SFNs for HD Radio

Synchronizing the IBOC Signal

Design, Implementation and Field Trials

WBA Engineering Sessions
11 October 2017

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Making Digital Broadcasting Work.

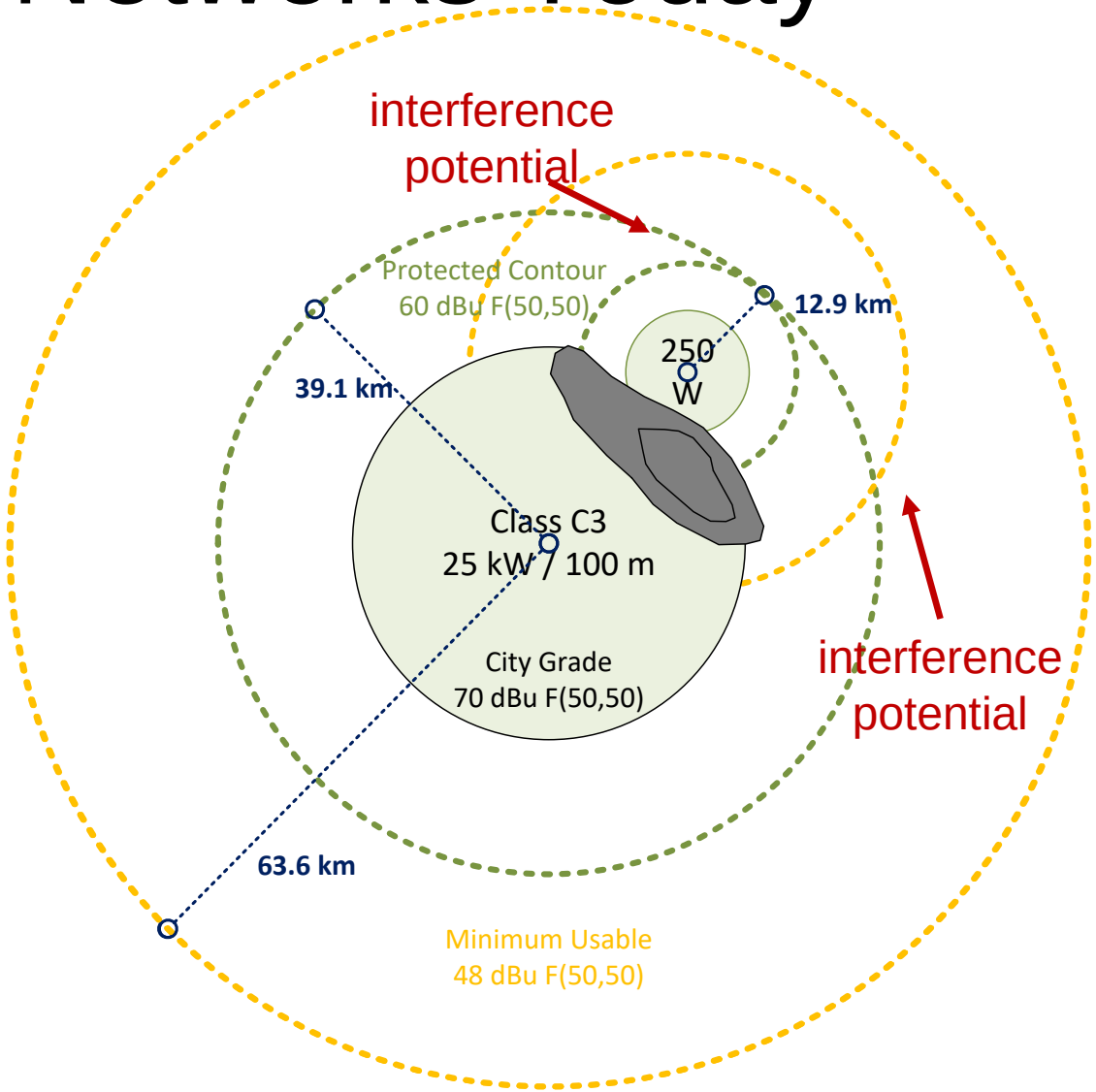
Presentation Overview

1. Single Frequency Networks Today
2. Application Areas
3. Establishing SFN Planning Parameters
4. Matching D/U Signal Ratios to Signal Delay
5. Nautel SFN Implementation
6. Field Trial: KUSC, Los Angeles

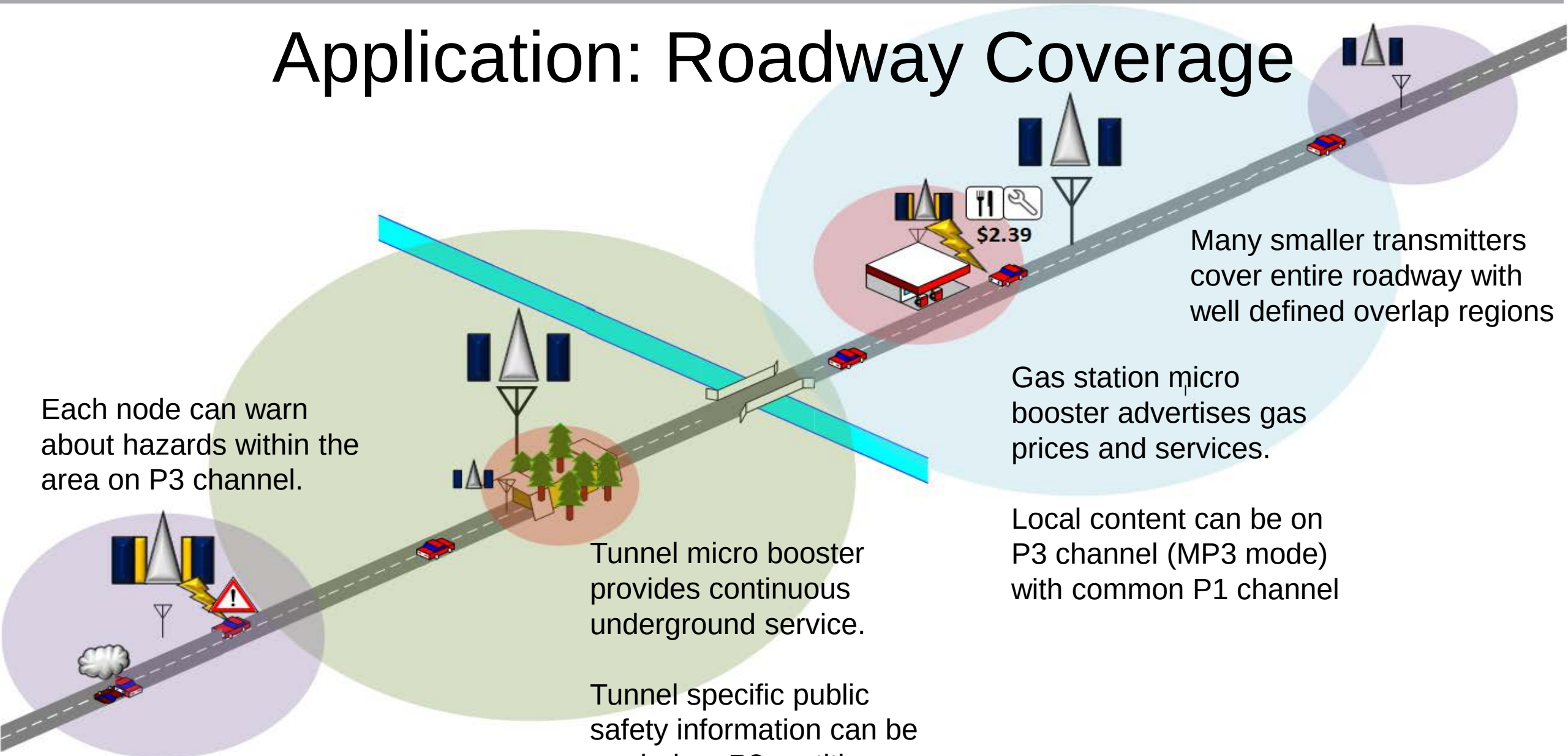
FM Single Frequency Networks Today

- **FM Booster stations** are **"fill-in" translator stations** on the **same** frequency as the main station.
  - Booster contour may not exceed the protected F(50,50) service contour of the primary station.
  - Boosters maximum ERP is 20% of primary station's class
  - FM booster call signs incorporate the call sign of the main station with the suffix -FM (booster number) added
    - A primary FM station may have more than one booster.
  - Increase city grade coverage with better building penetration
  - Booster stations may not cause interference to reception of the primary station's signal within the community of license

https://www.fcc.gov/media/radio/fm-translators-and-boosters



Application: Roadway Coverage



Many smaller transmitters cover entire roadway with well defined overlap regions

Gas station micro booster advertises gas prices and services.

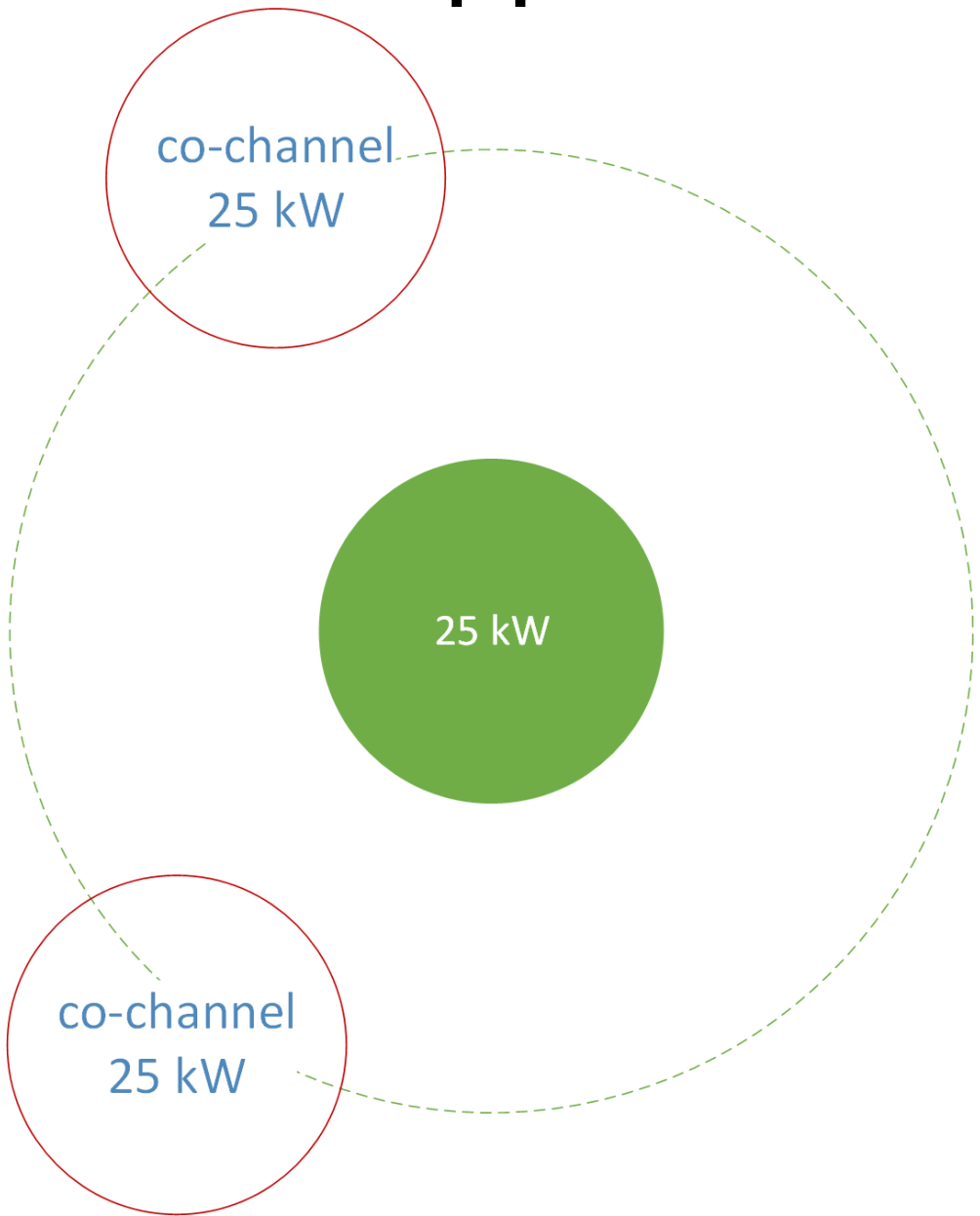
Local content can be on P3 channel (MP3 mode) with common P1 channel

Each node can warn about hazards within the area on P3 channel.

Tunnel micro booster provides continuous underground service.

