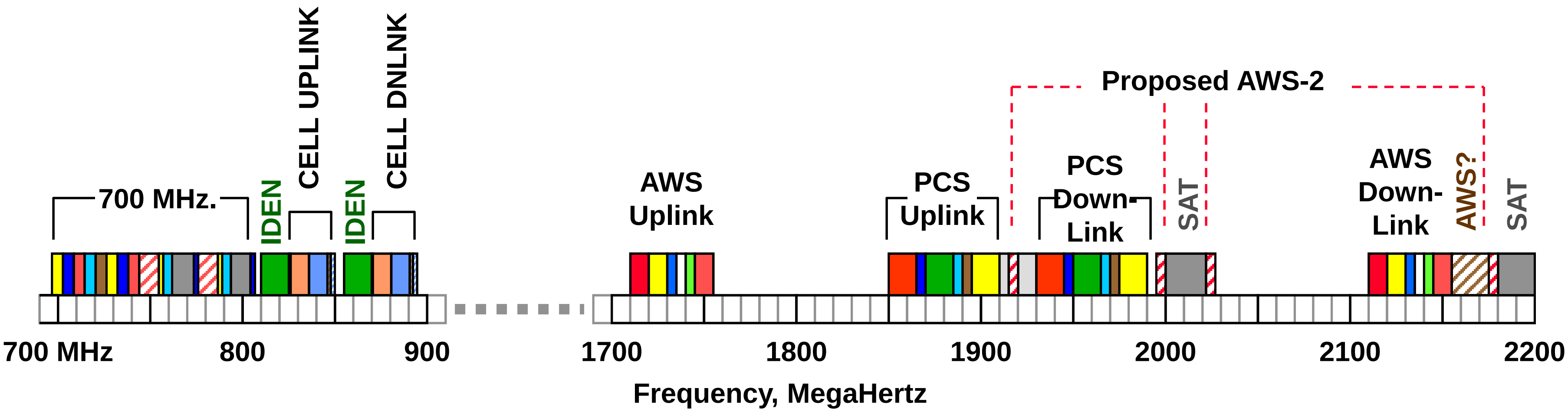
Foreward

- LTE, Long Term Evolution, is an internationally-popular wireless technology bringing high-speed broadband data to phones and computing devices on many cellular/wireless systems
- Since 2011, cellular operators have deployed new LTE broadband wireless operation at thousands of their sites.
- US Nationwide deployment is more than half complete in 3Q2013.
- The new OFDM-based LTE technology pushes spectral efficiency and data throughput close to the Shannon limit, but in so doing becomes particularly vulnerable to low-level uplink interference
- LTE operator complaints of interference from nearby FM broadcast station harmonics number in the hundreds.
- This presentation is intended to provide background and practical insights into these cases for broadcasters, LTE operators, and regulators.

FM Interference to Wireless: LTE Contents

- Introduction to the problem
- LTE technology
- Regulatory Environment
  - FCC spurious suppression requirements
  - FCC-required measurement techniques
- The RF Environment
  - Proximity, path loss, thermal noise, harmonic relationships
- Broadcast harmonic generation and control Techniques
  - Main transmitter output; low-level generation & cabinet leakage
- The Guiding Realities
- Summaries of example case details and outcomes

Introduction: The Problem



- LTE is currently in operation in most major markets and highways by Verizon, AT&T, Sprint, MetroPCS, and Cricket
  - Frequencies used vary by market due to operator spectrum holdings
- LTE systems above 1700 MHz. in the PCS and AWS bands only very rarely experience interference from external sources
- LTE systems in the 700 MHz. and 800 MHz. bands are vulnerable to interference from harmonics of nearby FM and TV operators
- While FCC spurious emission standards for broadcasters are clearly defined and most stations comply, in many cases the permitted levels still result in performance degradation to nearby LTE sites and both the engineering and regulatory/legal situations descend into uncertain territory

Introduction to LTE Technology

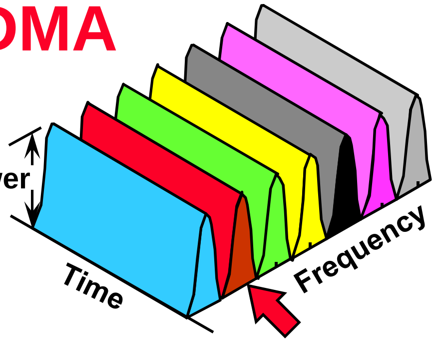
Key LTE Advantages Users and Operators

Available Bandwidth, MHz.	14	1.6	3.0	3.2	5	10	15	20
Downlink Speed, Mb/s	12	14	26	28	44	88	131	175
Uplink Speed, Mb/s	6	7	13	14	22	44	65	88

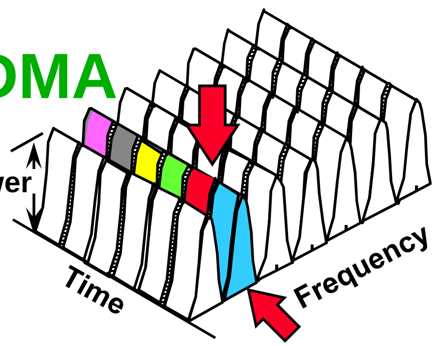
- LTE offers the best performance of any wireless technology thus far in the effort to bring the internet at broadband speeds to mobile users.
- LTE highlights:
  - Highest spectral efficiency (5.5 b/s/hz downlink, 2.5 b/s/hz uplink)
  - Better data throughput
    - figures above are total instantaneous throughput on downlink from base station (“eNodeB”) and on uplink from a mobile (“UE”)
    - Based on use of 2-branch MIMO (multiple input, multiple output), the most common mode of operation for systems at present
  - Lower latency– control plane <100 ms., user plane < 5 ms
  - Reliable and effective TCP/IP QoS Quality of Service implementation
  - Wide acceptance, ultimate use by 80% of wireless operators globally
  - Economies of scale, lower cost per bit than any other technology
  - Will replace 2G voice networks using voice-over-IP “VOLTE” standard

Multiple Access Methods

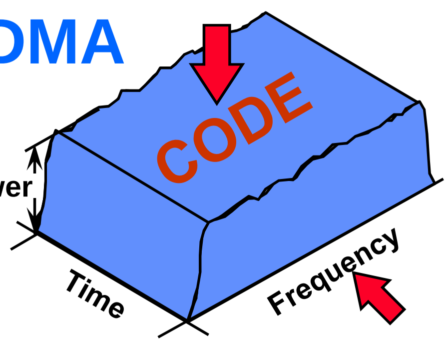
FDMA



TDMA



CDMA



FDMA: AMPS & NAMPS

- Each user occupies a private Frequency, protected from interference through physical separation from other users on the same frequency

TDMA: IS-136, GSM

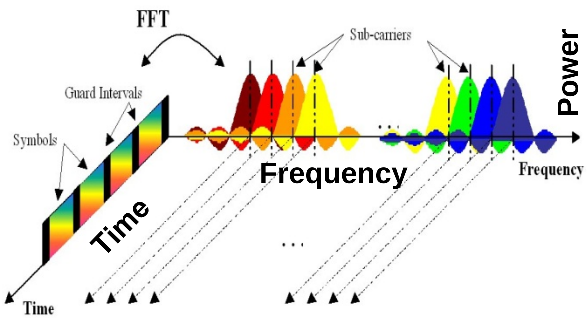
- Each user occupies a specific frequency but only during an assigned time slot. The frequency is used by other users during other time slots.

CDMA

- Each user uses a signal on a particular frequency at the same time as many other users, but it can be separated out when receiving because it contains a special code of its own

Highly Advanced Multiple Access Methods

OFDM

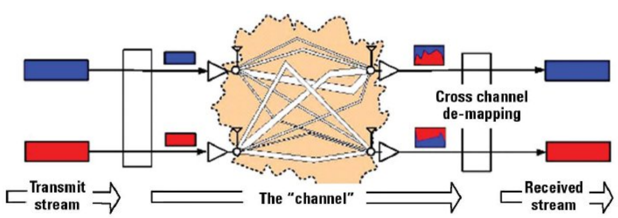


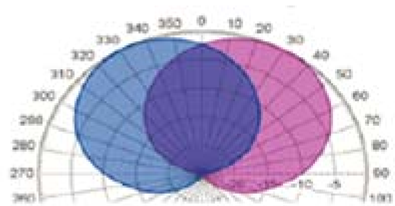
OFDM, OFDMA

- Orthogonal Frequency Division Multiplexing; Orthogonal Frequency Division Multiple Access
- The signal consists of many (from dozens to thousands) of thin carriers carrying symbols
- In OFDMA, the symbols are for multiple users
- OFDM provides dense spectral efficiency and robust resistance to fading, with great flexibility of use

Multiple-Antenna Techniques to Multiply Radio Throughput

MIMO



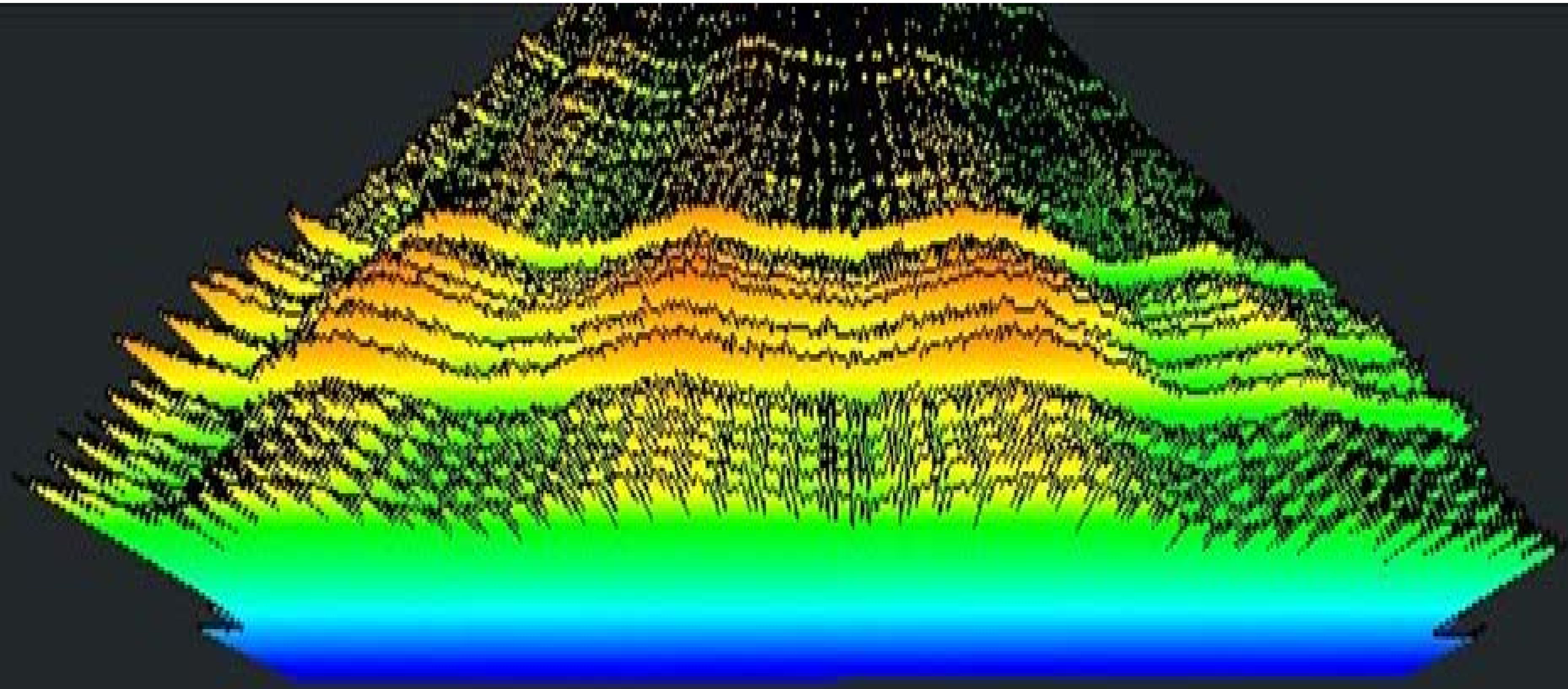


MIMO

- Multiple Input Multiple Output
- An ideal companion to OFDM, MIMO allows exploitation of multiple antennas at the base station and the mobile to effectively multiply the throughput for the base station and users

SMART ANTENNAS

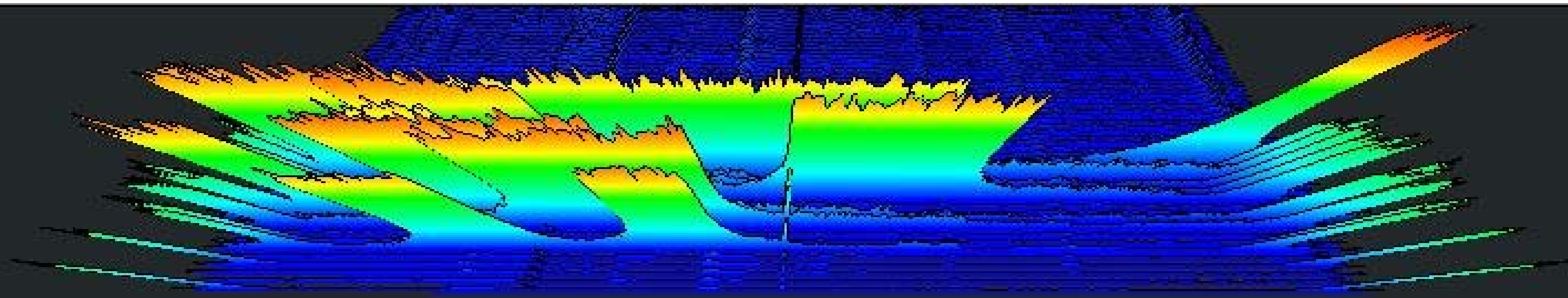
- Beam forming for C/I improvement and interference reduction



LTE Downlink: Above is a "spectragram" showing the output of an LTE eNodeB (base station). The bandwidth of the signal is 10 MHz., on the x-axis. The time covered by the spectragram is approximately 1 second, with present time at the front. Height of the signal is proportional to RF power level.