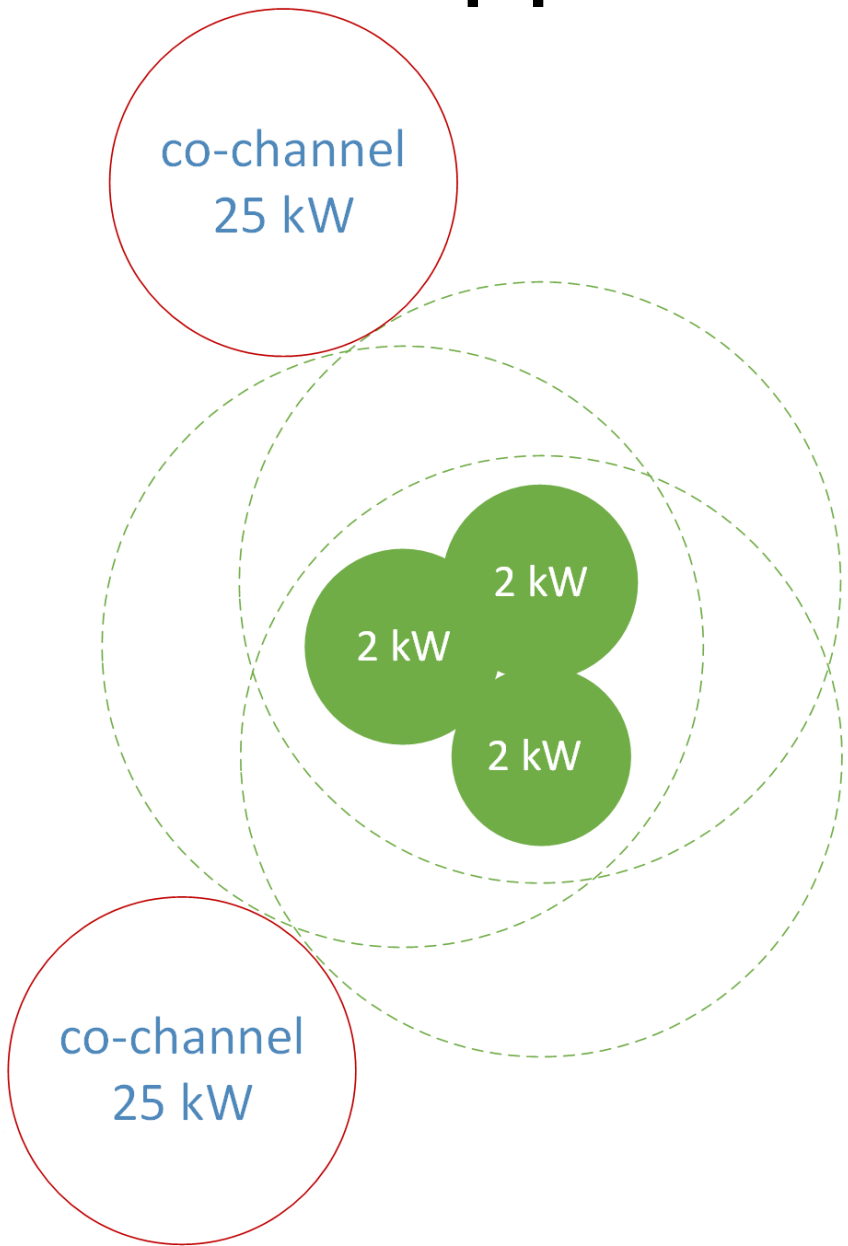
Tunnel specific public safety information can be carried on P3 partitions

Application: The FM Band is Full



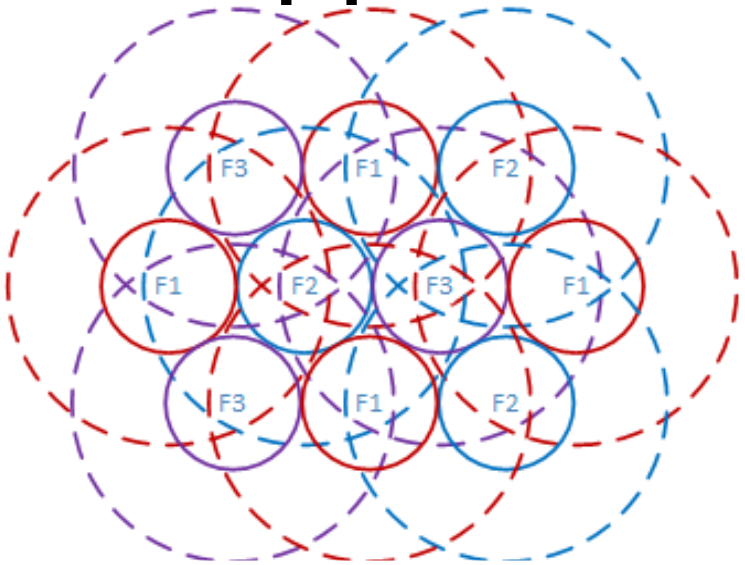
- Difficult to find white space for high power stations due to large F(50,10) interfering contour
- Also consider 1st and 2nd adjacent channel protection
- Directional Antenna patterns can only help so much
- Difficult to find translator frequencies

Application: The FM Band is Full



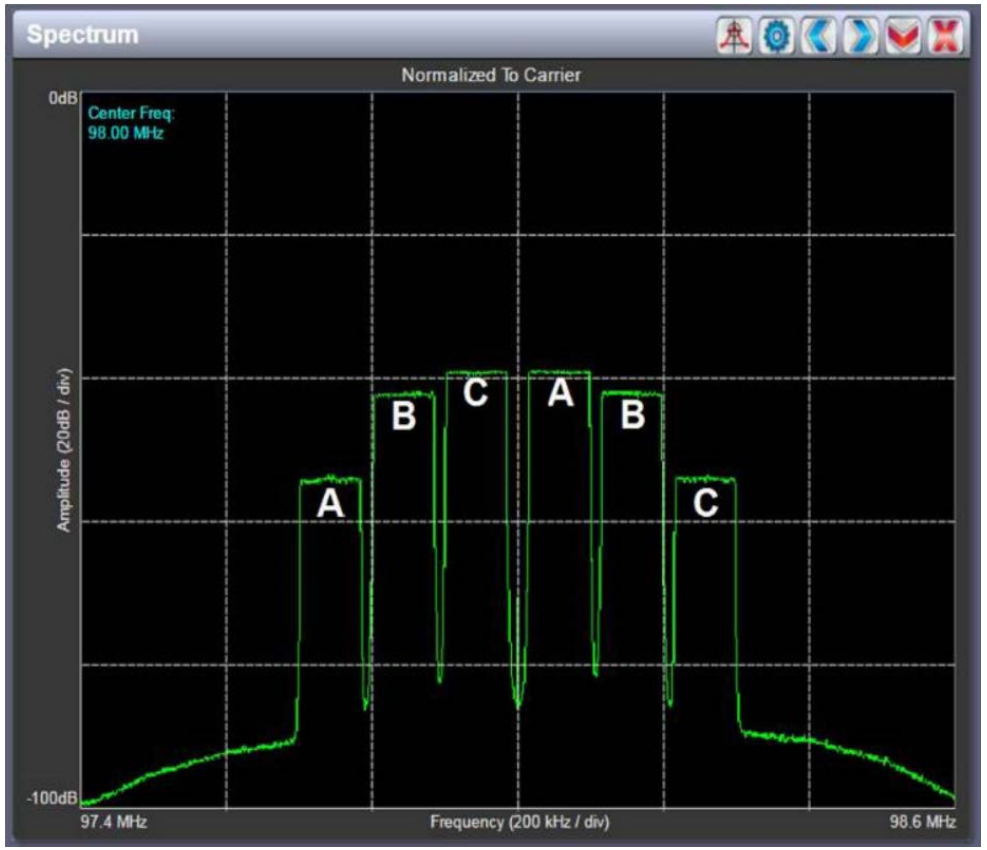
- Lower power transmitters reduce interfering contour
- Transmission power savings
- We can now create new “equivalent” full power stations for the community of license.
  - fringe listening will be reduced
- Future station expansion possibilities
- We must minimize SFN interference through synchronization and planning.

Application: Wide Area Coverage



- Public broadcasters with a mandate for national, state–wide, or wide area coverage
  - mandated to reach majority of population
- Translator network requires at least 3 channel allocations – more in difficult terrain
- Also consider adjacent channels
- SFN is spectrum efficient

Application: All Digital IBOC

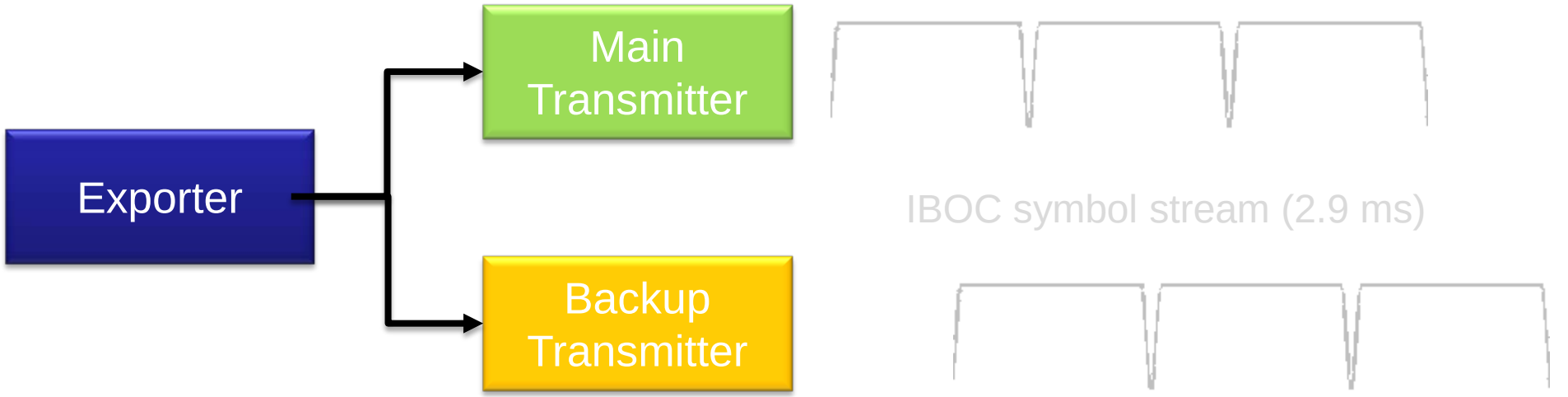


- Hybrid HD radio will remain limited by the FM carrier
- All Digital IBOC is ideally suited for SFN operation
- HD Multiplex combines multiple IBOC signals without the FM carrier
  - 380 kbps, 9-15 audio services
- HD Multiplex SFNs provide an **in-band DAB alternative** using standard HD Radio receivers
  - Stations A,B, or C are optional in SFN

Application: Backup Transmitter/Exciter

Today exgine modulators are not time synchronized.

Variances typically vary from 100μs to 10ms.

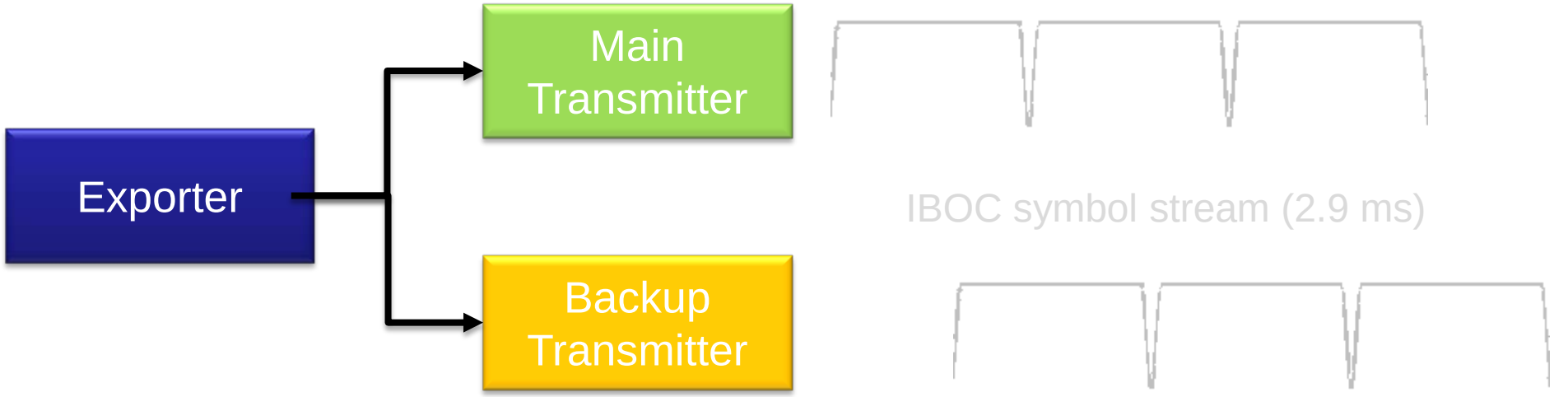


Receiver becomes confused having locked to the first IBOC symbol. Some receivers may lose HD lock for minutes until tuned off channel. Diversity delay has changed.

Application: Backup Transmitter/Exciter

IBOC modulation must be identical.

IBOC symbols must be aligned across main and backup.



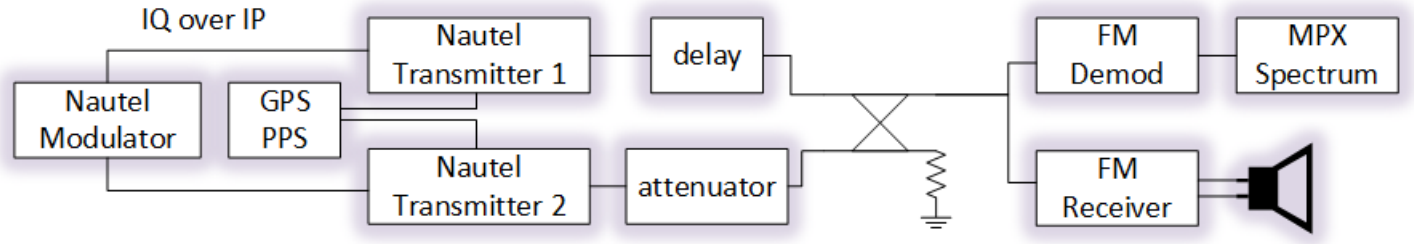
Receiver maintains HD lock. Diversity delay is maintained.

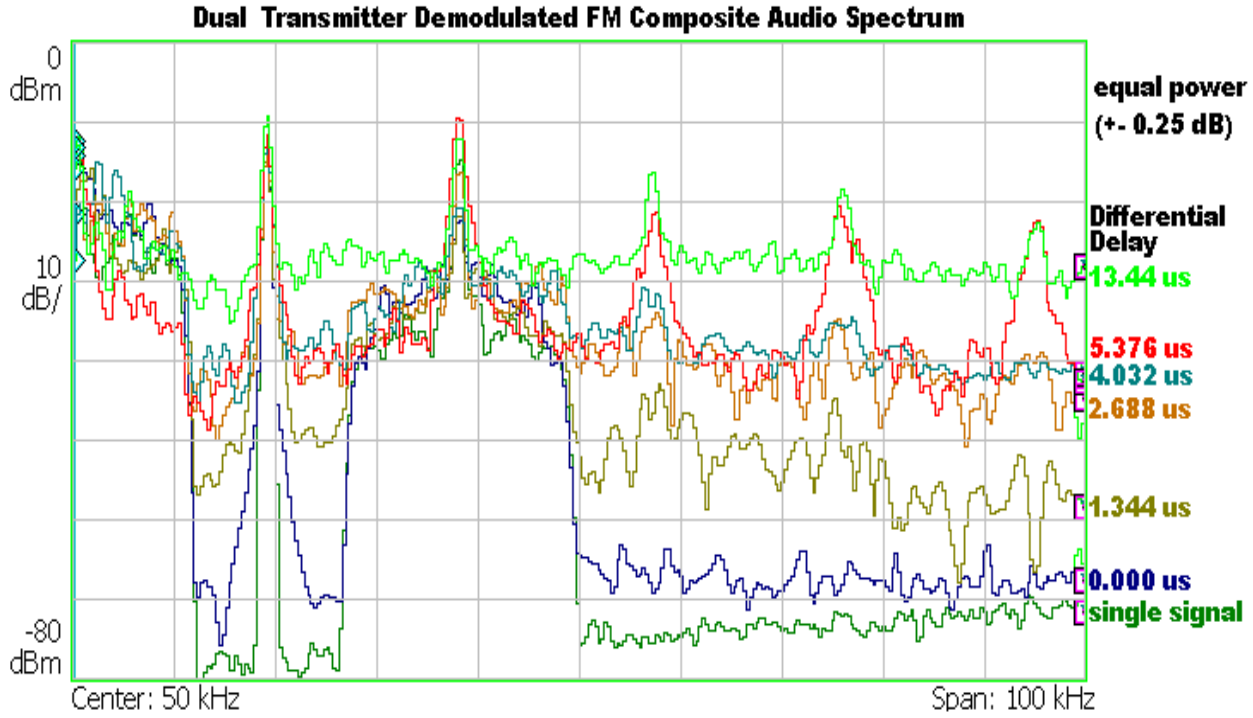
(see Nautel demonstration)

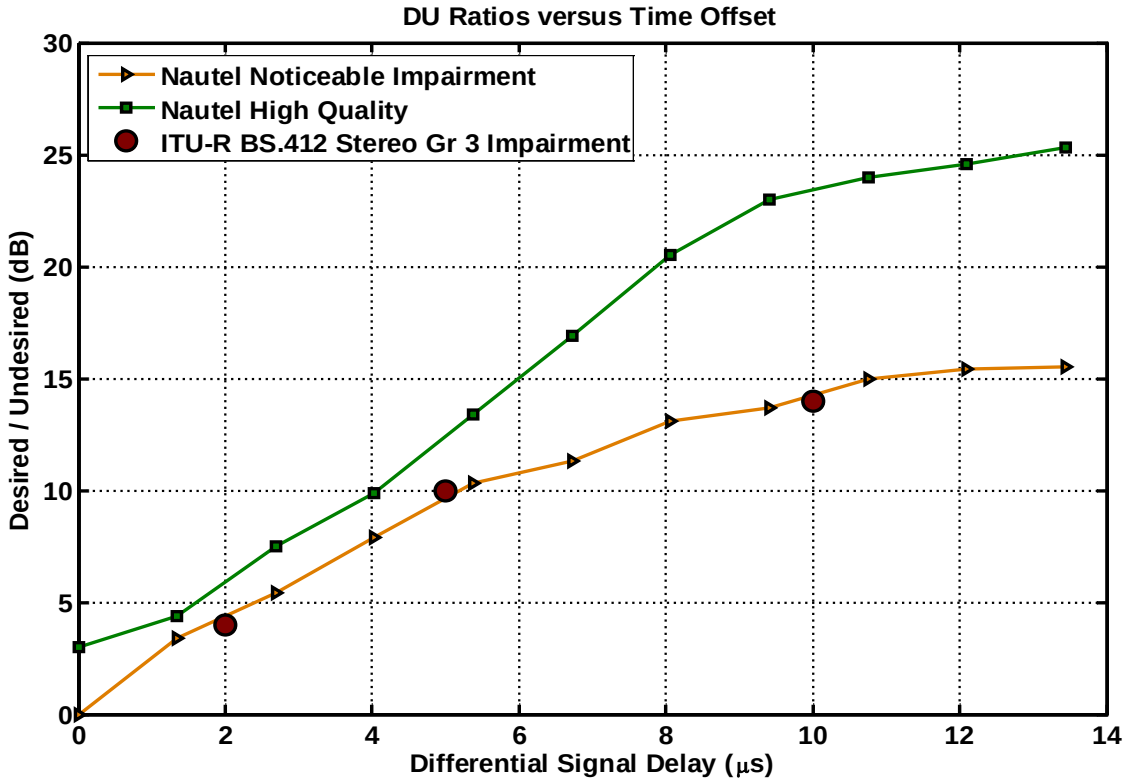
Establishing SFN Parameters

1. What are the required Desired vs Undesired (D/U) ratios?
2. What are the required timing parameters?

Nautel FM Stereo SFN Lab Tests







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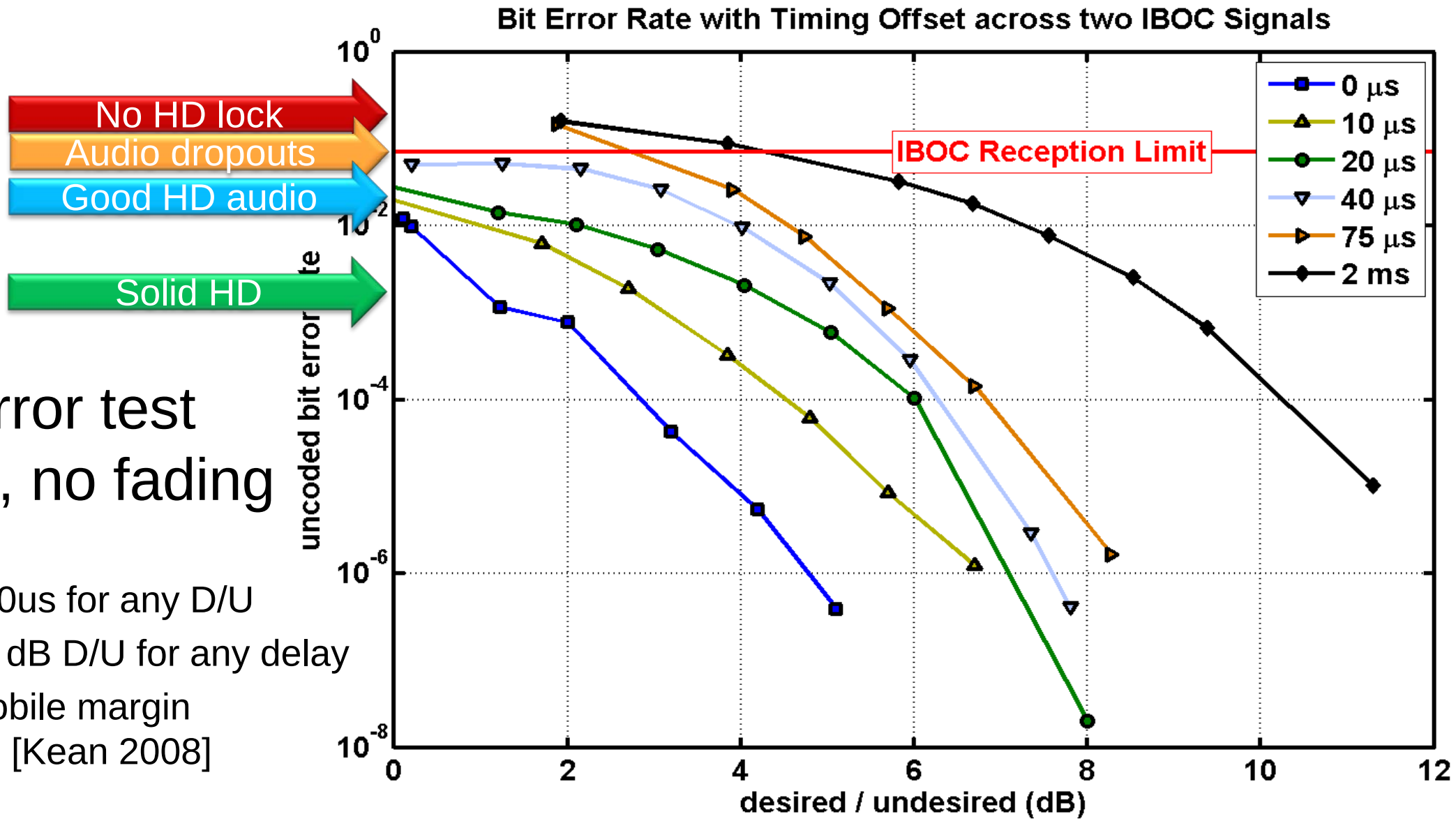
Nautel IBOC SFN Lab Tests



Raw bit error test prior FEC, no fading

- MP1 mode
- HD lock at 40us for any D/U
- HD lock at 4 dB D/U for any delay
- Add 3 dB mobile margin

[Kean 2008]

Solving for Constant Delay Lines

$d1 = vct$ $\quad d12 = (c + x)^2 + y^2$

$d2 = vc(t - \Delta t)$ $\quad d2^2 = (c - x)^2 + y^2$

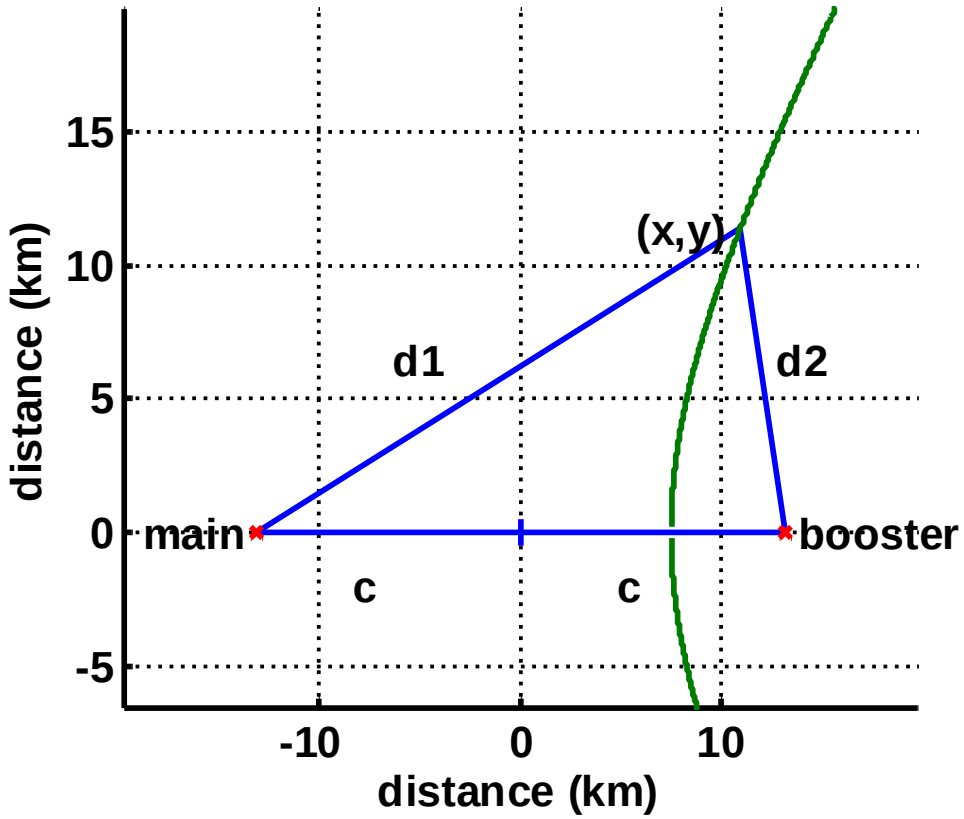
v_c	speed of light
Δt	configurable booster time offset