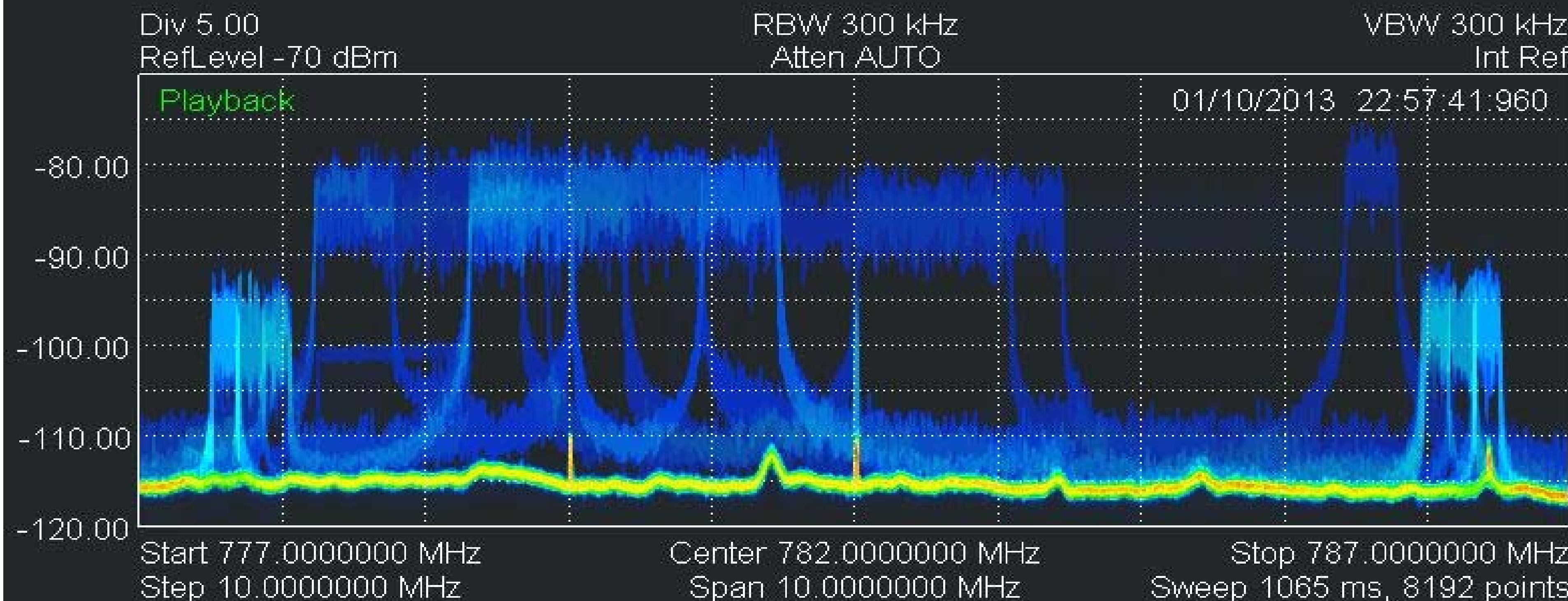
Notice the seven bursts of broadband data over a roughly 1/4 second period.

This is a direct off-air recording inside a building, and the wide spectral undulations are due to multipath effects.

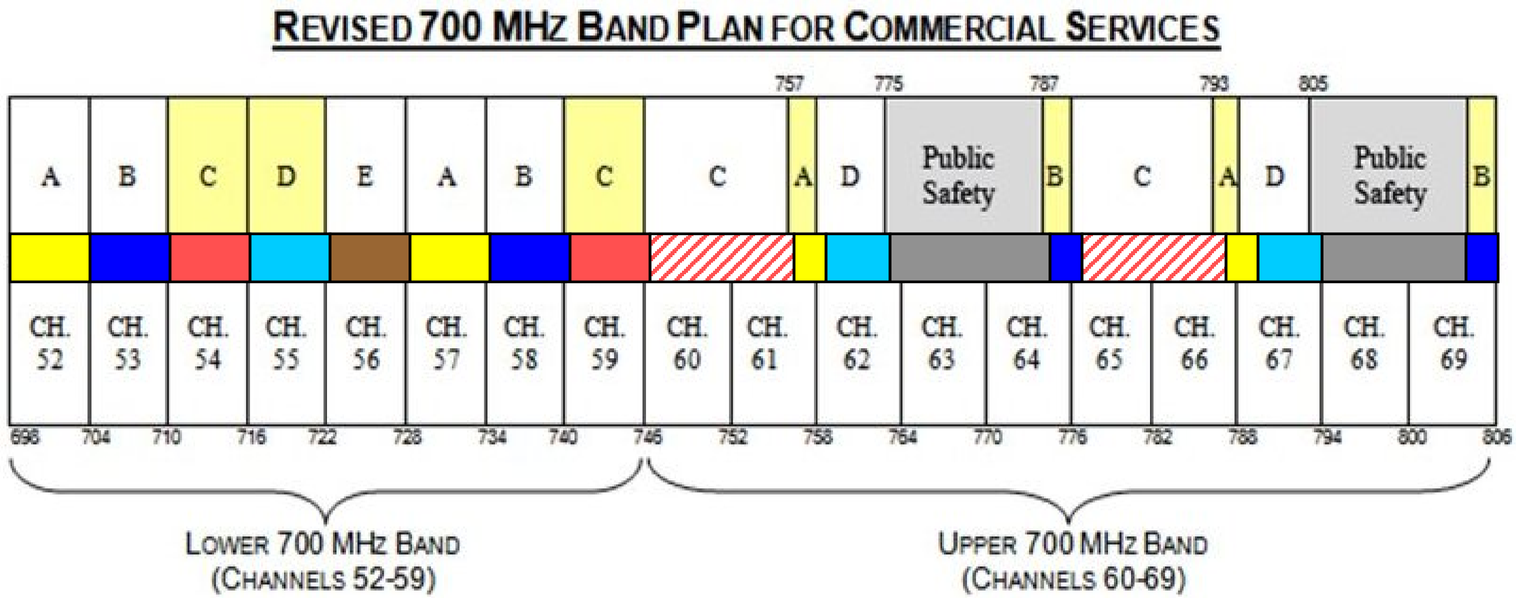


The above spectragram shows the intermittent uplink transmissions over a 1-second period from a close-by LTE phone two feet from the spectrum analyzer.

The lower display is a “persistence” view of the same signal period. The earlier rapid bursts linger on the display as ghostly blue traces which fade with time.



The US 700 MHz. Spectrum and Its Blocks



- In the U.S., the former television channels 52-69 have been re-allocated to wireless operators and public safety entities.
- The "Upper C" block (striped red) is now used by Verizon Wireless in virtually the entire U.S. with uplink in 776-787 MHz. and downlink in 746-757 MHz. Verizon's partnership with rural operators has given it a head-start in completing LTE service along virtually all interstate highways and many surrounding rural areas.
- AT&T has obtained the lower B and/or lower C block in many areas. After considerable delay it is now well along in its national rollout.
- Other operators also use lower A, B, and/or C blocks in many areas. There is controversy over adjacency of lower A to TV channel 51.

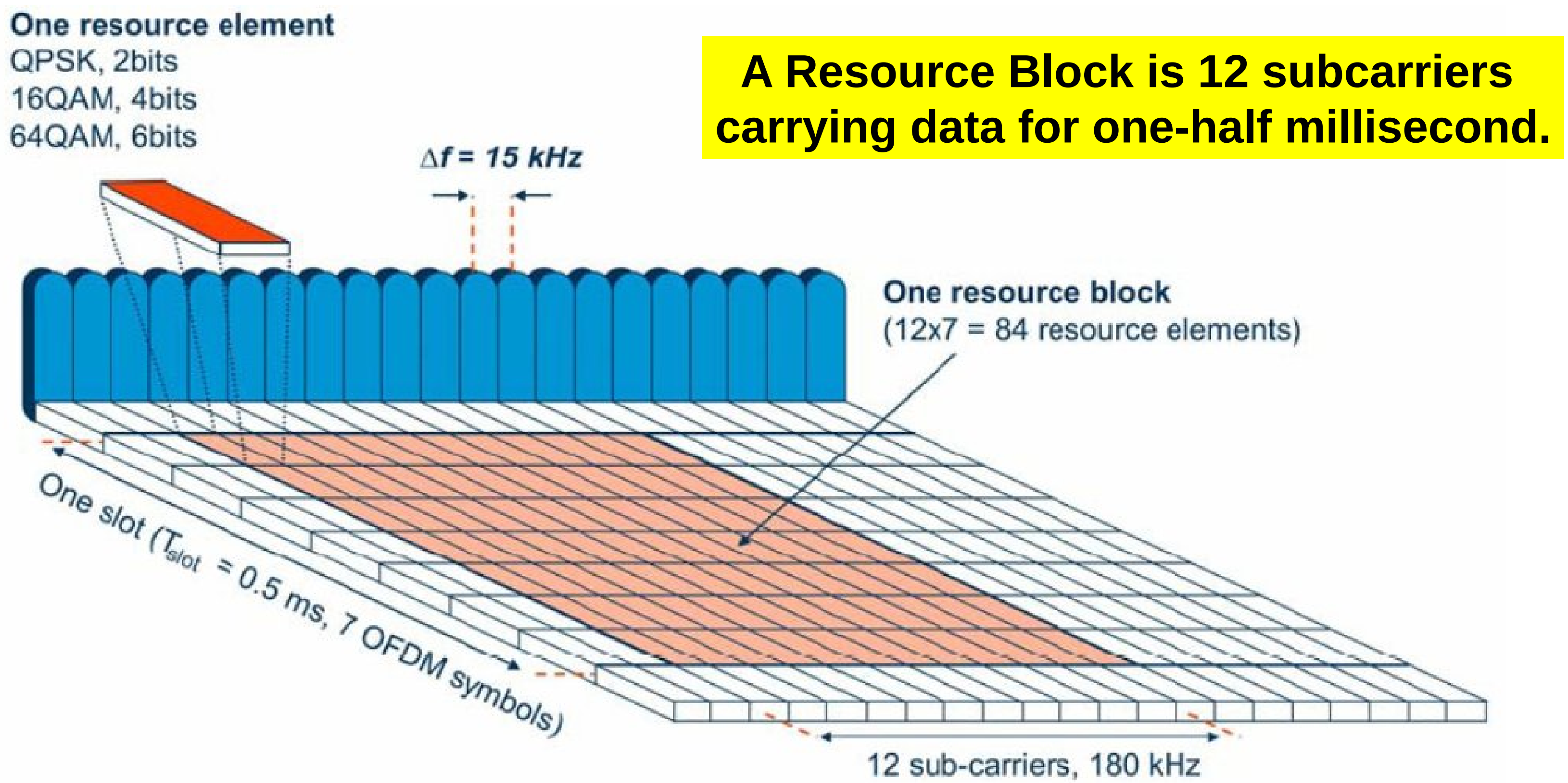
E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit	Downlink (DL) operating band BS transmit UE receive	Duplex Mode
	F_{UL_low} – F_{UL_high}	F_{DL_low} – F_{DL_high}	
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
6[1]	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
15	Reserved	Reserved	FDD
16	Reserved	Reserved	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
21	1447.9 MHz – 1462.9 MHz	1495.9 MHz – 1510.9 MHz	FDD
22	3410 MHz – 3490 MHz	3510 MHz – 3590 MHz	FDD
23	2000 MHz – 2020 MHz	2180 MHz – 2200 MHz	FDD
24	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD
25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
26	814 MHz – 849 MHz	859 MHz – 894 MHz	FDD
...			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
41	2496 MHz 2690 MHz	2496 MHz 2690 MHz	TDD
42	3400 MHz – 3600 MHz	3400 MHz – 3600 MHz	TDD
43	3600 MHz – 3800 MHz	3600 MHz – 3800 MHz	TDD
NOTE 1: Band 6 is not applicable			

LTE Band Classes

- The LTE Band Classes are listed in the ETSI document 36.101 in the table shown at left
- Blocks 1-26 are for FDD, Frequency-Division-Duplex use
- Blocks 33-43 are for TDD Time-Division-Duplex use
- As new frequencies are purposed for LTE around the world, new band classes will be added
- VZW US: Bandclass 14
- ATT US: Bandclass 17

The Smallest Assignable Traffic-Carrying Part of an LTE signal: a Resource Block

A Resource Block is 12 subcarriers carrying data for one-half millisecond.

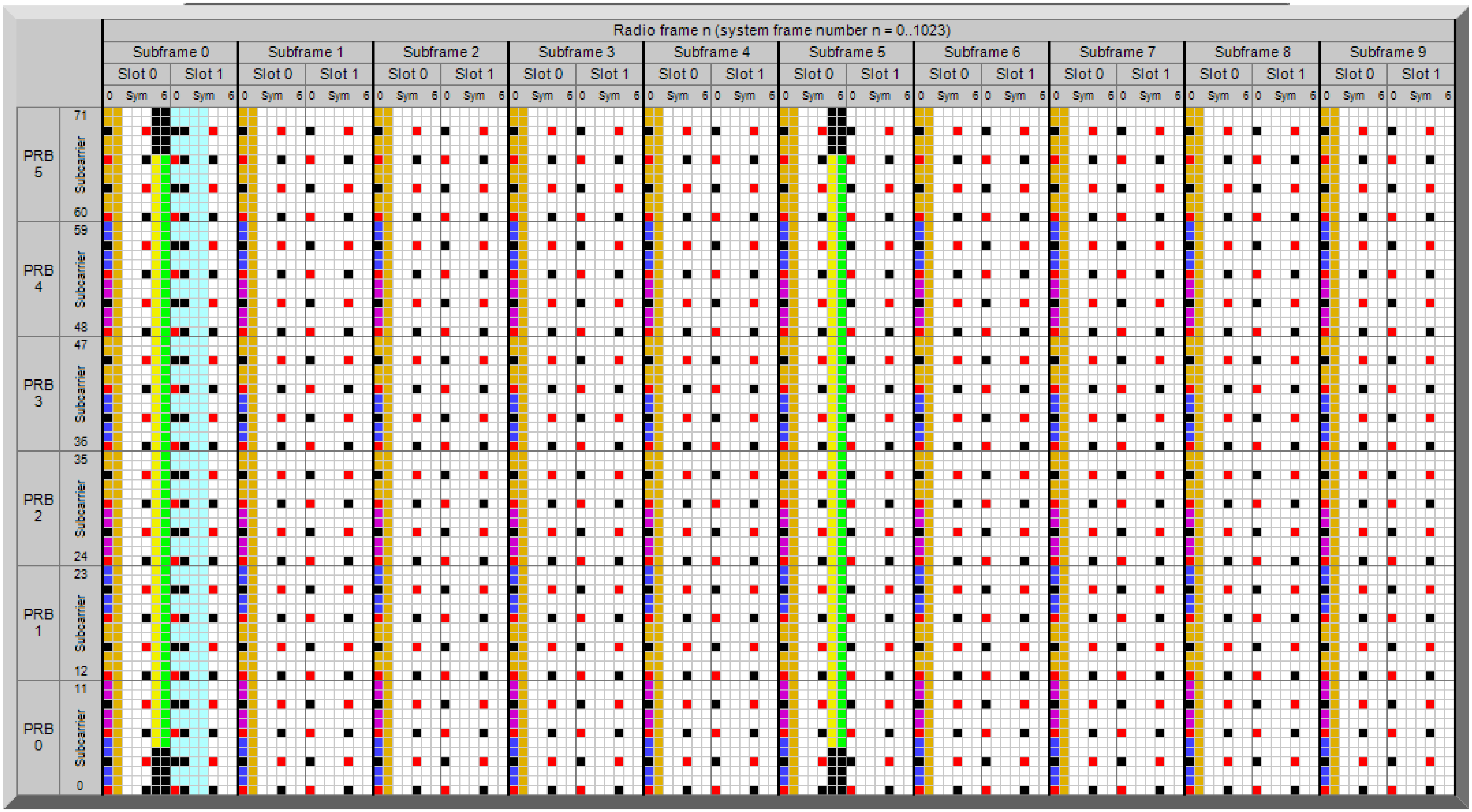


Physical resource block parameters

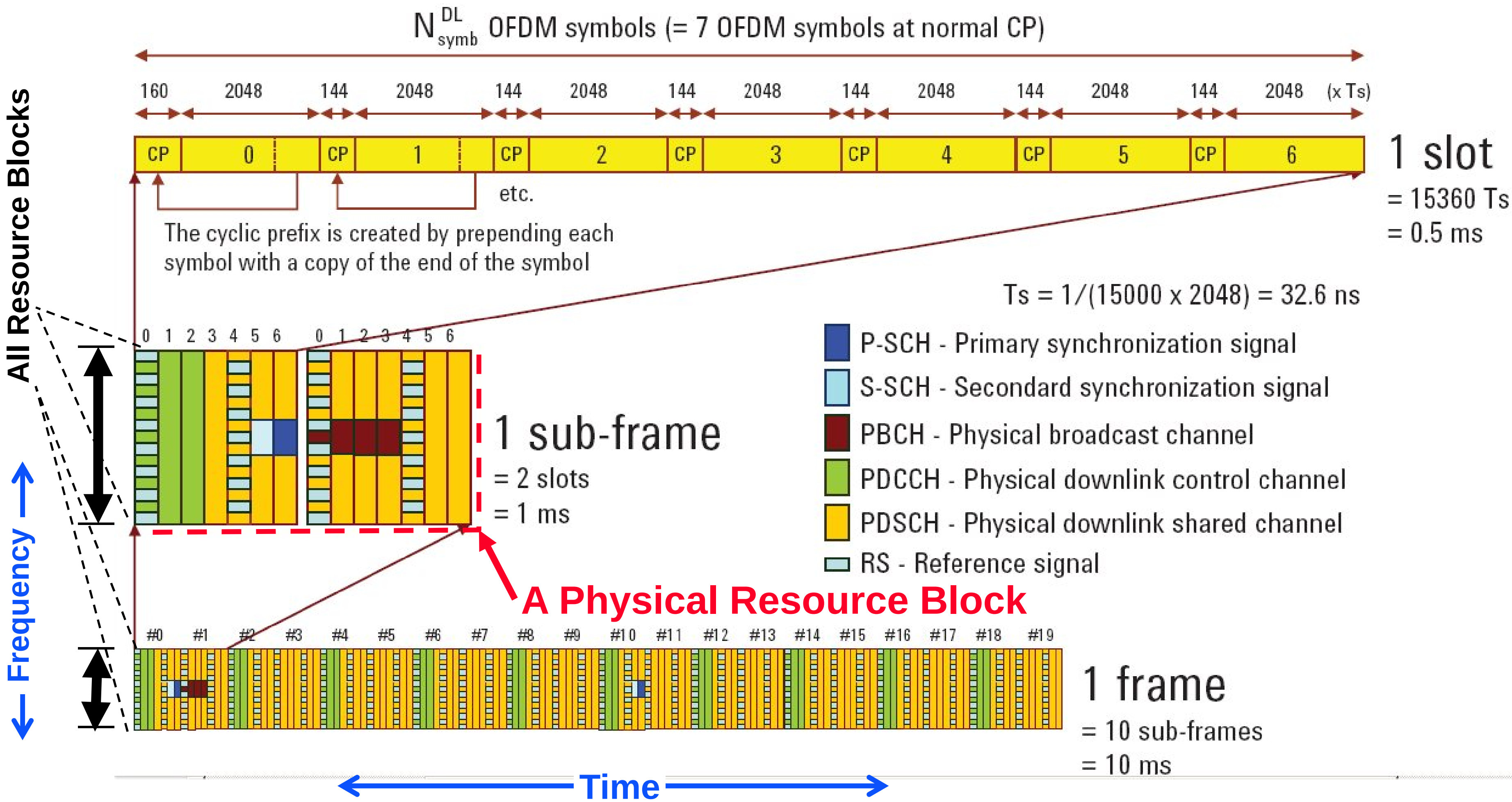
Configuration		N^{BR}_{BW}	N^{DL}_{symb} Frame structure type 1
Normal cyclic prefix	Δf = 15 kHz	12	7
Extended cyclic prefix	Δf = 15 kHz		6
	Δf = 7.5 kHz	24	3

LTE Resource Grid Interactive Example

http://paul.wad.homepage.dk/LTE/lte_resource_grid.html

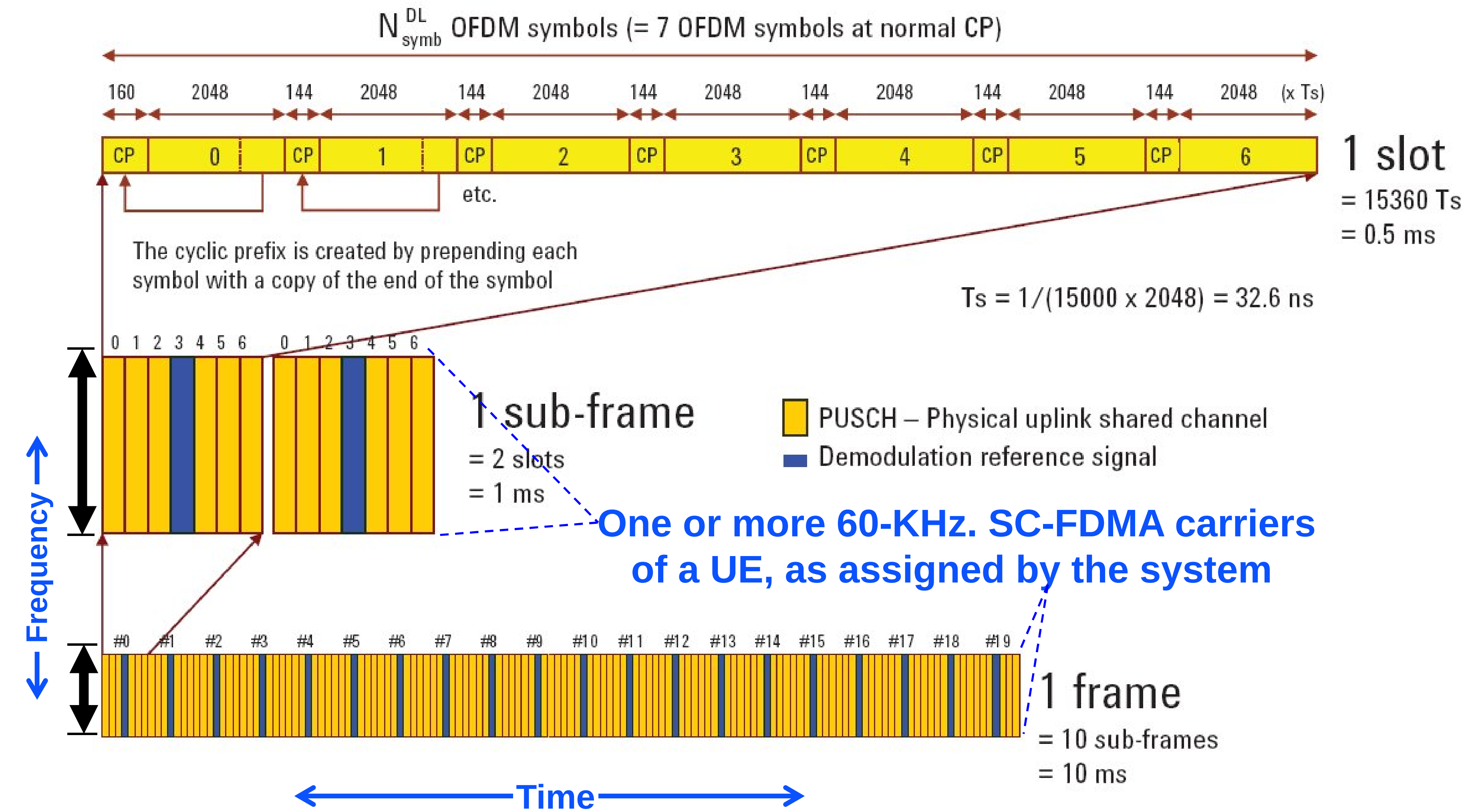


Downlink Physical Resources and Mapping

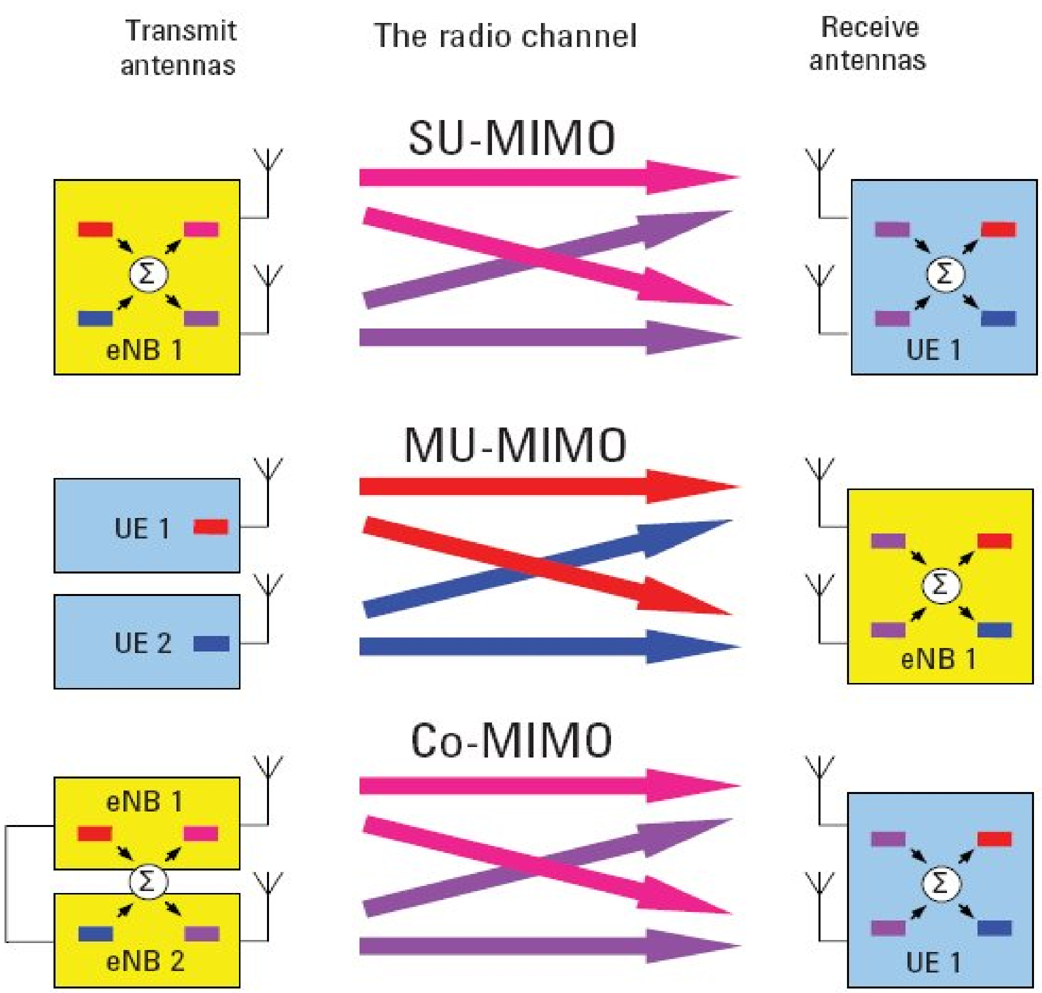


- A complete view of an FDD LTE Downlink Signal several MHz wide.

Uplink Physical Resources and Mapping



SU-MIMO, MU-MIMO, Co-MIMO in LTE

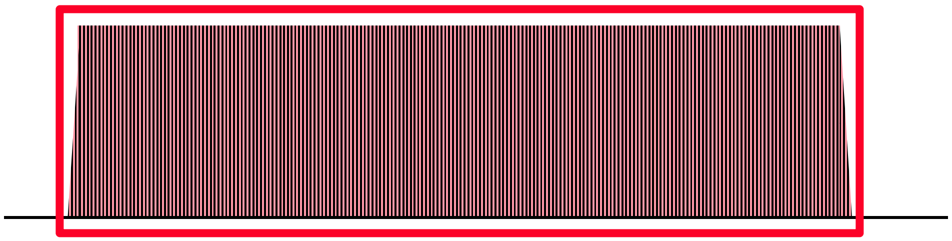


- Single-User MIMO allows the single user to gain throughput by having multiple essentially independent paths for data
- Multi-User MIMO allows multiple users on the reverse link to transmit simultaneously to the eNB, increasing system capacity
- Cooperative MIMO allows a user to receive its signal from multiple eNBs in combination, increasing reliability and throughput

LTE Measurement: RSSI

LTE Carrier Received Signal Strength Indicator (RSSI)

- Definition: The total received wideband power observed by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference and thermal noise within the bandwidth of the whole LTE signal.
- Uses: LTE carrier RSSI is not used as a measurement by itself, but as an input to the LTE RSRQ measurement.

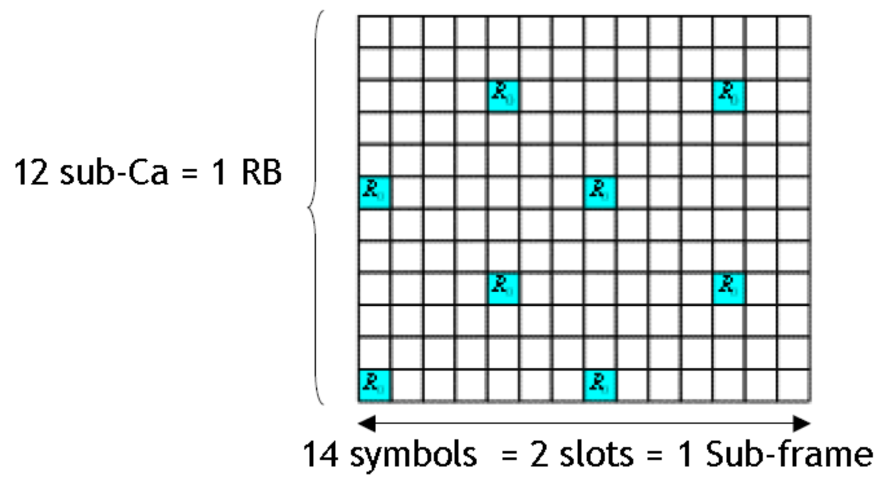


LTE Downlink

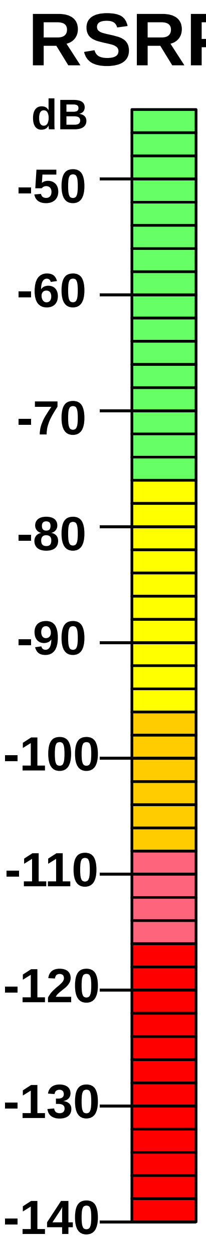
LTE Measurement: RSRP

LTE Reference Signal Received Power (RSRP)

- Definition: RSRP is the linear average power of the Resource Elements (REs) carrying a specific cell's RS within the considered measurement frequency bandwidth.
- Uses: Ranking cells for reselection and handoff.
- Notes: Normally based on the RS of the first antenna port, but the RS on the second antenna port can also be used if known to be transmitted.