Solve for x and y:

$$x(t) = \frac{d1^2 - d2^2}{4c} \qquad y(t) = \pm\sqrt{d12 - (x + c)^2}$$

$$\forall\, t > \frac{2c}{v_c} - \Delta t$$

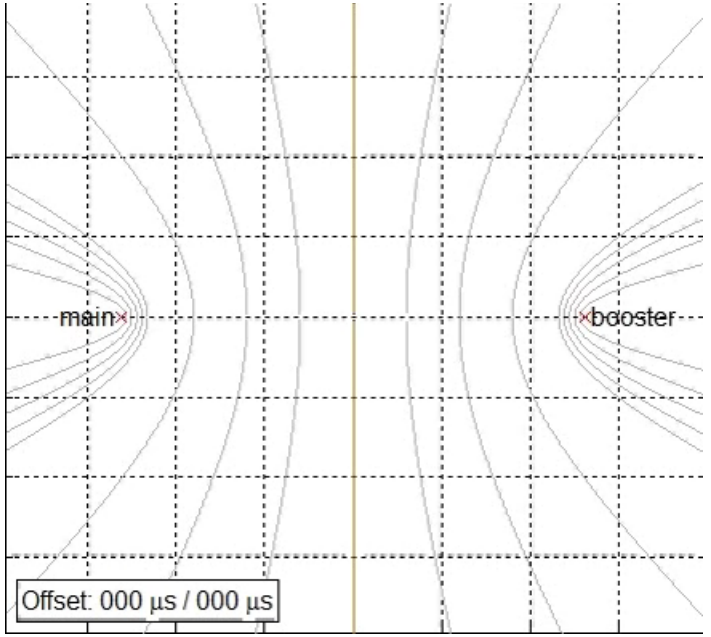
50us booster delay:



Time Sync: Synchronized Transmission

Step 1

Achieve modulation and time synchronization

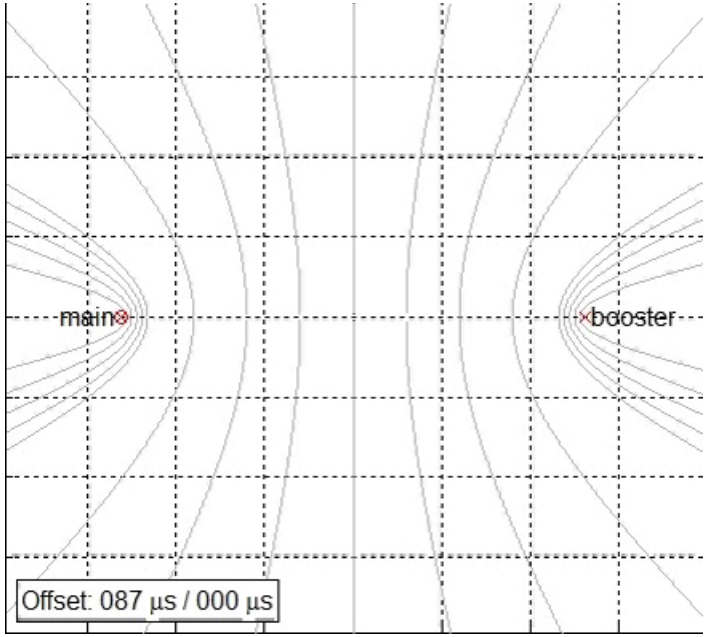


Time Sync: Zeroed Delay

Step 2

Calibrate out delay primary to booster delay

26.2 km or 87.3µs

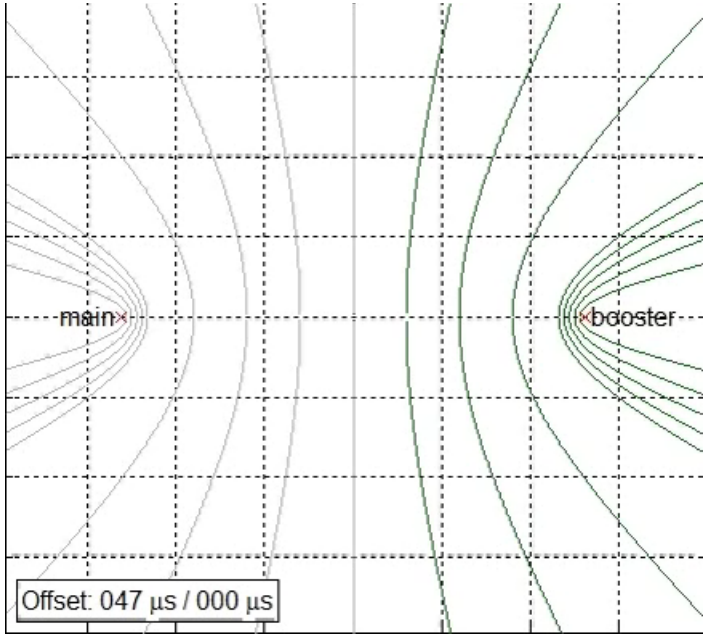


Time Sync: Advance Transmission

Step 3

Advance transmission
by desired offset (40µs)

87.3µs - 40µs = 47.3µs



Matching D/U Signal Ratios to Signal Delay

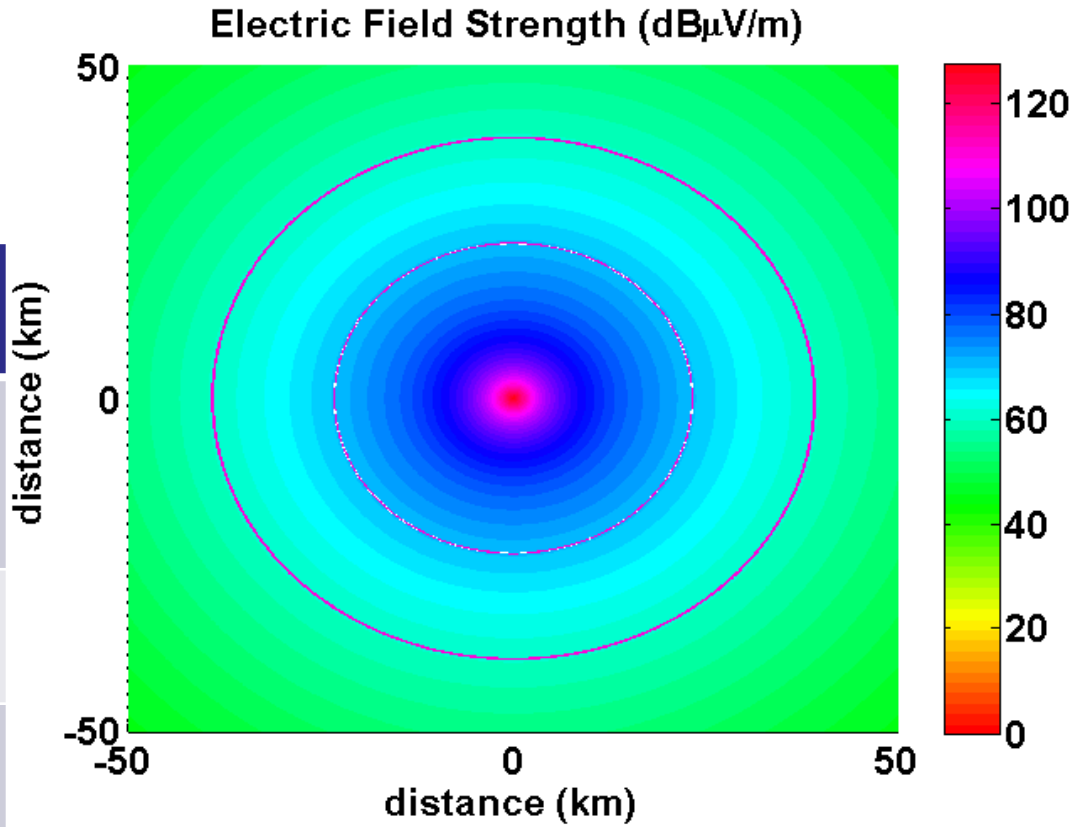
Simulation: Matching D/U to Delay

FCC F(50,50) curves for 25 kW, 100 m

- Omnidirectional antenna pattern
- Shown with **60 dBu and 70 dBu contour**

Worst case flat world – no terrain shielding

Mode	Desired / Undesired	Time Margin	Condition
FM Stereo	14 dB	10 µs	ITU-R BS.412-9 Grade 3 audio impairment Nautel FM impairment tests
FM Mono	3 dB	10 µs	ITU-R BS.412-9 Grade 4 audio impairment
IBOC	7 dB	40 µs	Potential loss of HD lock, Nautel IBOC bit error tests with 3 dB added fading margin (MP1/MP3)



Stereo FM Synchronization

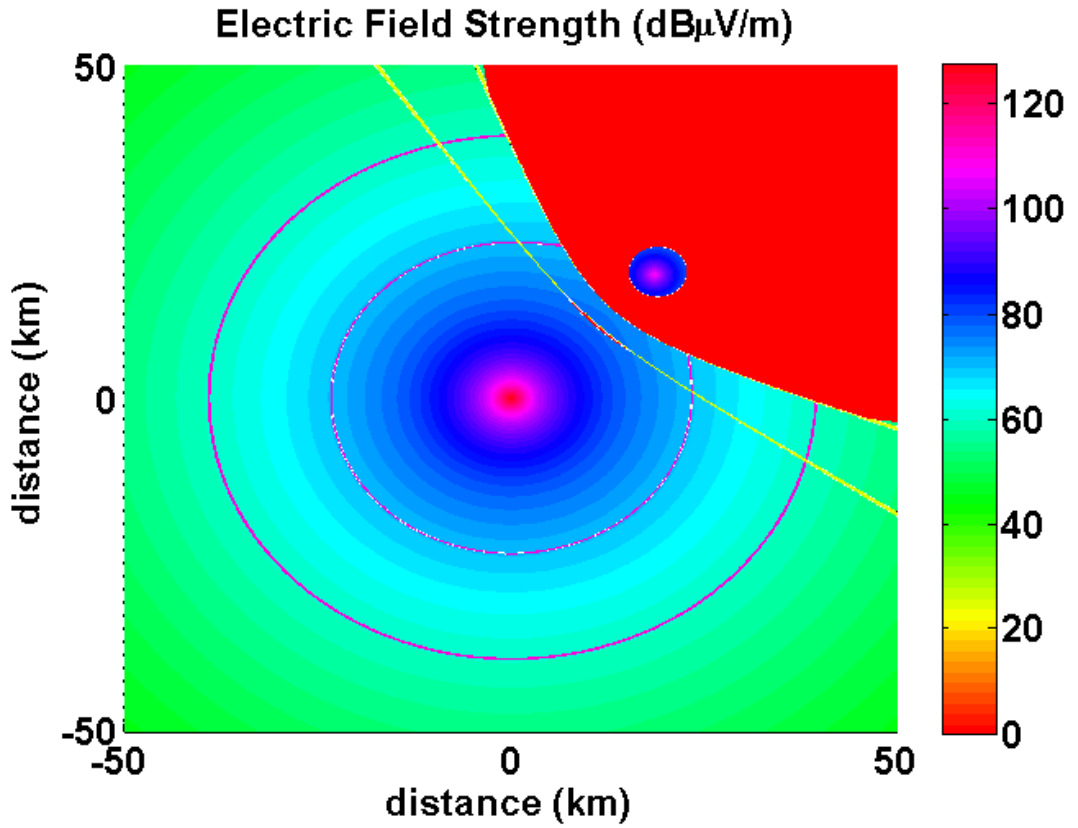
25 kW Class C3 and 250W Booster
- Shown with **60 dBu and 70 dBu contour**

26.2 km or 87.3 µs separation

Large **interference** potential (**14 dB D/U**)
- Booster not reaching city grade contour
- **Terrain shielding is a must !!!**

60 µs booster time advance
- Booster delay 87.3 µs – 60 µs = 27.3 µs
- Meets primary wave 30 µs or 9 km out

10 µs timing margin provides small buffer
- 14 dB D/U change over 3 km is not possible
- No seamless coverage



Mono FM Synchronization

Smaller **interference** potential (**3 dB D/U**)

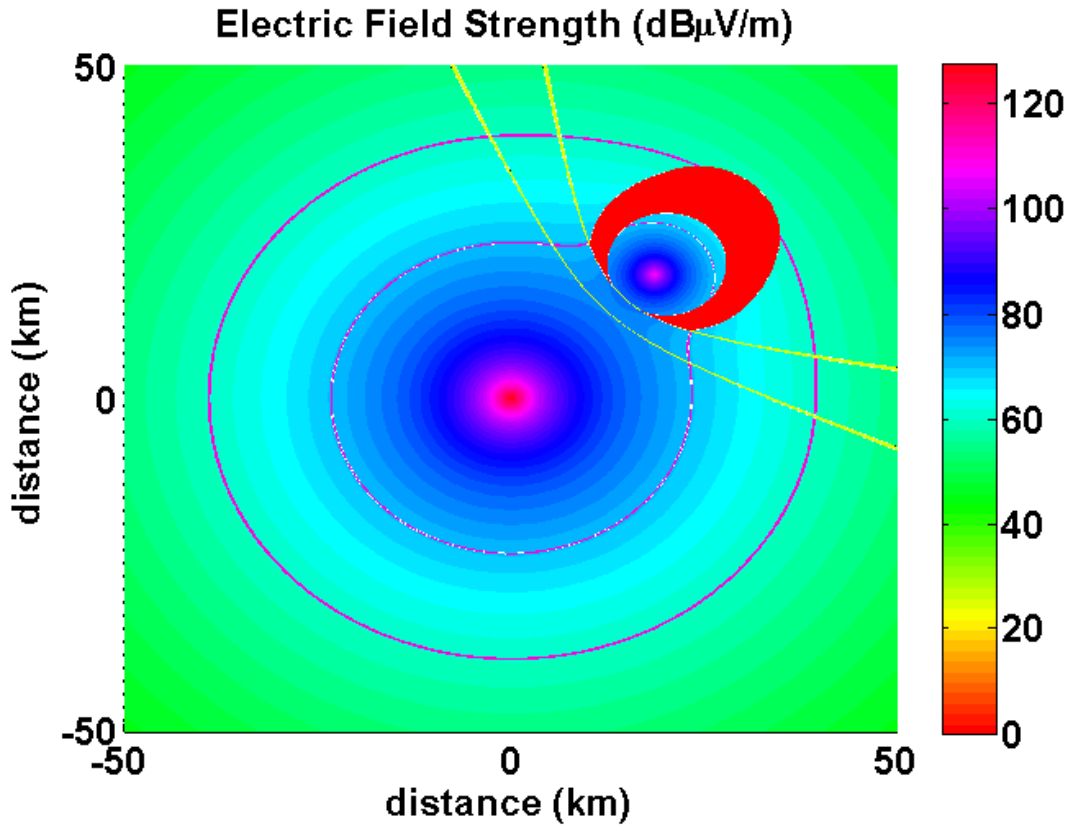
- Booster exceeds **city grade contour**