UE Measurements: RSRP



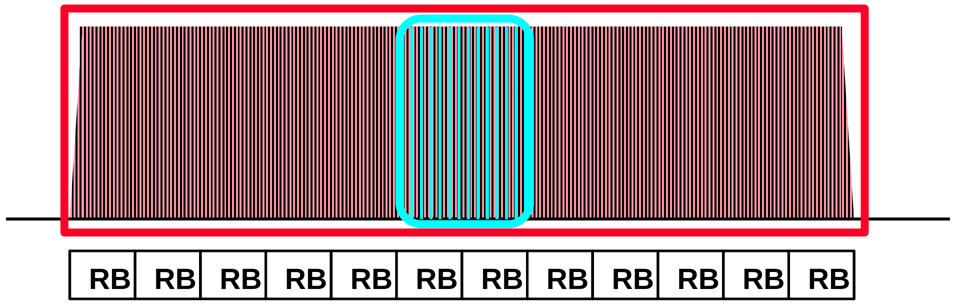
RSRP is a measure of cell downlink coverage

- When triggered, the UE sends RRC measurement reports including RSRP, which is defined from −140 to −44 dBm with 1 dB resolution.

Reported value	Measured quantity value	Unit
RSRP_00	$\text{RSRP} < -140$	dBm
RSRP_01	$-140 \le \text{RSRP} < -139$	dBm
RSRP_02	$-139 \le \text{RSRP} < -138$	dBm
...	...	...
RSRP_95	$-46 \le \text{RSRP} < -45$	dBm
RSRP_96	$-45 \le \text{RSRP} < -44$	dBm
RSRP_97	$-44 \le \text{RSRP}$	dBm

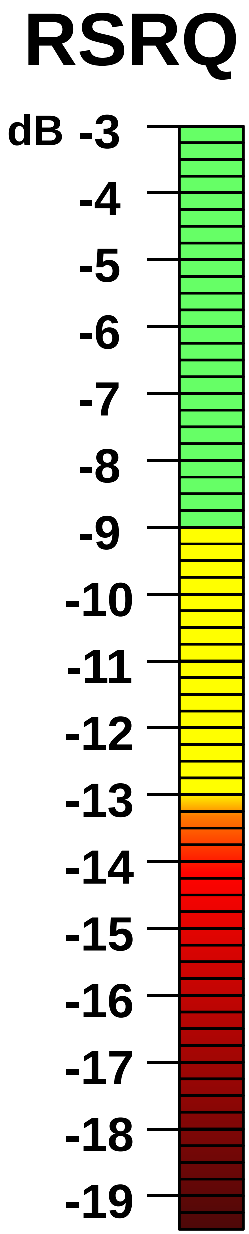
- UEs use RSRP to choose the best cell for access or handover.
- RSRP correlates with user plane QoS. Outdoor expectations:
  - RSRP > −75 dBm gives excellent QoS.
  - RSRP between −75 and −95 dBm gives a slight degradation of the QoS. Throughput declines by 30–50% between -75 and −95 dBm.
  - RSRP < −95 dBm gives unacceptable QoS. Throughput reaches zero at approximately −108 to −100 dBm. Call drops will occur.
  - In-House cells often give usable QoS with RSRP down to −115dBm, due to lower in-house interference levels

LTE Measurement: RSRQ



- LTE Reference Signal Received Quality (RSRQ)
- Definition: **RSRQ = N · RSRP / RSSI**
  - N is the number of Resource Blocks (RBs) of the LTE carrier RSSI measurement bandwidth. Since RSRQ exists in only one or a few resource blocks, and RSSI is measured over the whole width of the LTE signal, RSRQ must be "scaled up" for a fair apples-to-apples comparison with RSSI.
- Uses: Mainly to rank different LTE cells for handover and cell reselection decisions
- Notes: The reporting range of RSRQ is defined from −19.5 to −3 dB with 0.5 dB resolution. -9 and above are good values.

More RSRQ Details



- The reporting range of RSRQ is defined from −19.5 to −3 dB with 0.5 dB resolution
- Comparing measured values of RSRQ and RSRP at one location will show whether coverage or interference problems are present.
  - If RSRP remains stable or gets better, but RSRQ is declining, this indicates rising interference.
  - If both RSRP and RSRQ decline, coverage is weak.
- This kind of logic helps in finding the root cause of drops due to radio problems.
- Three quality ranges can be defined for RSRQ:
  - RSRQ values above −9 dB give the best subscriber experience.
  - RSRQ of −9 to −12 dB degrades QoS, but with fair results.
  - RSRQ values of −13 dB and lower give reduced throughput and a risk of call drops.

SINR: LTE Signal vs. Noise And Interference

- SINR is a more practical measure of signal quality than SNR
- It is not defined in the 3GPP specs but rather by UE vendor. It is not reported to the network.
- SINR is popular with operators since it better quantifies the relationship between RF conditions and throughput
  - Most UEs use SINR to calculate the CQI (Channel Quality Indicator) they report to the network
- The components of the SINR calculation are:
  - S: the power of measured usable signals, such as Reference signals (RS) and physical downlink shared channels (PDSCHs)
  - I: the power of measured interference from other cells in the current system
  - N: background noise power
- SINR can be defined as Wideband or Narrowband (for specific subcarriers or a specific resource element)

LTE Received Channel Quality Indication, CQI

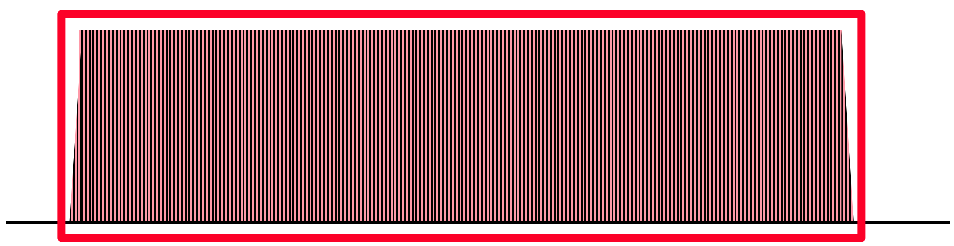
CQI Index	Modula-tion	Code rate x 1024	Efficiency b/s/Hz	Typ. Min. Req C/(I+N)
0	**Out of Range**			
1	**QPSK**	**78**	**0.152**	**-6**
2	**QPSK**	**120**	**0.234**	**-5**
3	**QPSK**	**193**	**0.377**	**-3**
4	**QPSK**	**308**	**0.601**	**-1**
5	**QPSK**	**449**	**0.877**	**+1**
6	**QPSK**	**602**	**1.176**	**+3**
7	**16QAM**	**378**	**1.477**	**+5**
8	**16QAM**	**490**	**1.914**	**+8**
9	**16QAM**	**616**	**2.406**	**+9**
10	**64QAM**	**466**	**2.731**	**+11**
11	**64QAM**	**567**	**3.322**	**+12**
12	**64QAM**	**666**	**3.902**	**+14**
13	**64QAM**	**772**	**4.523**	**+16**
14	**64QAM**	**873**	**5.115**	**+18**
15	**64QAM**	**948**	**5.555**	**+20**

- LTE downlink modulation is adapted in real-time to cope with UE-reported RF conditions.
- QPSK, 16QAM, or 64QAM modulation is chosen, along with variable rate coding resulting in a total of 16 available data speeds to best adapt to any radio conditions
- The table at left shows a range of C/(I+N) values at the mobile and the corresponding modulation and coding schemes with their spectral efficiency.
- Uplink data rates are also regulated by the uplink scheduling function in the eNodeB, which chooses the uplink modulation type and coding used by the UE.

LTE Measurement: RSSI

LTE Carrier Received Signal Strength Indicator (RSSI)

- Definition: The total received wideband power observed by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference and thermal noise within the bandwidth of the whole LTE signal.
- Uses: LTE carrier RSSI is not used as a measurement by itself, but as an input to the LTE RSRQ measurement.



LTE Downlink

Power Headroom

- Power Headroom (PH), in dB, is the difference between current UE PUSCH transmit power and the UE's maximum capable power output
  - it's how much extra transmit power the UE has left in reserve in case uplink conditions worsen
- PH reports can be sent either event-triggered or periodically. The most common trigger is a path loss change higher than a predefined value when a timer expires. Otherwise, periodic PH reporting starts when the PH measurement task is configured or reconfigured.
- UE PH reports are sent in MAC, not RRC.
- The eNB can set UE's maximum transmit power by the P-max parameter in RRC.
  - PH runs from −23 to +40 dB. The 64 values correspond to 6 bits of the PH control element in the MAC.

Reported value	Measured quantity value (dB)
POWER_HEADROOM_0	$-23 \le PH < -22$
POWER_HEADROOM_1	$-22 \le PH < -21$
POWER_HEADROOM_2	$-21 \le PH < -20$
POWER_HEADROOM_3	$-20 \le PH < -19$
POWER_HEADROOM_4	$-19 \le PH < -18$
POWER_HEADROOM_5	$-18 \le PH < -17$
...	...
POWER_HEADROOM_57	$34 \le PH < 35$
POWER_HEADROOM_58	$35 \le PH < 36$
POWER_HEADROOM_59	$36 \le PH < 37$
POWER_HEADROOM_60	$37 \le PH < 38$
POWER_HEADROOM_61	$38 \le PH < 39$
POWER_HEADROOM_62	$39 \le PH < 40$
POWER_HEADROOM_63	$PH \ge 40$

The Regulatory Environment

- The Commission's Rules specify mandatory spurious emission suppression requirements for every class of licensed RF operation
  - FM broadcast requirements R&R 73.317 (see following page)
    - See other sections for FM translators, TV, etc.
- The method for over-the air measurement of FM suppression compliance is not specifically spelled out, but
  - R&R 73.314 specifies the measurement techniques to be used in support of petitions for rulemaking to change FCC FM propagation prediction models or to demonstrate measured coverage of applicable contours
  - In spurious matters, a subset of 73.314 procedures is usually followed (drive or multiple spot measurements in the far-field of the broadcast facility, usually around 1 Km distance)
- Remember, the measurements must be made close enough to the broadcast source so that the sought-after spurious remains within the dynamic range/noise floor of the measuring instrument

§ 73.317 FM Transmission System Requirements

- (a) FM broadcast stations employing transmitters authorized after January 1, 1960, must maintain the bandwidth occupied by their emissions in accordance with the specification detailed below. FM broadcast stations employing transmitters installed or type accepted before January 1, 1960, must achieve the highest degree of compliance with these specifications practicable with their existing equipment. In either case, should harmful interference to other authorized stations occur, the licensee shall correct the problem promptly or cease operation.
- (b) Any emission appearing on a frequency removed from the carrier by between 120 kHz and 240 kHz inclusive must be attenuated at least 25 dB below the level of the unmodulated carrier. Compliance with this requirement will be deemed to show the occupied bandwidth to be 240 kHz or less.
- (c) Any emission appearing on a frequency removed from the carrier by more than 240 kHz and up to and including 600 kHz must be attenuated at least 35 dB below the level of the unmodulated carrier
- **(d) Any emission appearing on a frequency removed from the carrier by more than 600 kHz must be attenuated at least 43 + 10 Log10 (Power, in watts) dB below the level of the unmodulated carrier, or 80 dB, whichever is the lesser attenuation.**

§ 73.314 Field Strength Measurements

Section 73.314 of the Commission's Rules provide procedures for the measurement of FM field strength data for propagation analysis in support of rulemaking petitions to change the Commission's FM propagation prediction methods. These measurement procedures are also applicable to the measurement of FM spurious signal suppression and are commonly used in measuring the radiated spurious suppression of an FM transmitter and antenna systems.

The relevant portions of the Rule are excerpted below:

§ 73.314 (b) Collection of field strength data for propagation analysis.

(2) Measurement procedure. All measurements must be made utilizing a receiving antenna designed for reception of the horizontally polarized signal component, elevated 9 meters above the roadbed. At each measuring location, the following procedure must be used:

(i) The instrument calibration is checked.

(ii) The antenna is elevated to a height of 9 meters.

(iii) The receiving antenna is rotated to determine if the strongest signal is arriving from the direction of the transmitter.

(iv) The antenna is oriented so that the sector of its response pattern over which maximum gain is realized is in the direction of the transmitter.

§ 73.314 Field Strength Measurements (continued)

(v) A mobile run of at least 30 meters is made, that is centered on the intersection of the radial and the road, and the measured field strength is continuously recorded on a chart recorder over the length of the run.

(vii) If, during the test conducted as described in paragraph (b)(2)(iii) of this section, the strongest signal is found to come from a direction other than from the transmitter, after the mobile run prescribed in paragraph (b)(2)(v) of this section is concluded, additional measurements must be made in a ‘‘cluster’’ of at least five fixed points. At each such point, the field strengths with the antenna oriented toward the transmitter, and with the antenna oriented so as to receive the strongest field, are measured and recorded. Generally, all points should be within 60 meters of the center point of the mobile run.

(viii) If overhead obstacles preclude a mobile run of at least 30 meters, a ‘‘cluster’’ of five spot measurements may be made in lieu of this run. The first measurement in the cluster is identified. Generally, the locations for other measurements must be within 60 meters of the location of the first.

A Word About Dynamic Range

- Dynamic range is the range of input and/or output powers that an electronic device can amplify faithfully without experiencing distortion, generating troublesome intermodulation products, or experiencing noise which would mask or hide sought-after signals
  - Modern communications devices use bandpass filtering and various combiner technologies to ensure devices are not driven beyond their dynamic range by strong signals on adjacent frequencies
- When transmitters and receivers are located near one another at a favorable communications site (hilltop, building top, etc), it is very common for an extremely wide mix of signal amplitudes to exist in the vicinity
- When facilities are in close proximity, it is common for a facility to produce harmonics, broadband noise, or other spurious which comply with the Commission’s suppression requirements yet are still orders of magnitude stronger than another nearby facility can tolerate
- Remember, even state-of-the-art measuring equipment is vulnerable to internally-generated spurious signals when driven beyond its dynamic range

Path Loss in Free Space and Thermal Noise

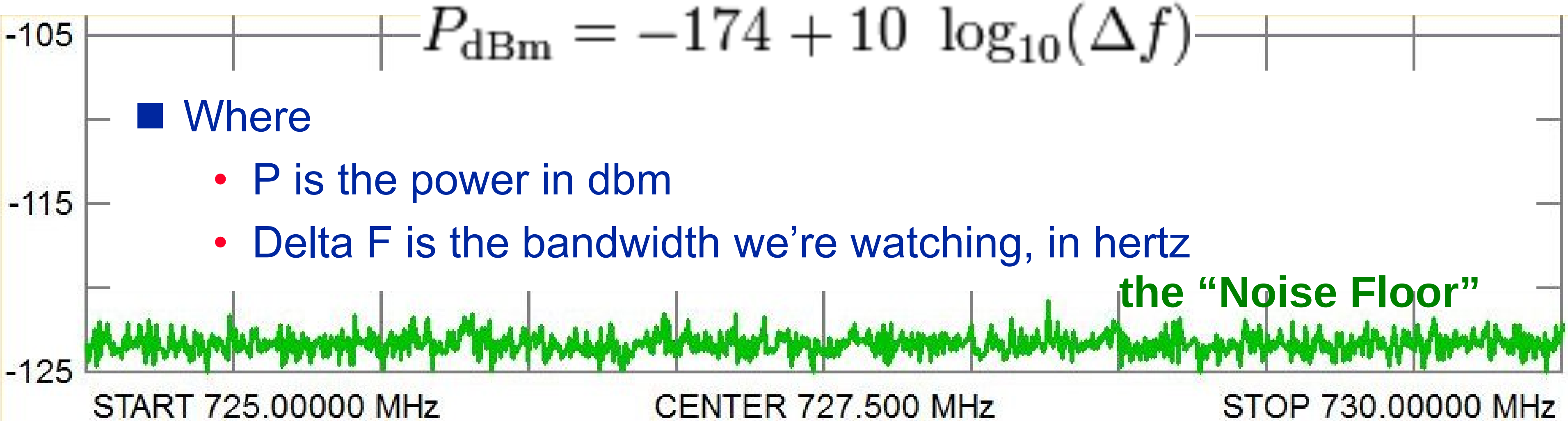
- Path Loss, db (between two isotropic antennas)

  = 36.58 +20*Log10(Fmhz)+20Log10(Distance,Miles)
- Path Loss, db (between two dipole antennas)

  = 32.26 +20*Log10(Fmhz)+20Log10(Distance,Miles)
- Notice the rate of signal decay:
  - 6 db per octave of distance change, which is
  - 20 db per decade of distance change

$$P_{\mathrm{dBm}} = -174 + 10\ \log_{10}(\Delta f)$$

- Where
  - P is the power in dbm
  - Delta F is the bandwidth we’re watching, in hertz



Thermal Noise Strength
in the Bandwidths of Common Signals

Thermal Noise Power in bandwidths of Common Signal Types			
T, deg K	BW, Hz	Noise, dbm	type of signal
290	1	-174.0	power in 1 Hertz of bandwidth
290	12,500	-133.0	analog FM land mobile radio
290	15,000	-132.2	one LTE subcarrier
290	25,000	-130.0	IDEN signal
290	30,000	-129.2	original AMPS analog cellular signal
290	200,000	-121.0	GSM/GPRS/EDGE signal
290	1,000,000	-114.0	bluetooth channel
290	1,228,800	-113.1	CDMA or EVDO signal
290	2,000,000	-111.0	commercial GPS channel
290	200,000	-121.0	GSM/GPRS/EDGE signal
290	3,840,000	-108.1	UMTS/WCDMA/HSPA signal
290	6,000,000	-106.2	DTV or analog TV signal
290	6,000,000	-106.2	lower 700 A, B, or C LTE signal
290	11,000,000	-103.6	upper 700 C LTE signal
290	20,000,000	-101.0	802.11 20 MHz. channel
290	40,000,000	-98.0	802.11 40 MHz. channel

FM Harmonics Blog by Richard B. Johnson: Summary of Good Recommendations

- http://fm-harmonics.blogspot.com/ by Richard B. Johnson
- Measure the entire transmitting system after the harmonic filter.
- Use a dummy load. Antenna impedances are unknown at harmonic frequencies and can result in very abnormally high or very low erroneous indications of harmonic power
- Since FM antennas offer some inherent selectivity, a transmitter that passes suppression requirements on a dummy load will pass even more comfortably on a normal antenna.
- Use a capacitive probe into the transmission line. These have a known 6dB/octave 20dB/decade attenuation factor provable with simple math, and accepted by the FCC. This gives extra sensitivity for detecting higher-frequency harmonics, too.
- Be careful to avoid overload of the spectrum analyzer or receiver.
  - Use an attenuator when measuring the fundamental, if needed
  - When measuring harmonics, reduce the fundamental with a trap or band-reject filter, or use a bandpass filter to pass only the individual harmonic(s) you want to measure

Harmonic Relationships

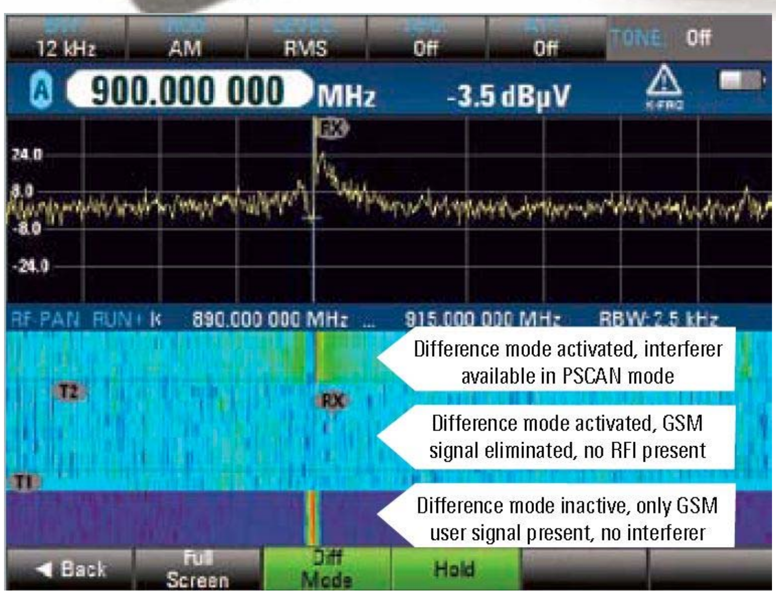
- See http://scottbaxter.com/harmonicstable.pdf
- This chart shows the harmonics of every TV and FM channel, along with whether and where they fall in the wireless communications bands
- A detailed table is also presented

The Guiding Realities
What do you think?

- All FCC licensees are obligated to comply with applicable FCC spurious emission requirements, at their own expense.
- When a newcomer encounters interference from an existing compliant licensee
  - The newcomer must accept the interference, or
  - The newcomer at its own expense may seek solutions
    - And the existing licensee(s) must reasonably cooperate, but at the newcomer's expense
- But if the problem is extremely destructive to the newcomer, and the public interest is clearly impacted, the Commission may require more stringent suppression by the existing licensee
- If solving the problem becomes more disruptive than living with it, the injured party will stop resistance (at least for the moment)
- Whichever party can afford the best counsel, best engineer and the most political friends for the longest time will eventually prevail

Measurement Tools

Rohde & Schwarz PR100 Receiver

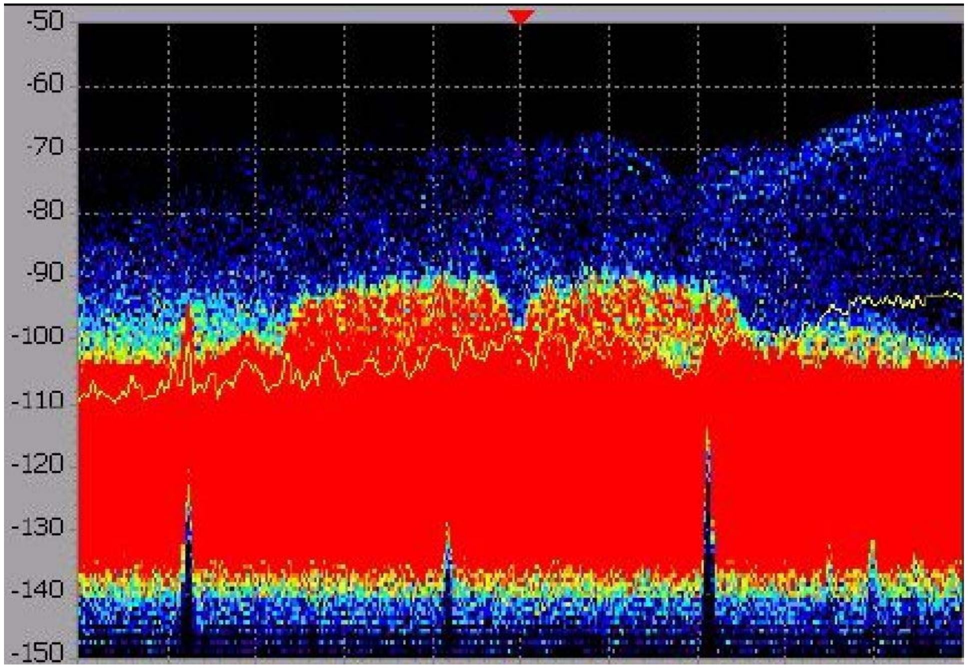


- The PR100 is a real-time DSP based receiver/analyzer able to catch elusive interference ordinary analog swept analyzers simply can't see
- 10 MHz realtime IF spectrum DSP displays all types of signals – no matter how unstable they are
- Pulses as short as 500 us are clearly visible on spectrogram and captured trace display
- Built-in electronic compass and GPS receiver for rapid trackdowns on displayed map
- Remote logging and remote control software
- List $55,000, but best-in-class

Tektronix SA2600/H600

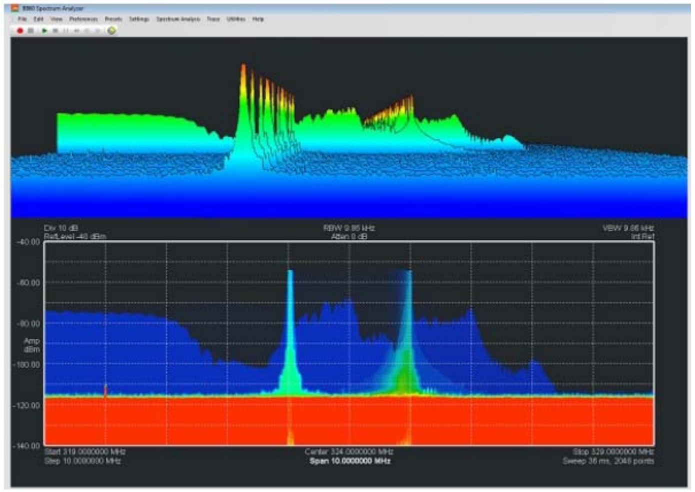
- The Tektronix SA2600 or H600 has the same capabilities as the Rohde-Schwarz PR100, but in a little more cumbersome package
- The SA2600's "digital phosphor" display provides excellent views of transient pulsed signals analog analyzers miss
- The H600 version can match received signals against an internal database of signal signatures, useful especially for military users
- SA2600 list price $28,000, the H600 is over $40,000

"Topographic" Density Displays and Display Decay Features ("Variable Phosphor")



- RTSAs provide statistically-derived information in traces, a feature called "DPX" by Tektronix and "topographic displays" by others
- Each pixel on the display represents a signal power level at a specific frequency, but the color of the pixel is determined by the number of times it was recently illuminated by a received signal
- This allows seeing even highly intermittent interferences as wispy, ethereal blue envelopes above the level of a main signal

The Test Equipment Plus
Signal Hound BB60A



- The Test Equipment Plus BB60A is a very affordable real-time spectrum analyzer powered by a USB-3 port on a PC. The PC does the signal processing and display.
- The BB60A can also be used as an RF recorder, storing up to an hour of complete capture of wideband signals in up to a 20 MHz. bandwidth which it can play back at different speeds
- The BB60A has the same type of core computing engine as the more expensive PR100 and SA2600, but without dynamic tuned preselectors. A bandpass filter is advised along with a low-noise preamplifier for serious interference detection.
- Because of its real-time capabilities, the BB60A is on the ITAR list, export-restricted to western allies only.
- The cost is under $2,600, including the software shown above.

Using Bandpass Filters to Eliminate DeSensitization and Intermod

- Both tunable and fixed bandpass filters are available for wireless frequencies from many manufacturers
- The K&L BT-series tunable bandpass filters have bandwidth of 5% (1-8% special order), very steep skirts, are tunable over a 2:1 frequency range; Trilithic has a similar line of filters.
- Fixed filters for each 700 MHz. uplink and downlink block are available from numerous manufacturers

Using Low-Noise Preamplifiers to Improve Analyzer Sensitivity

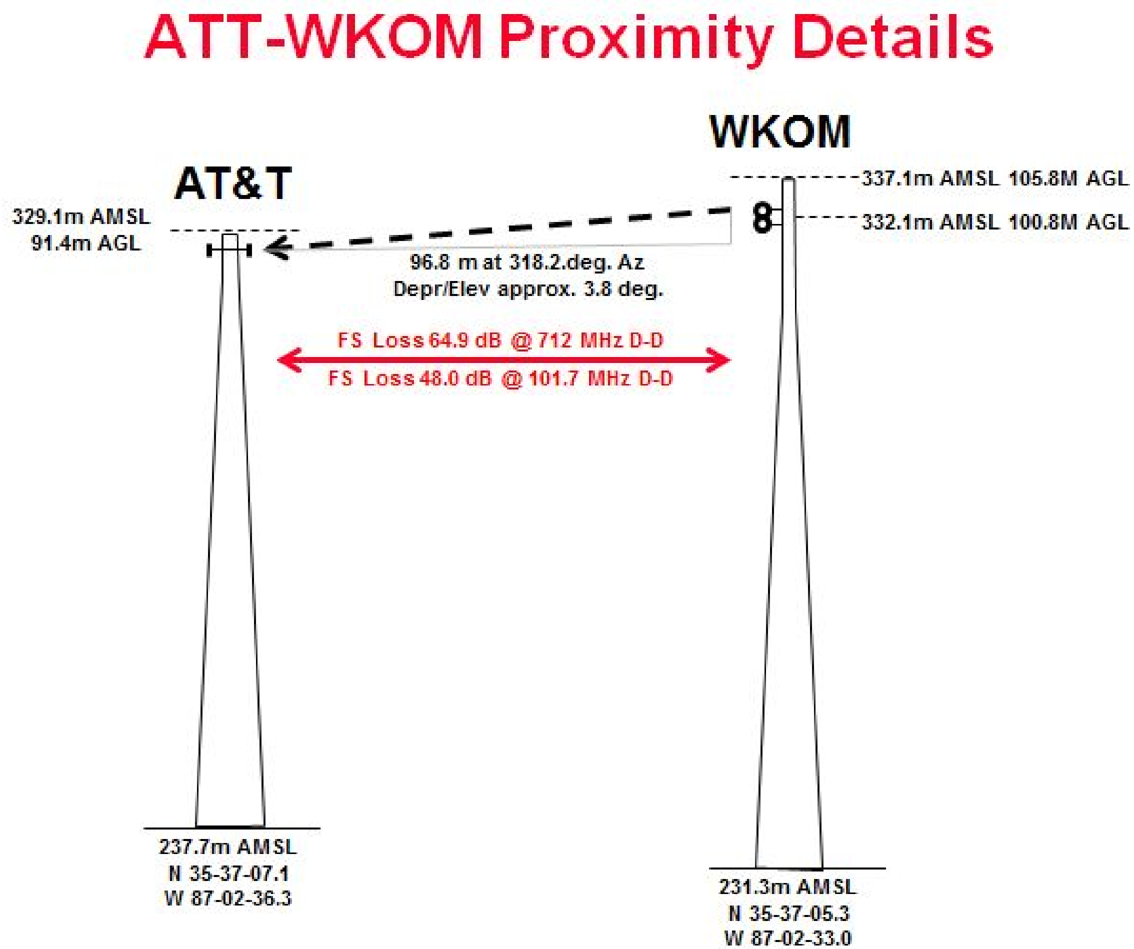
- The sensitivity and noise figure of all but the most advanced spectrum analyzers can be improved by use of a wideband low-noise preamplifier
- The Mini-Circuits Labs LNA model ZRL-1150LN+ in 698-896 MHz. has gain 30 db, NF 0.8 db, IP3 intercept (output) +40 dbm; 1 db compression at +24 dbm out
- The unit requires12 volts from a battery or filtered cigar lighter plug
- To maintain calibrated signal level readings on the analyzer, measure and set the reference level offset
- A bandpass filter is essential ahead of the LNA to prevent overloading, distortion and intermodulation

Example Case 1

Example Case 1 Summary
WKOM-FM Columbia, TN.