45 µs booster time advance

- Booster delay 87.3 µs – 45 µs = 42.3 µs
- Meets primary wave 22.5 µs or 6.7 km out

10 µs timing margin provides small buffer

- 3 dB D/U change over 3 km can be possible
- Limited seamless coverage is possible
- Time advance could be decreased to curve the timing margin for a better match



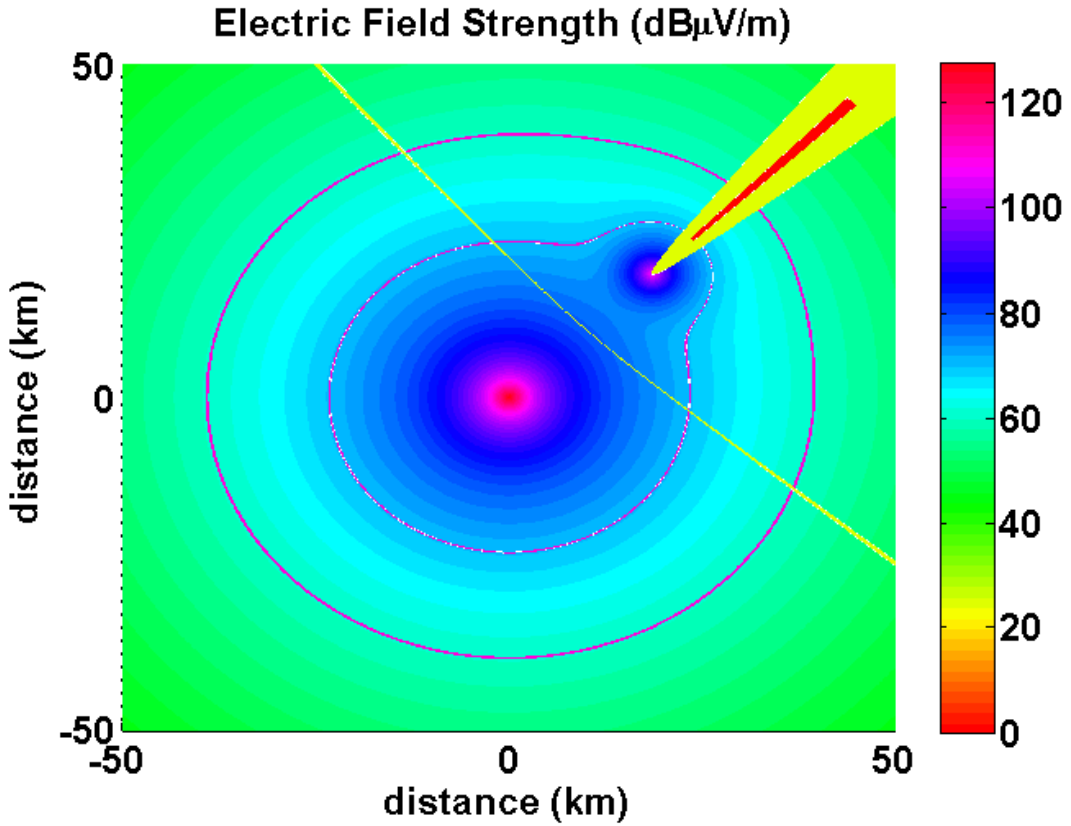
IBOC Synchronization

Hybrid FM+IBOC System
- Primary 2.5 kW IBOC at -10 dBc injection
- Booster 25 W IBOC at -10 dBc injection

Minimal **interference** potential (7 dB D/U)
- Booster increases **city grade contour**
- Little impact on combined **60 dBu contour**

40 µs booster time advance
- Booster delay 87.3 µs – 40 µs = 47.3 µs
- Meets primary wave 20 µs or 6 km out

40 µs timing margin provides large buffer
- Seamless coverage is possible



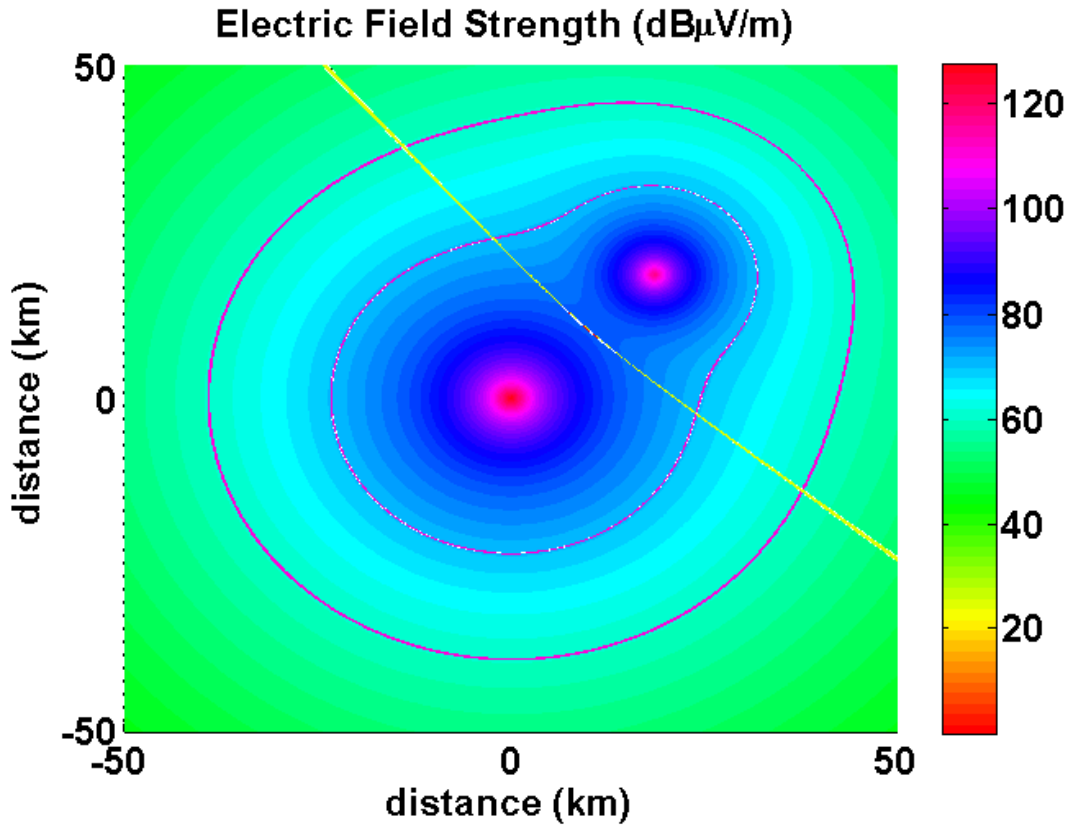
Elevated IBOC Power Levels

Hybrid FM+IBOC System
- Primary 2.5 kW IBOC at -10 dBc injection
- Booster **250 W IBOC at 0 dBc** injection

No **interference** (7 dB D/U)
- Booster increases **city grade contour**
- Big increase in combined **60 dBu contour**

39 µs booster time advance
- Eliminates back end interference entirely
- Booster delay 87.3 µs – 40 µs = 47.3 µs
- Meets primary wave 20 µs or 6 km out

40 µs timing margin provides large buffer
- Extended seamless coverage is possible



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Booster Elevated IBOC Power Levels

Increase IBOC to 0dBc injection? **Yes**

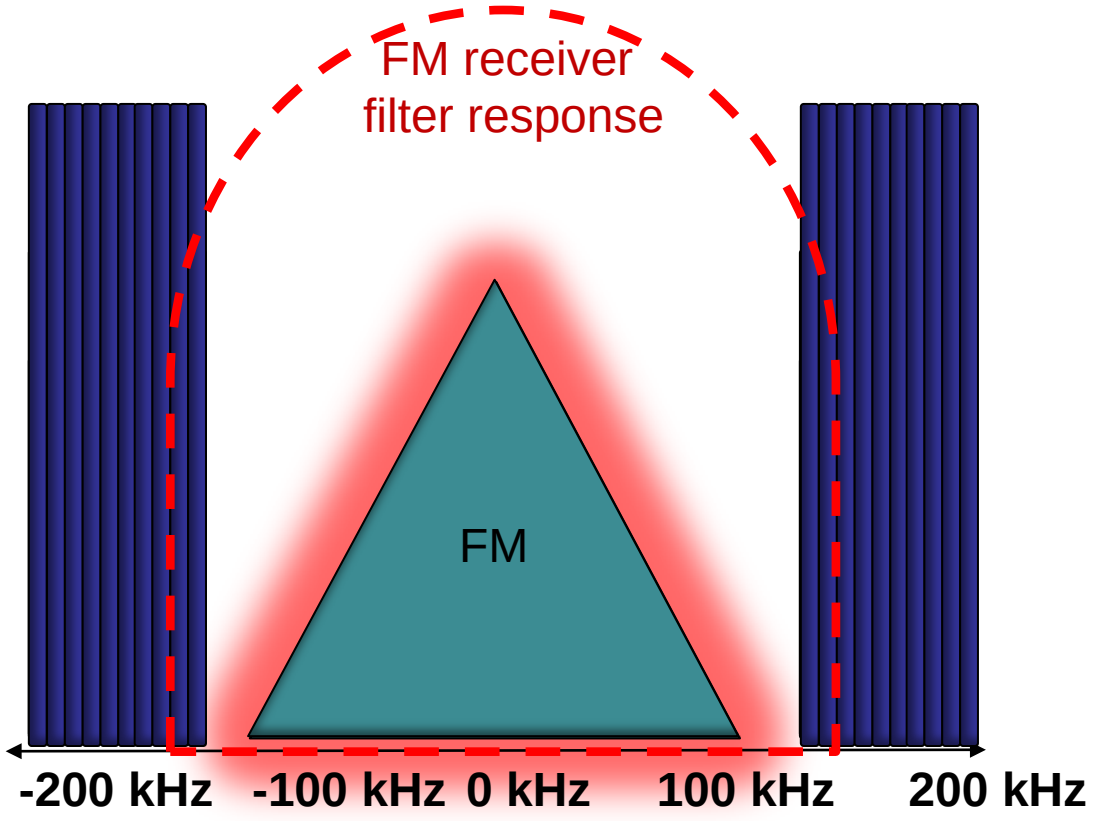
- Smaller FM interference region
- Large IBOC coverage
- Place booster closer to protected contour
- Tests conducted at WD2XAB Baltimore

Increase IBOC higher? **Caution**

- Risk to drown out FM receivers close by
- FM receiver selectivity captures IBOC
  - 20 dB bandwidth ~260-500 kHz

IBOC only boosters? **No for hybrid FM+HD**

- Future application in all-digital operation

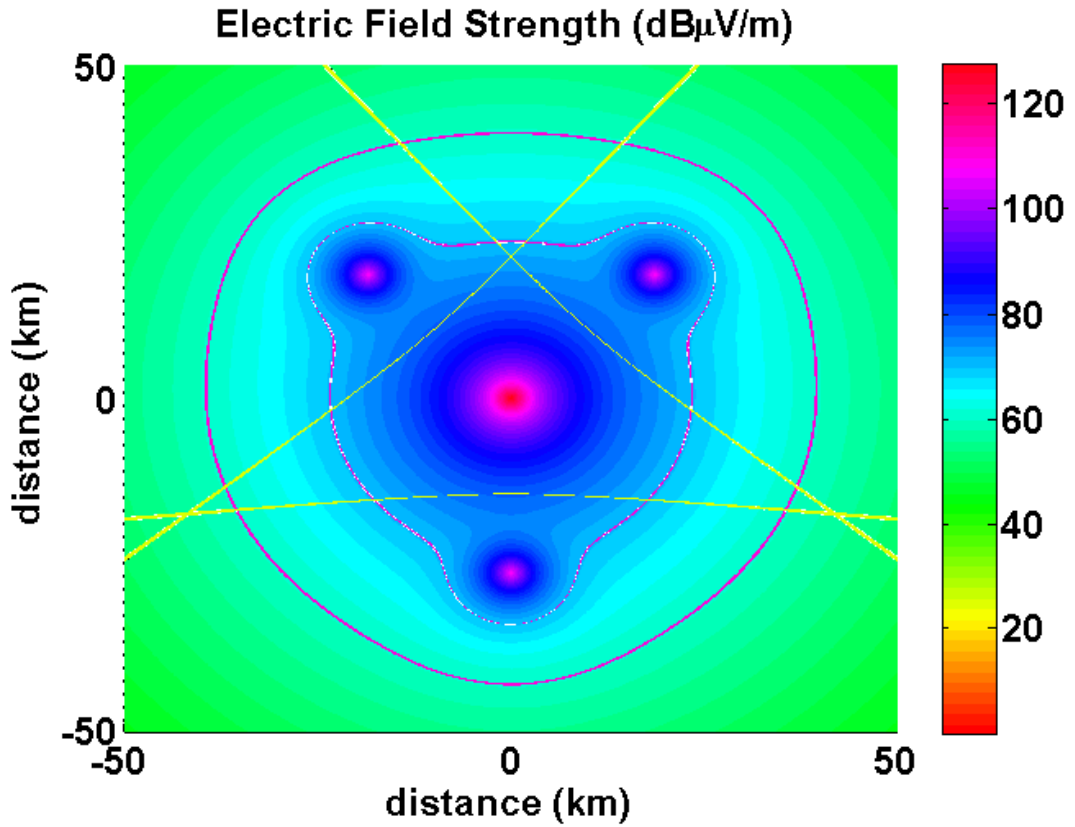


Expanding Your IBOC Coverage

Hybrid FM+IBOC System
- Primary 2.5 kW IBOC at -10 dBc injection
- 3 Boosters at 25 W IBOC at -10 dBc injection

No IBOC **interference** expected
- Big increase in **city grade contour**
- Some increase in combined **60 dBu contour**

39 µs booster time advance
- Booster to booster interference not shown
- Extended seamless coverage beyond station protected contour
- Perhaps reduce primary IBOC injection and save transmission power



In theory this is legal today !!!

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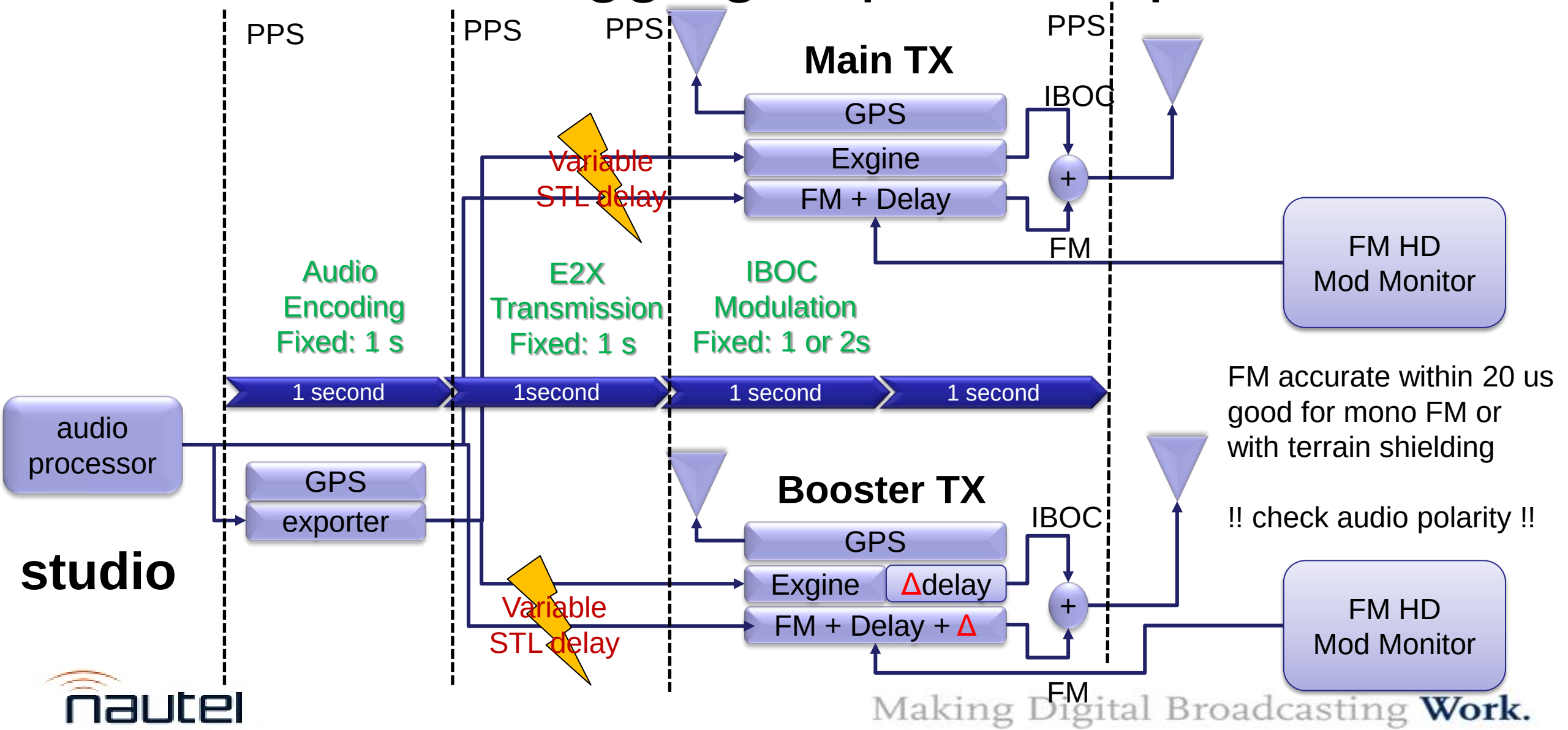
Nautel SFN Implementation

Time Tagging: Input→Output



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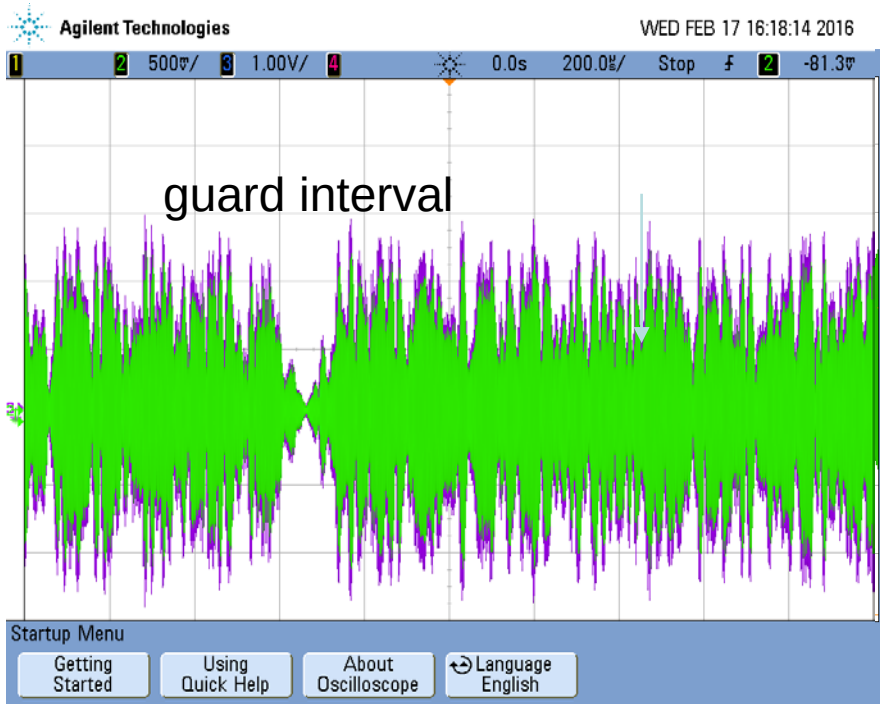
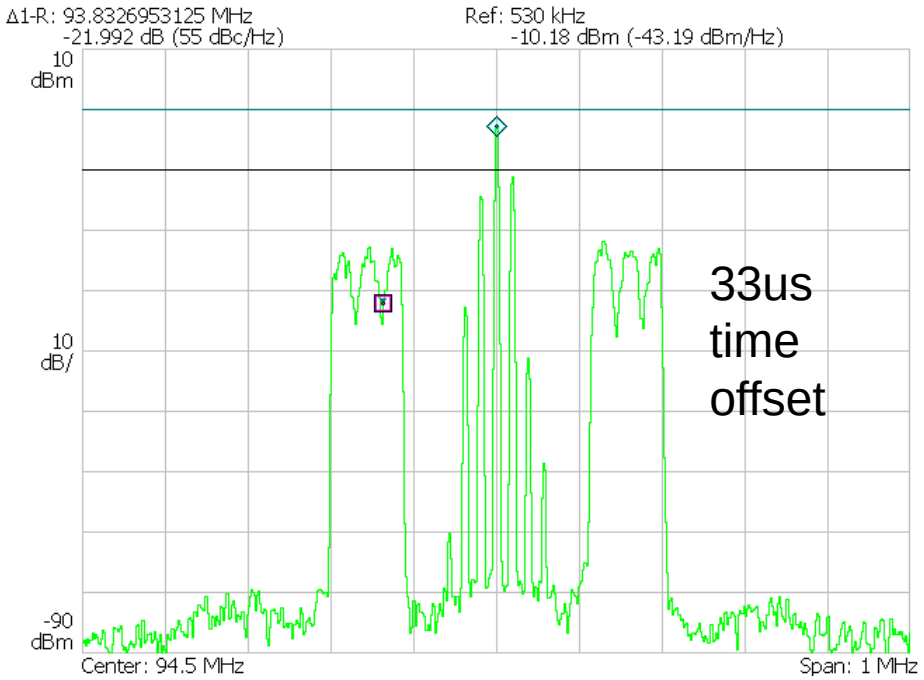
Lab Results: Digital Startup





Startup Delay: better than ± 2µs (0 samples)

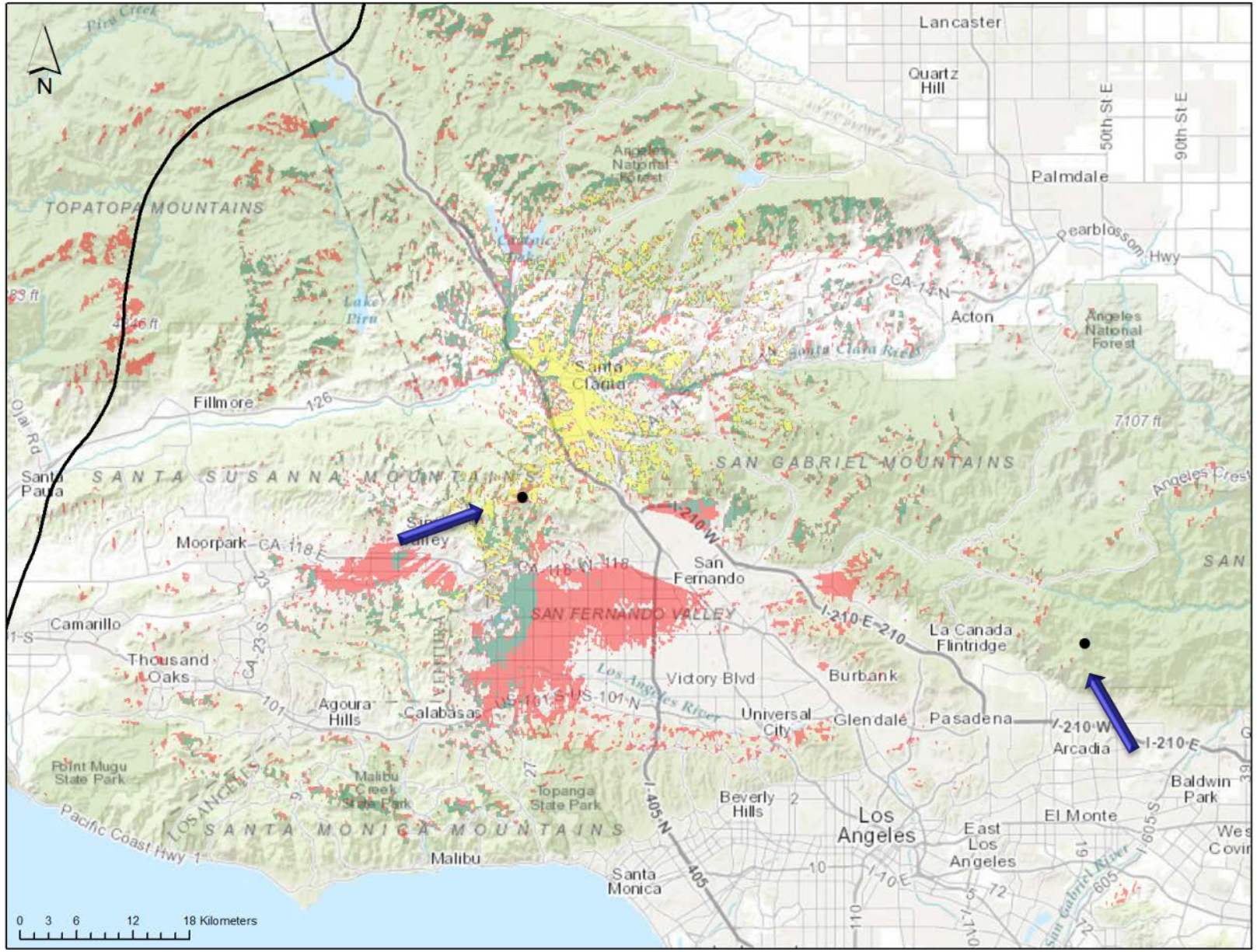
Improved Digital Diversity Delay Stability