- FM Frequency 101.7 MHz., ERP 4.1 kW
- FM harmonic and spectral width: 7^{th}, 711.9 MHz., 1.4 MHz. wide
- Harmonic at LTE RX, -87.4 dbm, 25.2 db above noise -112.6 dbm
- LTE Operating Frequency 740-745 MHz.
- Physical Separation between FM and LTE sites: 96.8 Meters
- Free-Space path loss
  - At FM fundamental frequency 48.0 db
  - At FM harmonic/LTE uplink Frequency 64.9 db
- Initial standing of parties: AT&T complaint
- Proposals or communications
  - WKOM indicated willingness to cooperate, suggested filters.
- Disposition
  - WKOM received no further communications from AT&T.

Proximity of Facilities



- The WKOM and AT&T antenna radiation centers are within a few meters of the same elevation, and separated by a little less than 100 meters. This places the WKOM antennas squarely in the main lobes of the vertical patterns of the AT&T antennas.

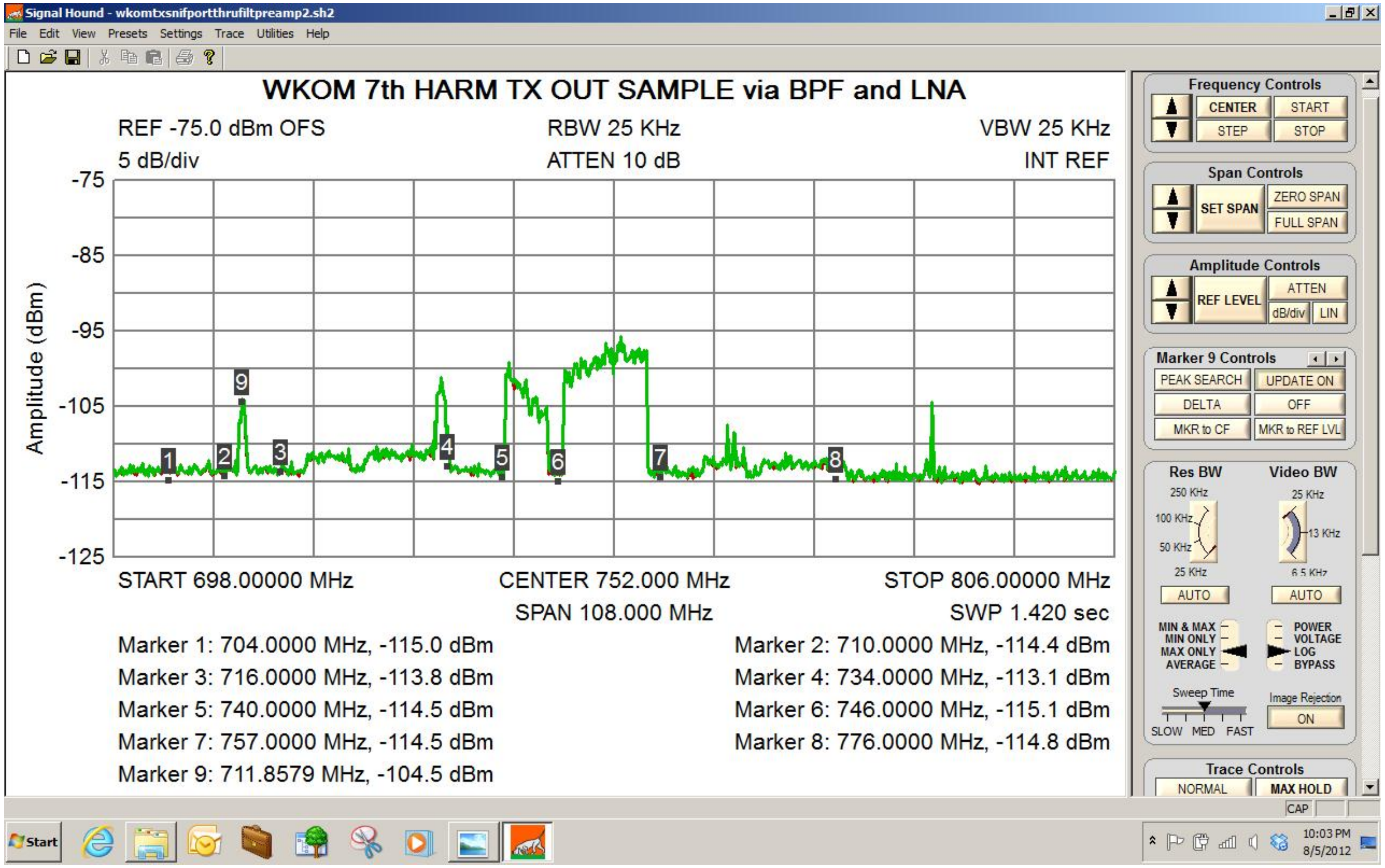
Harmonic Measurement Process

- A WKOM transmitter test port an attenuated sample of the transmitter output. A TEP SA124B spectrum analyzer was connected through a wideband 30 db attenuator to this port.
  - The WKOM fundamental signal at 101.7 MHz. was observed at a level of -17.2 dbm.
- A K&L 5BT00012 tunable bandpass filter was adjusted to 711.9 MHz. and connected between the spectrum analyzer and the attenuator output. The insertion loss of this filter is less than 1 db and signals outside its tunable 40 MHz. passband window are attenuated more than 50 db.
- A Mini-Circuits Labs model ZRL-1150LN+ low noise amplifier was connected after the tunable filter feeding directly into the spectrum analyzer. The amplifier gain and filter loss were measured using a calibrated tracking generator.
- The observed seventh harmonic signal at 711.9 MHz. was measured at -104.9 dbm.

Analysis

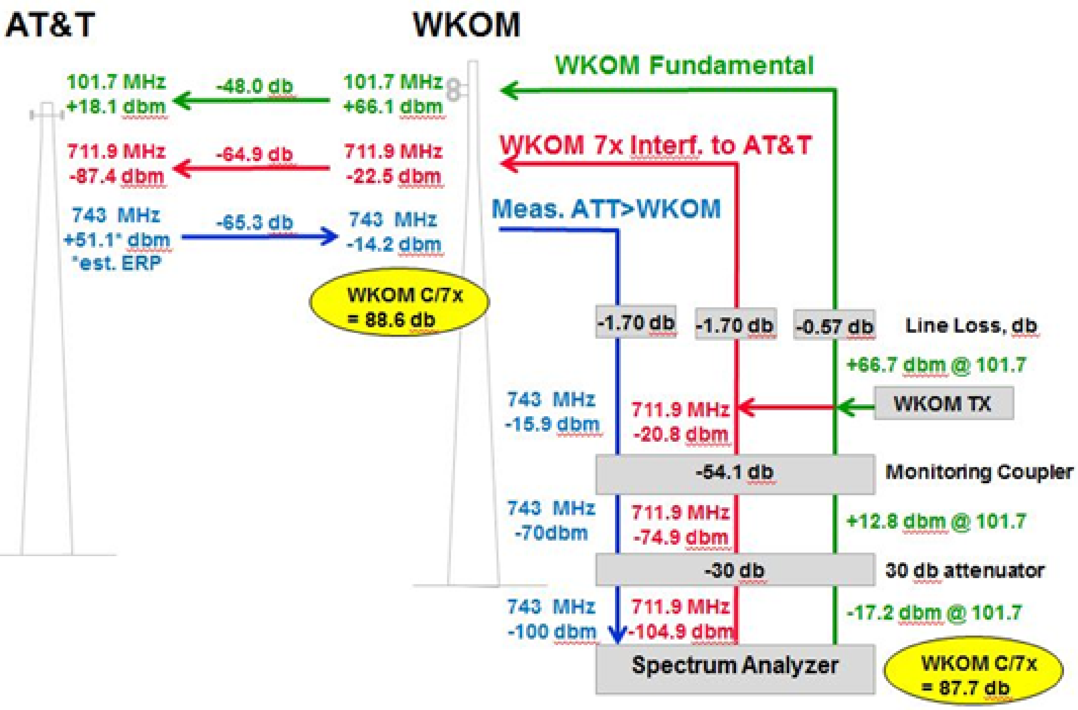
- FCC R&R 73.317 (d) requires "Any emission appearing on a frequency removed from the carrier by more than 600 kHz must be attenuated at least 43 + 10 Log[10](Power, in watts) dB below the level of the unmodulated carrier, or 80 dB, whichever is the lesser attenuation". In the case of WKOM, with ERP of 4.1 kW, the required spurious attenuation is 43 + 10 Log (4100) = 79.1 db
- The measured seventh harmonic attenuation at 711.9 MHz. was about (-17.2) – (-104.9) = 87.7 db, approximately 8.6 db better than required.
- The spectrum analyzer display below shows the seventh harmonic as well as trace amounts of the 700 MHz. AT&T and Verizon LTE signals as well as public safety signals received by the WKOM antennas and fed down the transmission line and through the sample coupler. The presence and levels of these signals reveal additional details of the existing situation and the paths over which they have travelled. The resulting information is also useful to understand the interference presently received by AT&T.
- In tests around the outside of the WKOM transmitter building with the spectrum analyzer and a directional antenna, seventh harmonic energy was not seen unless the antenna was pointed upward toward the antenna system. Cabinet radiation from the WKOM transmitter was not seen.

Spectrum Analyzer Display



- This display taken at the sample port shows the WKOM seventh harmonic, feedthrough of 700 MHz. AT&T and Verizon LTE downlink signals, and public safety signals received by the WKOM antennas and fed down the transmission line and through the sample coupler.

Further Analysis



- The WKOM transmitter output is normally +66.7 dbm. The sampling coupler delivers +12.8 dbm at the monitoring port, which yields -17.2 dbm as observed on the spectrum analyzer after the 30 db pad. The sampling coupler's attenuation is 54.1 db at the WKOM fundamental frequency. The coupler is designed by the manufacturer for use in harmonic amplitude measurements and is essentially flat from below the fundamental to the 10th. harmonic.
- The AT&T downlink LTE signal at 740 to 746 MHz. is about -100 dbm. peak. This signal has travelled the 96.8 meter distance between the antennas of the two sites, accumulating 65.3 db of free space path loss plus the small incidental gain or loss of the WKOM antenna at 700 MHz. frequencies. It has passed through the WKOM feedline, with additional attenuation of about 1.7 db. It has also passed from the main transmission line through the sampling coupler with an attenuation of 54.1 dbm, then through the 30 db pad to the spectrum analyzer input, yielding -100 dbm at that point.
- Calculating back up this chain, an AT&T ERP of +51.1 dbm would be required to deliver these levels. This value is within the capabilities of the AT&T LTE eNodeB equipment.

Apparent Interference Level at AT&T Antennas

- Following similar reasoning, we can trace backward from the observed seventh harmonic level seen on the spectrum analyzer to estimate the amount of seventh harmonic energy seen at the AT&T antennas.
- -104.9 dbm is observed at the spectrum analyzer, so the level is 30 db higher at the top end of the 30 db attenuator, -74.9 dbm. At the transmitter output side of the monitoring coupler, the seventh harmonic level would be -20.8 dbm. Note that this is 87.5 db below the carrier, significantly better than the -79.1 db FCC-required suppression.
- With 1.7 db attenuation in the transmission line the seventh harmonic power radiated by the WKOM antennas is -22.5 dbm. At the 700 MHz. band the pattern of these elements is very broad with little gain. After passing through 64.9 db free space path loss to the AT&T antennas, a dipole there would receive approximately -87.4 dbm.
- The actual power delivered to the receivers depends on the additional gain of the antennas used (typically 10-14 dbd or 12-16 dbi) and loss in the transmission lines, typically 2-3 db. In an LTE receiving environment interference will ideally be below -120 dbm at the E-node B receiver input.
- Conclusion: Additional harmonic suppression of approximately 40 db. is desirable. The consistency of these observed signals and path calculations strongly supports this conclusion.

WKOM Response to AT&T Wireless and Present Status of Situation

- WKOM responded to AT&T wireless making the following points:
  - WKOM is already presently compliant with FCC spurious suppression requirements.
  - WKOM recognizes that despite its compliance, AT&T is experiencing problematic interference. WKOM is happy to cooperate with AT&T in any tests, investigations, or practical remedies it may wish to pursue at its own expense.
  - From WKOM's analysis, another 40 db of attenuation of the seventh harmonic would eliminate it as a problem for AT&T.
  - WKOM has researched several commercial filters approaching this level of additional suppression. The average cost of these items was around $5,000.
- AT&T Wireless made no response to WKOM and has not contacted WKOM again during the last 18 months.

Example Case 2

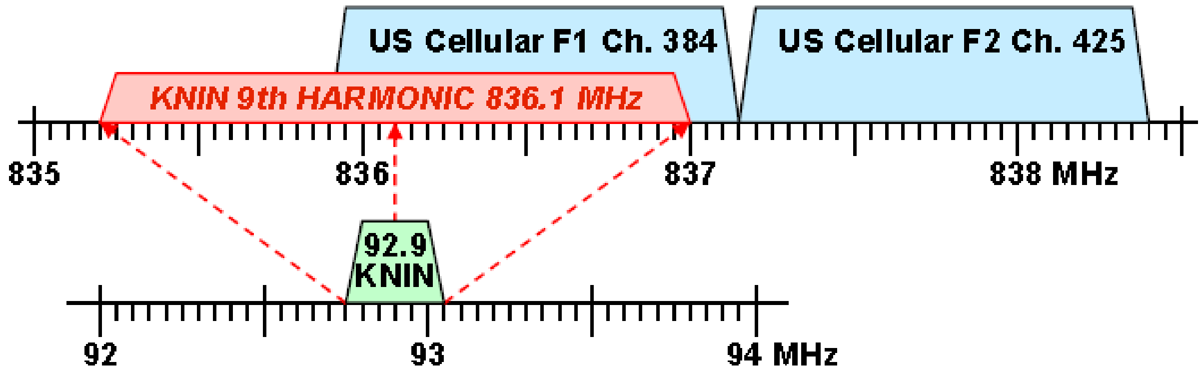
Example Case 2 Summary
KNIN-FM Wichita Falls, Texas

- FM Frequency 92.9 MHz., ERP 100 kW
- FM harmonic/spectral width: 9^{th}, 836.1 MHz., 1.1 MHz. overlap
- Harmonic at CDMA RX, -74 dbm, 39.6 db above noise -113.6 dbm
- CDMA Operating Frequency 835.9-837.1 MHz.
- Physical Separation between FM and LTE sites: 540 feet
- Free-Space path loss
  - At FM fundamental frequency 61.3 db
  - At FM harmonic/LTE uplink Frequency 80.4 db
- Initial standing of parties: Cellular company tolerated for several years, then made new attempt to correct
- Proposals or communications
  - KNIN engineer assisted in tests and experiments
- Disposition
  - Both parties tired and concluded solution was too expensive