(unsync'ed typical ±400 µs to 3 ms)

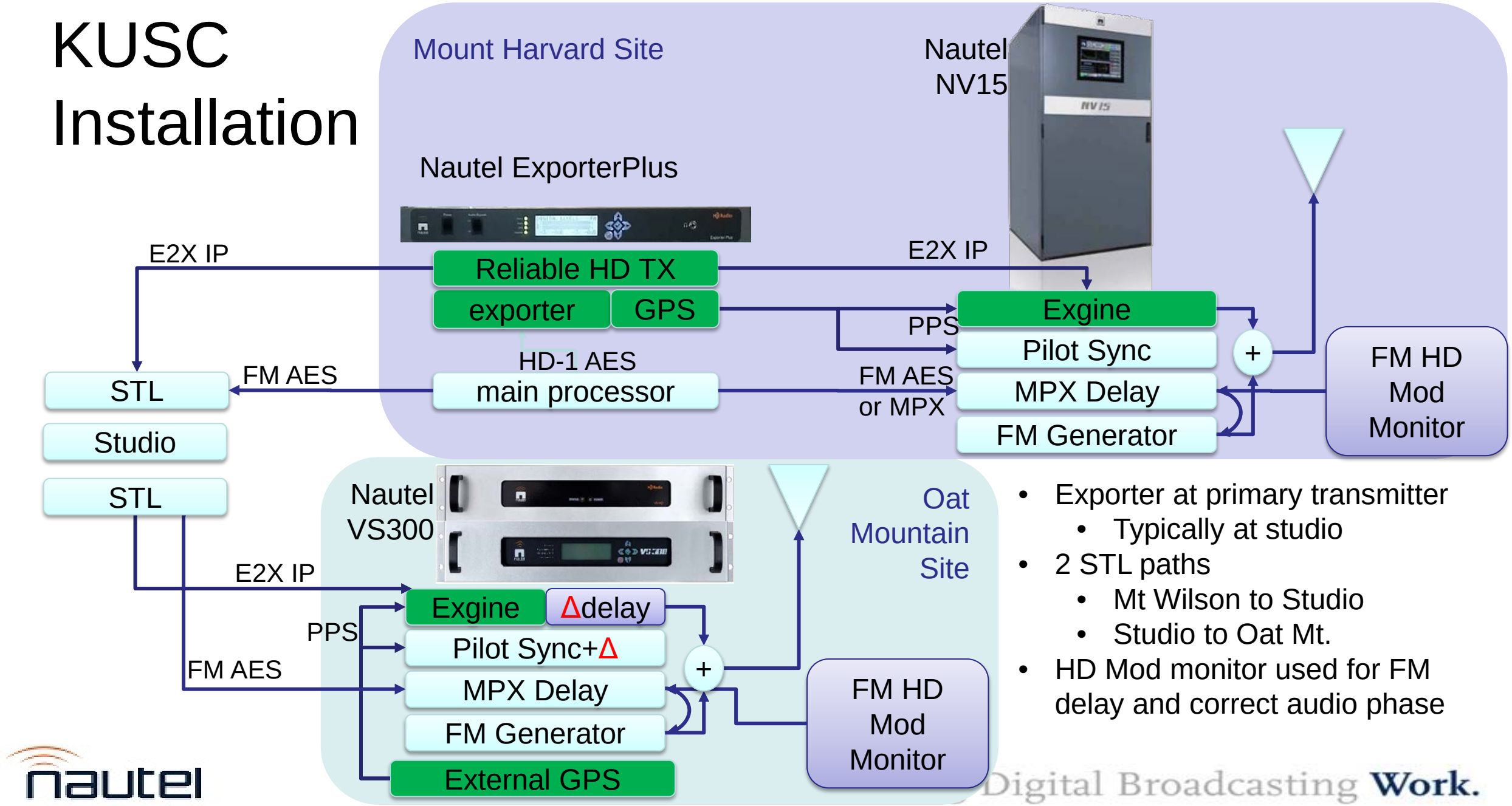
Field Trial: KUSC, Los Angeles

Signal coverage Comparison: KUSC-FM

- Main transmitter, 39 kw DA on Mt. Harvard (no booster)
  - Yellow: portable
  - Green: in-home
  - Red: in-car
- Signal coverage from booster, 200w DA on Oak Mountain, Porter Ranch, toward Santa Clarita
  - Same color coding
  - High signal levels in Santa Clarita
  - Terrain causes signal fragmentation
  - Side and back radiation on antenna causes signal in San Fernando Valley



KUSC Installation



- Exporter at primary transmitter
  - Typically at studio
- 2 STL paths
  - Mt Wilson to Studio
  - Studio to Oat Mt.
- HD Mod monitor used for FM delay and correct audio phase

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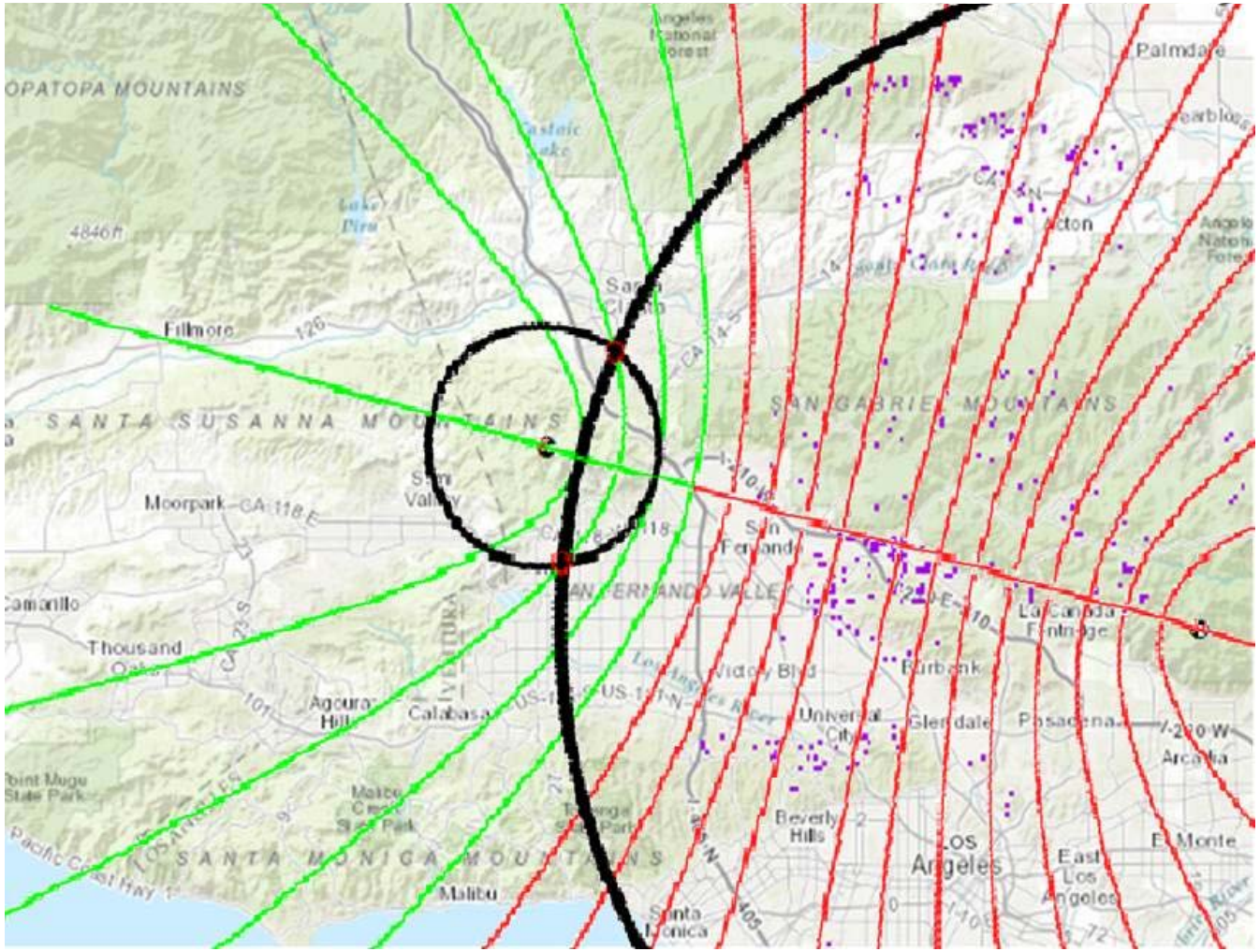
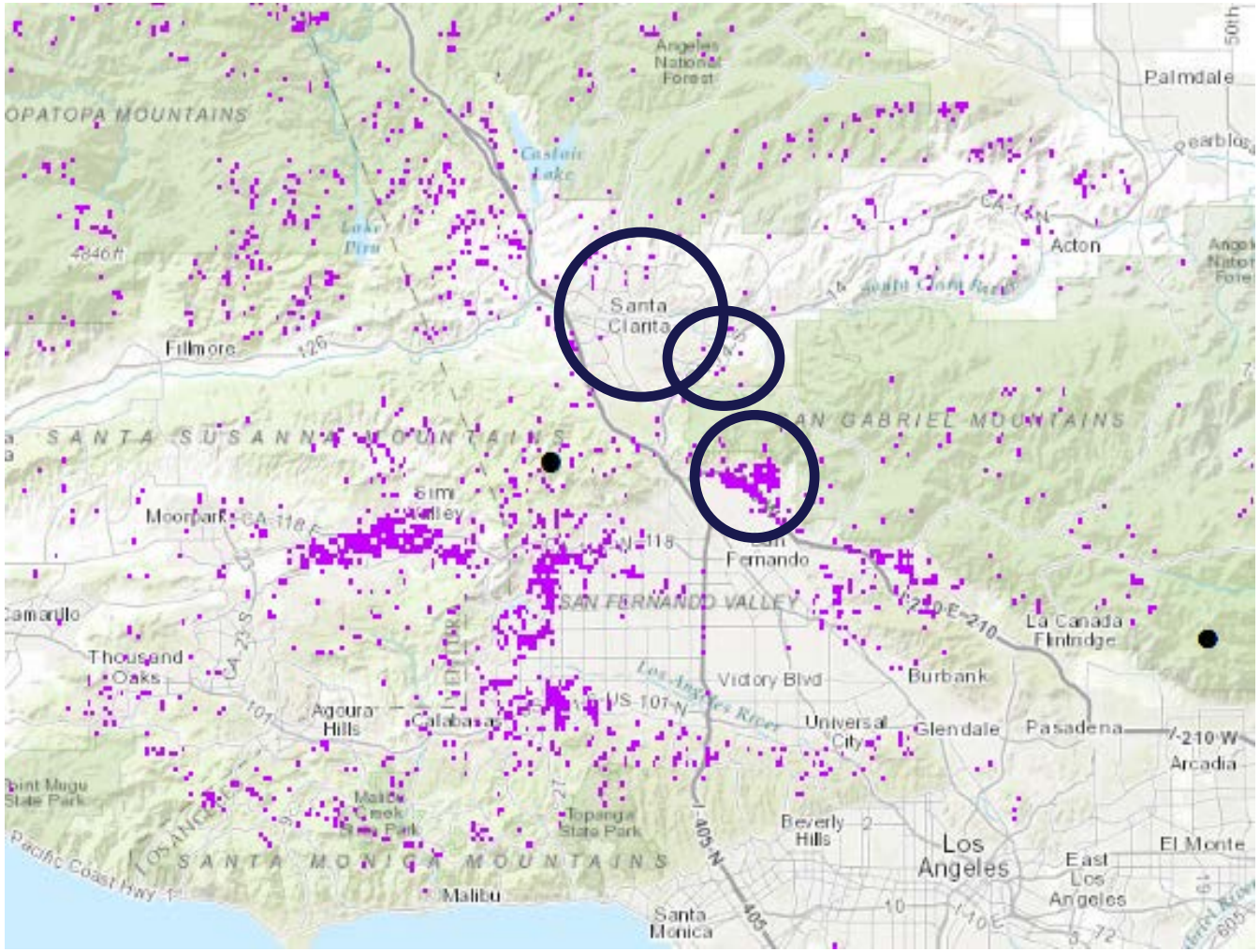
KUSC multipath effects for HD Radio

- **Unsynchronized HD Radio**
  Predicted digital reception difficulties for present -20 dBc injection on both Main and booster
- **Synchronized HD Radio**
  Flight time to booster 176µs, booster is delayed by 176µs - 40µs
- **Time of Arrival Contours**
  Equal delay is 20µs from booster



KUSC Drive Test Results
Thursday Apr 14, 2016

- Tested both -20 dBc and -14 dBc on Booster
- Solid IBOC coverage of Santa Clarita valley
- Good coverage along route 14 in Canyon Country. HD is locked even with severe FM impairment. Intermittent drops only with expected terrain shielding in canyons.
- Only short intermittent drops in Sylmar region only with clear obstruction like underpasses with little signal from either transmitter.
  - Proves IBOC is synchronized
- Significantly Impressed with coverage from **2W IBOC transmission** at 3000’
- **Test was successful**: HD Boosters are an effective option to extend coverage