KNIN-FM and US Cellular Frequencies

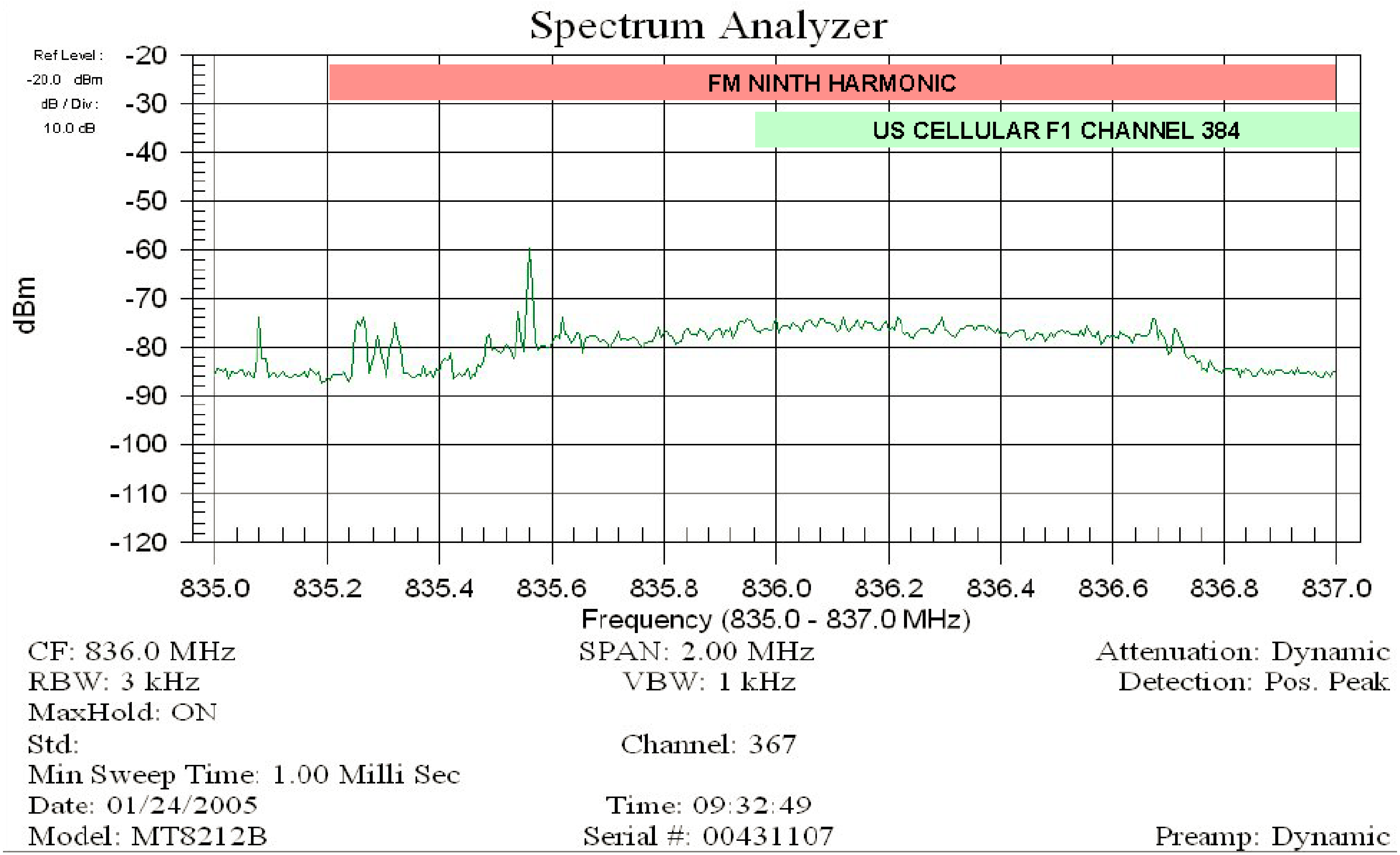
Channel	BTS RX	BTS TX
384	836.52	881.52
425	837.75	882.75

KNIN-FM		9th Harmonic
92.9	X9=	836.1

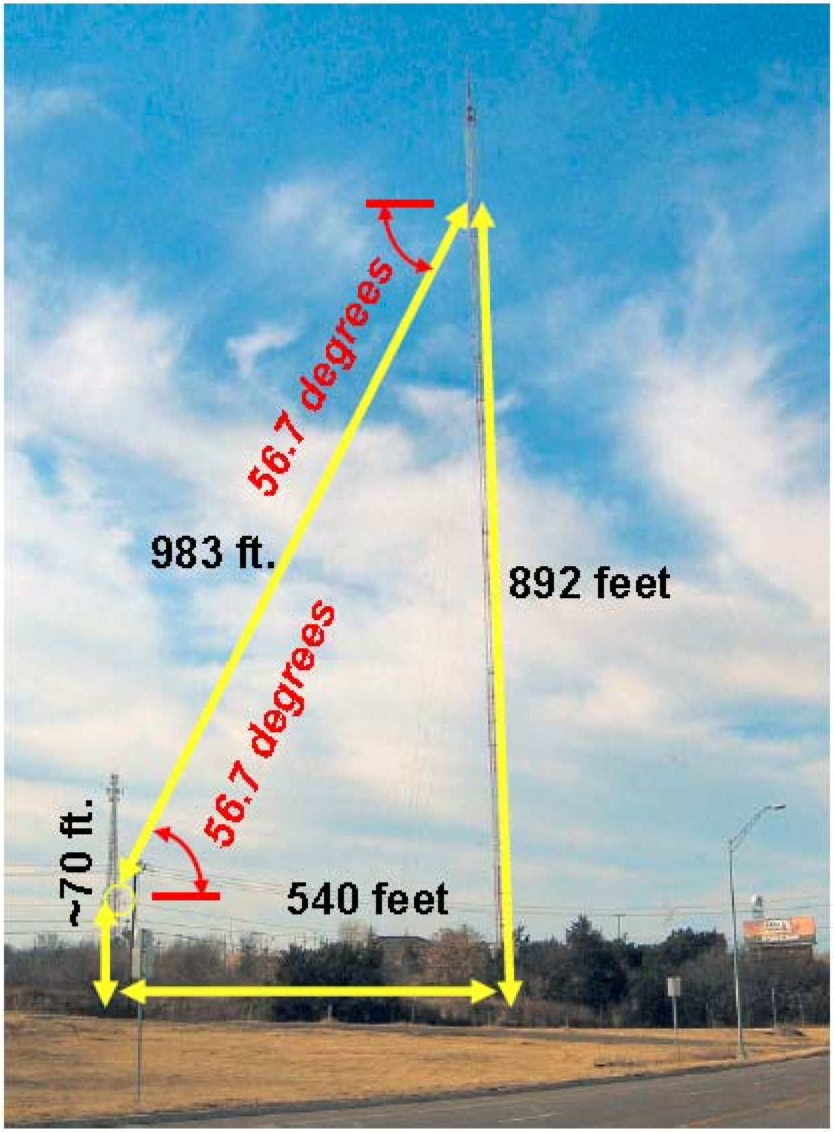


- Since installation of the site several years earlier, US Cellular had noticed significantly degraded uplink performance on its lowest-frequency CDMA carrier, “F1”, only on Alpha (10 degree) sector
- With the growth of traffic on the cellular system, the problem became more objectionable
- An attempt was made to identify the specific interference path to identify and eliminate the source

Spectrum at Cell Receive Antenna Alpha

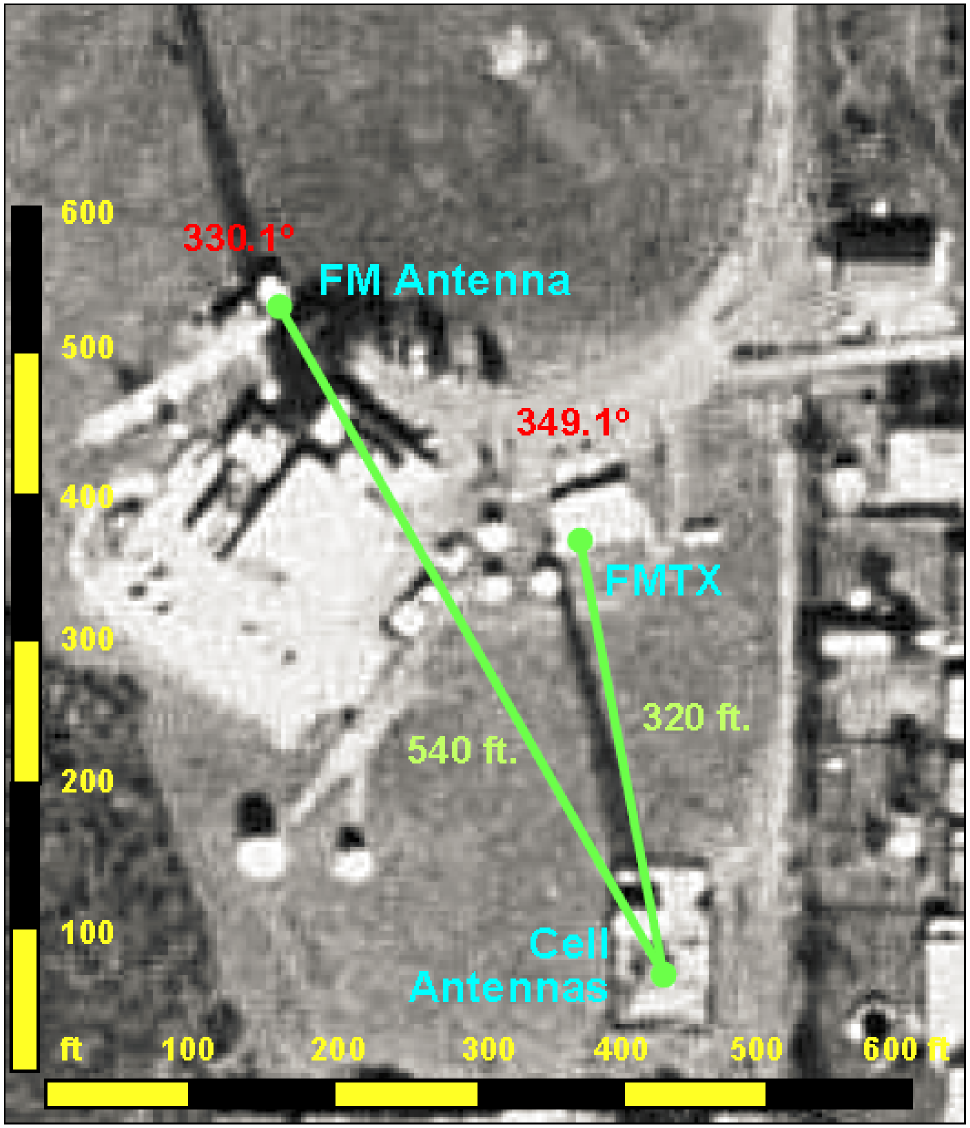


KNIN / US Cellular Ground View



- Path Loss of 983 ft @ 836 MHz
  - 80.4 db (isotropic-isotropic)
- Path Loss 983 ft @ 92.9 MHz
  - 61.3 db (isotropic-isotropic)
- The US Cellular alpha sector main lobe includes both the FM transmitter building and the tower holding the FM antenna

KNIN Site Proximity



- Path loss 320 ft @ 836 MHz
  - 70.7 db (isotropic)
- US Cellular CDMA Azimuths
  - Alpha 10 degrees
  - Beta 130 degrees
  - Gamma 280 degrees

Antenna Identification

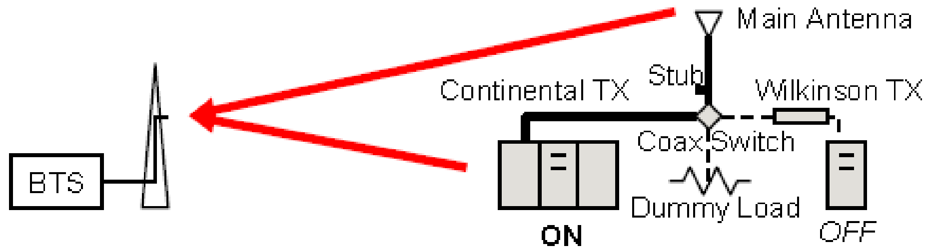
- Top left shows the alpha-sector dual-polarized antenna
- Bottom left shows the FM transmitter building with the US Cellular site behind
  - the alpha sector antenna is highlighted
- At right is the TV6 tower with the FM antenna highlighted. The view is from the US Cellular site

Summary of Investigated Conditions

1

Results

Interference approx. 10 db. above noise floor, equivalent to heavy traffic loading of cell



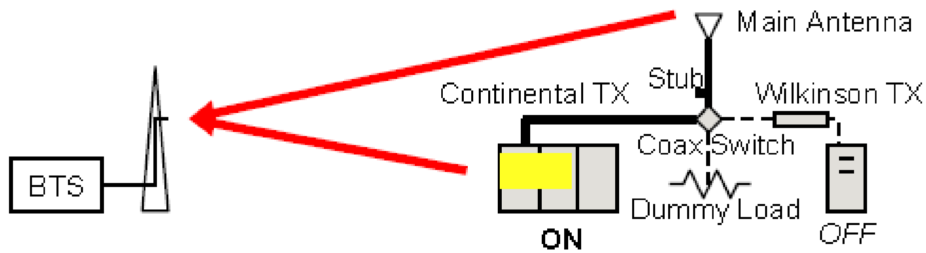
Normal Operation

1. Continental transmitter running into main antenna
2. Wilkinson transmitter off

2

Results

Interference source was not located. Interference continued approx. 10 db. above noise floor



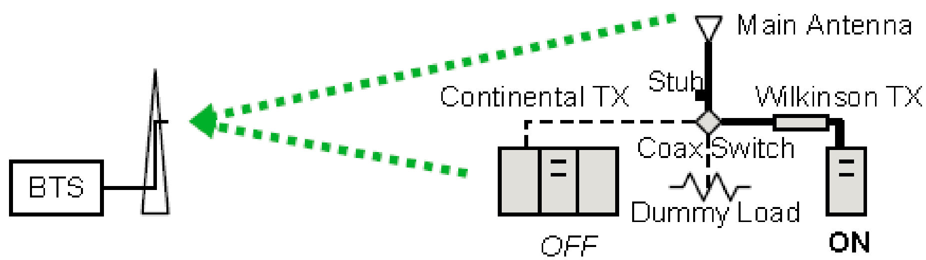
Normal Operation

1. Continental transmitter running into main antenna, with extensive temporary shielding of driver, other modules, seams
3. Wilkinson Transmitter off

3

Results

No interference detectable



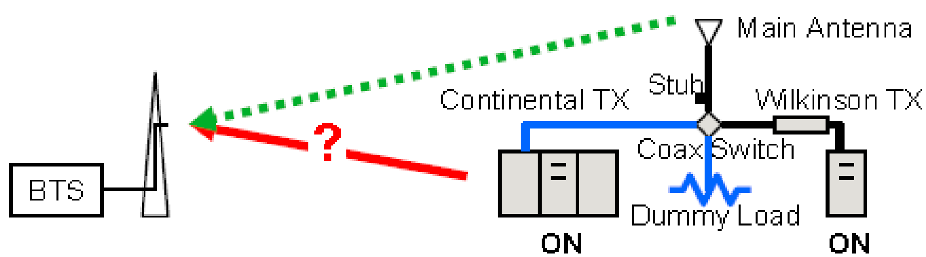
Backup Transmitter

1. Wilkinson Transmitter running into main antenna
2. Continental transmitter **off**

4

Results

Interference was reduced but still detectable.