Thank you Ron Thompson and Tom King of KUSC

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Conclusion

- SFNs must be aligned in time within interference zone
  - FM Stereo: Difficult
  - FM Mono: Workable
  - IBOC: Possible, increase coverage beyond protected contour
- Elevated IBOC power on booster can be beneficial
  - More IBOC coverage, smaller FM interference zones, avoids drowning FM
- Nautel offers industry first SFN implementation
  - Fixed HD audio throughput delay
  - Align FM with Modulation Monitor
- Field trials at KUSC, Los Angeles, are a success

Thank You

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FM SFN Protection Ratios

Time Delay	Mono FM		Stereo FM	
Impairment Grade	3	4	3	4
2 µs	<1 dB	1 dB	4 dB	6 dB
5 µs	1 dB	2 dB	10 dB	12 dB
10 µs	1 dB	3 dB	14 dB	16 dB
20 µs	-	11 dB	-	-
40 µs	-	20 dB	-	-

Results from ITU-R BS.412

- ITU Impairment Grades
  - 5: Excellent quality — imperceptible impairment
  - 4: Good quality — perceptible impairment, but not annoying
  - 3: Fair quality — slightly annoying impairment
- e.g. a stereo FM signal 14 dB stronger to a 10 µs delayed interferer produces grade 3 impairment.
- 10 µs represents 3 km signal flight time

Mono FM Synchronization

Smaller **interference** potential (**3 dB D/U**)

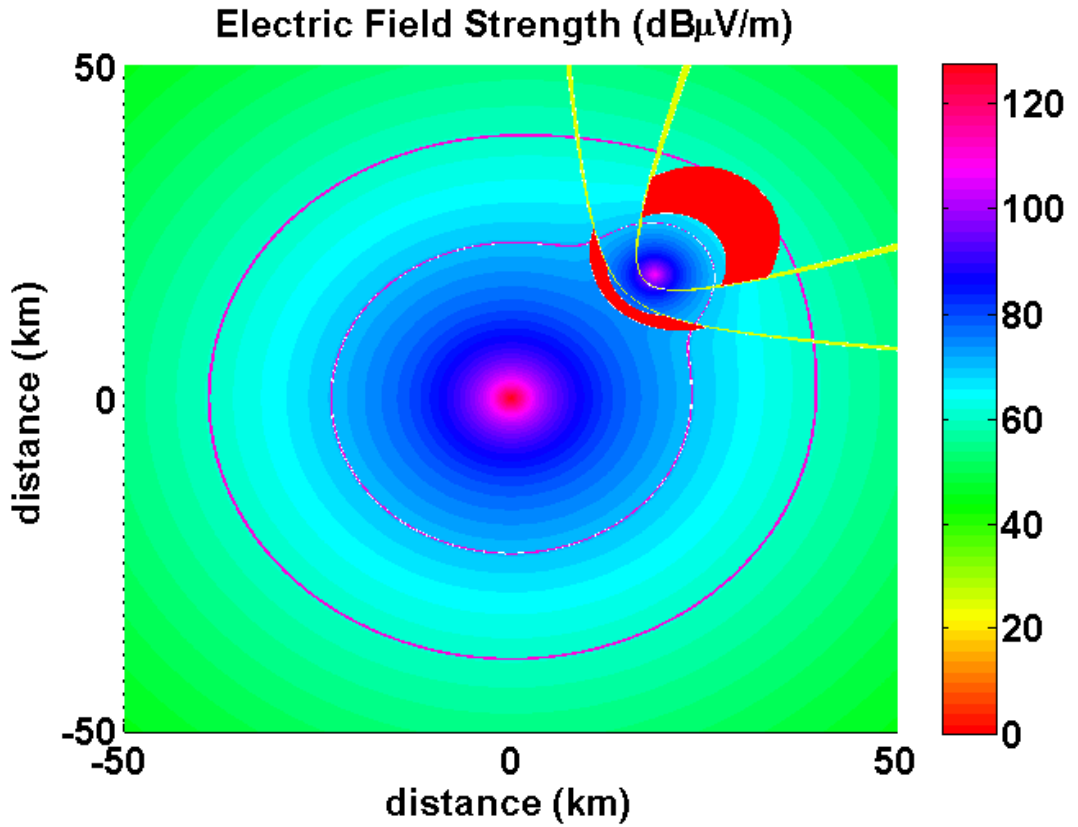
- Booster exceeds **city grade contour**

20 µs booster time advance

- Booster delay 87.3 µs – 20 µs = 67.3 µs
- Meets primary wave 10 µs or 3 km out

10 µs timing margin provides small buffer

- Seamless coverage area has shifted
- Interference toward primary can be addressed with booster directional antenna pattern

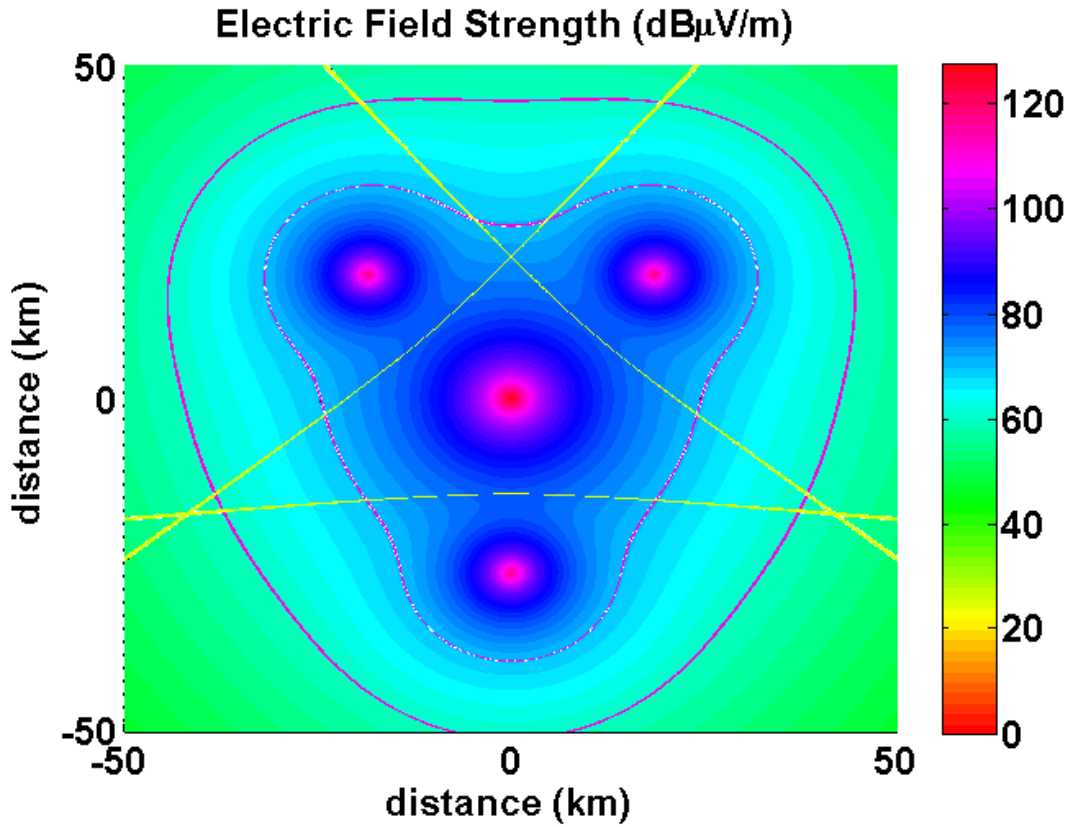


Expanding Your IBOC Coverage

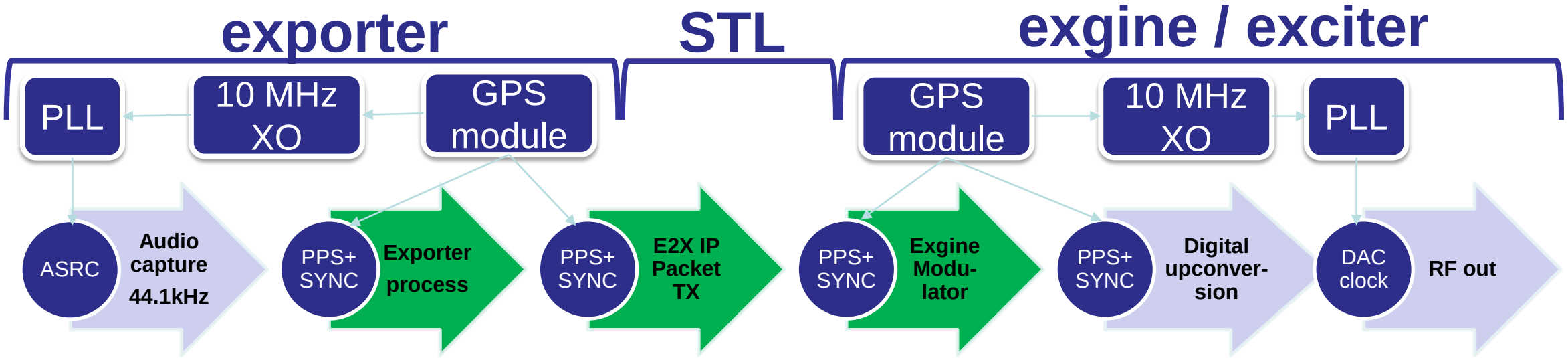
Hybrid FM+IBOC System
- Primary 2.5 kW IBOC at -10 dBc injection
- 3 Boosters at **250 W IBOC at 0 dBc** injection

No IBOC **interference** expected
- Big increase in **city grade contour**
- 10 km gain in combined **60 dBu contour**

39 µs booster time advance
- Booster to booster equal delays in between
- Extended seamless coverage beyond station protected contour
- Requires approval of 0 dBc Booster
- Must have clear 1st adjacent spectrum



IBOC SFN Pipeline



Sample count 0-44099

PLL maintains true sample rate

4096 audio Samples

SYNC <= first sample count after last PPS

Clock packet (SYNC) Data packet

Variable STL latency (< 1s)

1 E2X packet 32 Symbols

Optional added stages

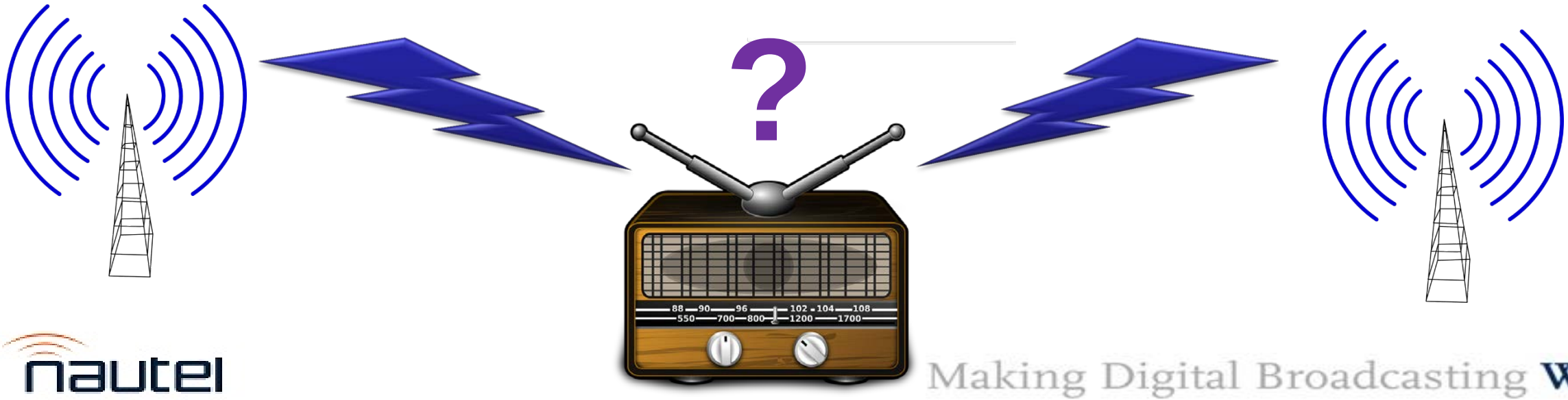
Start RF at PPS+SYNC

PLL maintains sync after start

Previous Work and Implementations

Previous Work: KCSN

- 2006 NAB Broadcast Engineering Conference
  - Mattson and Kean report on KCSN unsynchronized IBOC booster
  - IBOC interference even in strong signal areas (60 dBu+)
    - Nautel finds HD Radio receivers struggle with unsynchronized IBOC



Previous Work: IQ over IP

- 2009 NAB Broadcast Engineering Conference
  - Distributes modulated baseband signal over IP
  - Single IBOC modulator
  - High IP bandwidth requirement (24 Mbps)
- HD Radio™ Single Frequency Network Field Test Results
  - 2009 test at WD2XAB Baltimore & WKLB Boston
  - Successful experimental IBOC SFN demonstration
  - Implementation does not guarantee constant audio throughput delay

Previous Work: IQ over IP

- 2012 Over the Air Relay Booster at KUOW Seattle
  - Receives signal off-air, echo cancels, transmits
  - Simple content delivery to booster
  - Unable to time advance booster transmission
    - Not suitable for high quality FM booster, marginal for IBOC
- 2016 Nautel commercial IBOC SFN implementation
  - Fixed audio HD audio delays
  - Field trial at KUSC-FM1