Backup Transmitter

1. Wilkinson transmitter running into main antenna
2. Continental TX **running** into dummy load

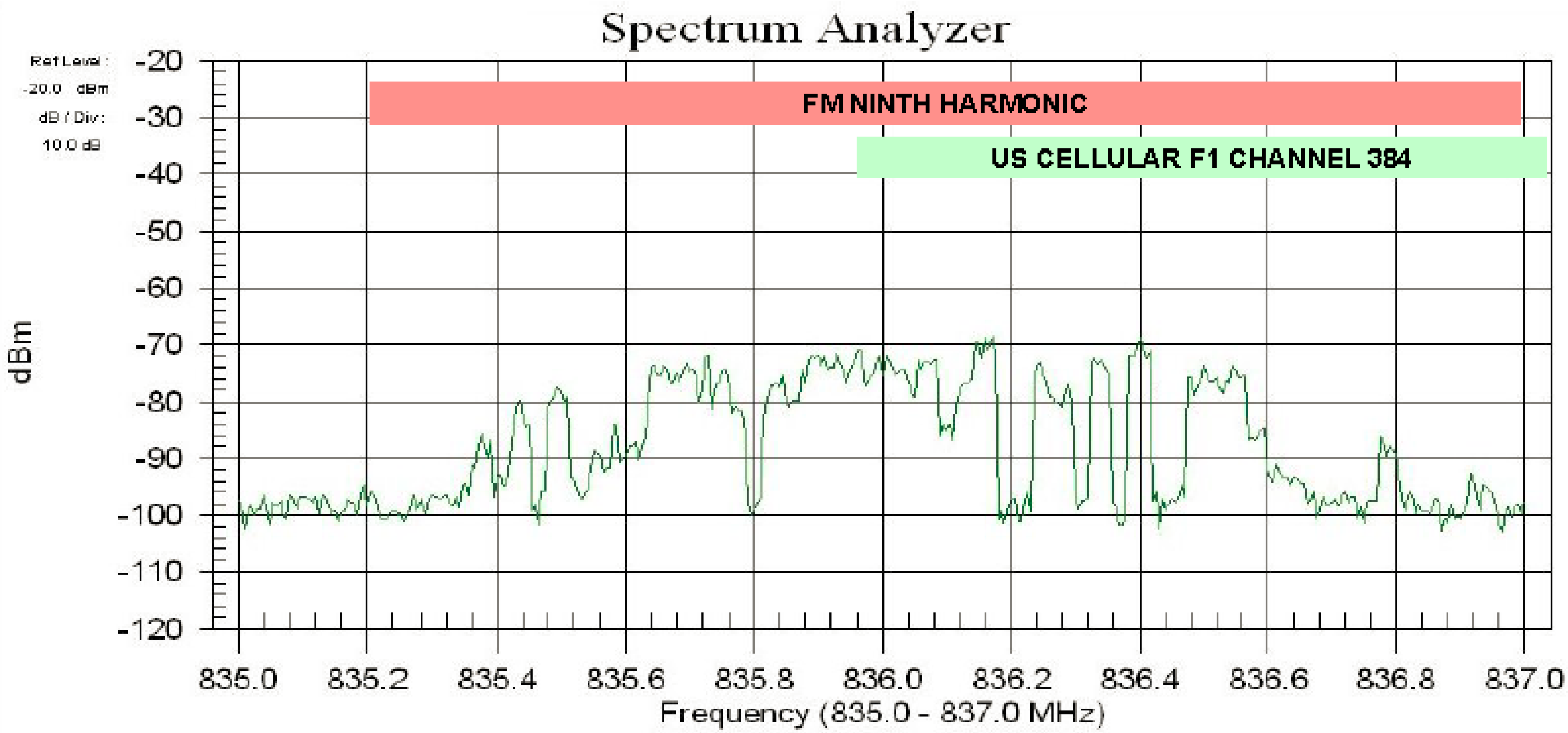
Summary of Interference Conditions

- KNIN used a Continental 816 R3 as its main transmitter, and a Wilkinson auxiliary
- With the Wilkinson operating into the antenna and the Continental off, no interference was noted
- With the Continental operating into the dummy load and the Wilkinson off, moderate interference was still observed
- With the Continental operating into the main antenna and the Wilkinson off, full interference was observed
- Conclusion:
  - The Continental transmitter had serious cabinet leakage and some radiation through the antenna as well

Significant Cabinet Radiation Detected

- The FM harmonic was visible on a spectrum analyzer at the alpha sector receive multicoupler outputs
- At the cell on the ground using a Yagi antenna, the harmonic was too weak to be seen
- Midway between the cell and the FM transmitter building, the harmonic could be seen coming from the building with vertical polarization
  - harmonic radiation from the actual FM antenna overhead was too weak to detect on the yagi antenna
- Harmonic levels were high pointing the YAGI toward unshielded windows of the building, vertically polarized

Spectrum Analyzer Trace:
Yagi In Front of Transmitter Building, VPol



CF: 836.0 MHz
RBW: 3 kHz
Std:
Min Sweep Time: 1.00 Milli Sec
Date: 01/24/2005
Model: MT8212B

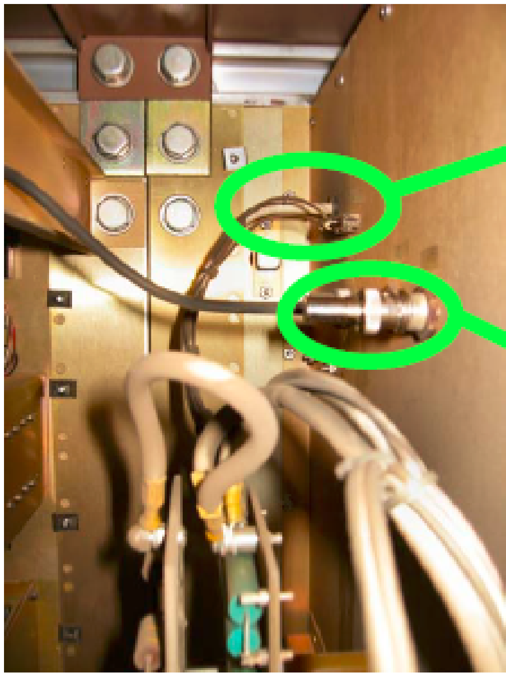
SPAN: 2.00 MHz
VBW: 1 kHz
Channel: 367

Time: 09:46:49
Serial #: 00431107

Attenuation: 11 dB
Detection: Pos. Peak

Cleaning, Repairs, Experiments to reduce Continental Cabinet Radiation

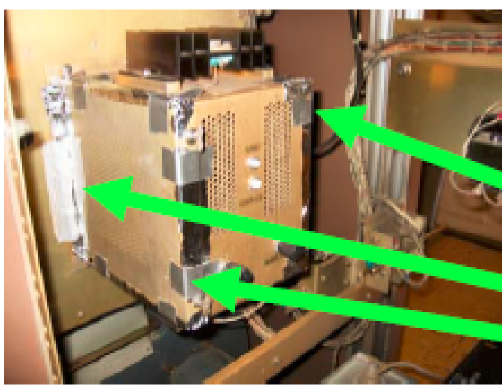
Continental Electronics model 816R3 Transmitter, s/n 369



DC plate supply feed to PA leaves "dead" side of PA cavity with no bypassing. Improvised cellular ¼ wave decoupler shield; no change observed.

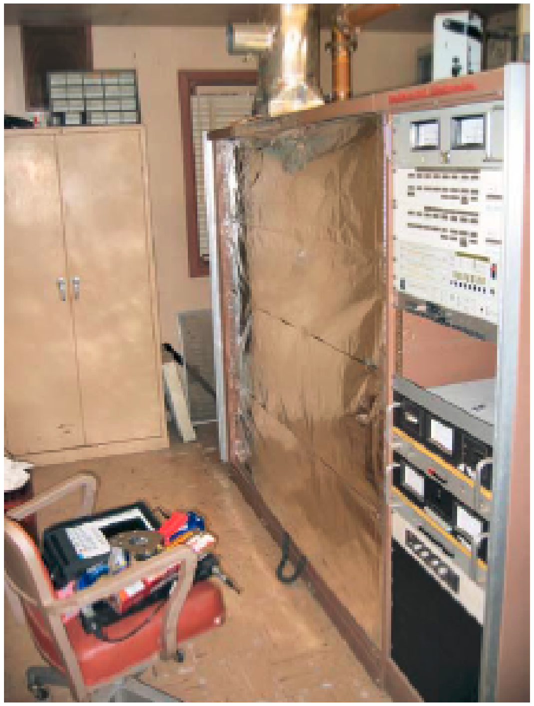
Modulation monitor ports: one was properly terminated, other in use via cable with shield OK/intact.

PA plate and driver cavity door seals were dirty; were carefully cleaned. No difference was observed.



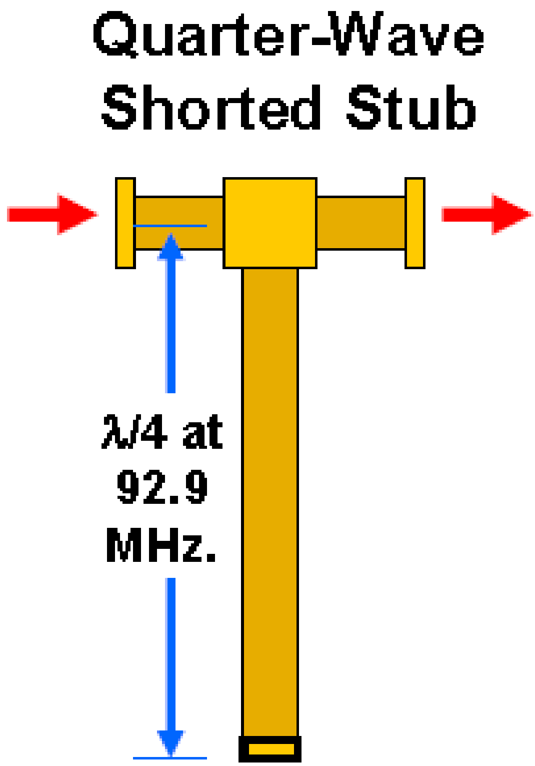
Intermediate Power Amplifier (IPA) chassis seams were taped. No change in cabinet leakage was observed.

Temporary Shielding Experiments on Continental Transmitter



- After localized measurements and individual shielding and testing of suspected transmitter sections failed to disclose the source of the cabined radiation, we attempted to enclose the transmitter completely.
- The front RF panels were completely covered with overlapping foil and the back side door seams were taped over with foil.
  - The PA and exciter cabinet seam was covered with taped foil.
- These measures did not produce a significant difference in the interference observed at the cell Alpha diversity receive antenna.

Previously-Installed Ineffective Stub Filter



- Early in the history of this site, US Cellular purchased a custom quarter-wavelength shorted stub which the FM station allowed to be placed in the antenna feedline just past the transmitter coaxial switch
- A quarter-wavelength stub suppresses even harmonics (2, 4, 6, 8, 10) but does not affect odd harmonics such as the 9^{th}, which is the actual interferer in this case
- The filter types which would reduce the 9^{th} harmonic are
  - low-pass filter
  - “notch” filter
- A suitable low-pass filter has been identified, and requests for quotations have been sent to several sources

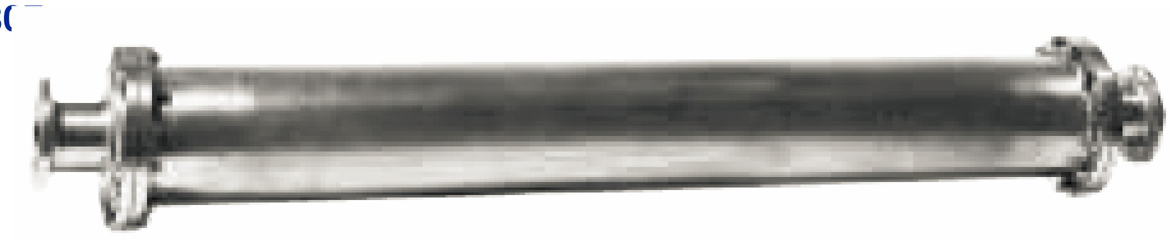
Low-Power Low-Pass Filter (for Exciter)

- Progressive Concepts
  - 125 watt low-pass filter, model LPF7002 with type-N connectors $89.95 [recommended]
  - 305 South Bartlett Road
  - Streamwood, IL 60107
  - 630-736-9822
  - fax 630-736-0353
  - www.progressive-concepts.com

High-Power Low-Pass Filter (for PA)

Filter Manufacturers:

- Andrew Corporation
  - Model CFH314-OFM (20 kW) or CFH315-OFM (40 kW) [recommended]
  - 10500 W. 153rd Street
  - Orland Park, IL 60462
  - 800-255-1479, 708-873-230
  - Fax 800-349-5444
  - www.andrew.com
- MicroCommunications, Inc.
  - PO Box 4365
  - Manchester, NH 03103
  - 800-545-0608, 603-624-4351, fax 603-624-4822
  - Harmonic notch filter model #42144 is $3600.00, delivery 6 weeks ARO
- Dielectric Communications
  - 22 Tower Road
  - PO Box 949
  - Raymond, ME 04071
  - 800-341-9678, 207-655-4555, fax 207-655-7120
  - Harmonic notch filter #C76519, list price $10,800



Screen Room Techniques

- Copper mesh is the most durable material
  - 0.011-dia. 16-per-inch copper mesh
  - available in rolls 36"x, 48", 60", and 72" wide
  - floor, walls, ceiling covered, with 3" overlap at all seams
  - price above $3/sq ft small lots to $1.65/sq ft for 100+ sq ft lots
  - 16' x 10' x 8' room is 736 sq. ft. total; with overlap & small pieces, about 1000 sq. ft. would be needed
- Door Treatment
  - the door is the most critical and difficult problem
  - commercial doors are available in the $2000-$3000 range
- All wires or conduits entering shielded area require one of these:
  - feedthrough capacitors at a bulkhead bonded to the shield
  - custom ferrite inductors and "sleeve" bypassing
  - self-coiling in improvised mesh "plenum" with sleeve bypassing
  - post installation testing is required to confirm effectiveness
- Cost of materials alone for the project exceeds $4000, and assuming shielding is applied to existing room surfaces without requiring new construction or a separate supporting frame

Screen Room Consultants and Contractors

- VitaTech Engineering, LLC
  - Quotation Requested
  - 7405 Alban Station Court, Suite A-105, Springfield, VA 22150
  - (703) 440-9400, FAX: (703) 440-0045
- Braden Shielding Systems (also manufactures doors, materials)
  - Verbal estimate received: ~$30K. Budgetary quote requested
  - 9260 Broken Arrow Expressway, Tulsa, OK 74145
  - 918-624-2888, Fax 918-624-2886, www.bradenshielding.com
- ETS-Lindgren
  - Represented by Charles Ferris, Scientific Systems/Dallas (817) 467-0970
  - Verbal Shielding Estimate ~15K; Budgetary Quotation requested
  - But also has better measurement tools available to locate radiation source; will provide quote for inspection visit to investigate actual source within transmitter, possibly making shielding unnecessary
  - 400 High Grove Blvd., Glendale Heights, IL 60139
  - (630) 307-7200, Fax: (630) 307-7571, info@lindgrenrf.com
- EMC Compliance – Ken Javor
  - kenjavor@emccompliance.com, 256-650-0646 (not a contractor, an information resource)
  - believes less stringent shielding may be successful if combined with additional absorbing material on part of the room surfaces

Screen Room Material Sources

- TWP Inc. (mainly mesh)
  - 2831 Tenth Street
  - Berkeley, CA 94710
  - 800-227-1570, 510-548-4434
  - fax 510-548-3073
  - www.twpinc.com
- RA Mayes Co. (doors, foil, mesh, assembled screen rooms, etc)
  - 10064 Deerfield Rd.
  - Franktown, CO. 80116-8808
  - 800-742-9447 303-761-9447
  - fax 303-761-5067
  - www.ramayes.com
- Braden Shielding Systems (doors, other materials)
  - 9260 Broken Arrow Expressway
  - Tulsa, OK 74145
  - 918-624-2888
  - Fax 918-624-2886
  - www.bradenshielding.com