APCO Project 25 and Other Digital Radio Technologies Overview

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Transition to Narrowband

- Late 1980's – FCC, user representative organizations (APCO) and manufacturers looked for solutions to spectrum overcrowding
- Moving to narrower channel bandwidths selected as solution
- 1996 - FCC Rules *encourages* migration from 25 KHz to 12.5 KHz, but now *require* transition by Jan 1, 2013
- FCC indicates that a transition to 6.25 KHz (or equiv. using very narrow FDMA or two/four slot TDMA) is expected

Better Spectral efficiency = More Users

25 kHz analog → 12.5 kHz analog
12.5 kHz digital
Digital

- Manufacturers and user representative organizations realized that analog narrowband operation imposes performance limitations and isn't practical with very narrowband channels.
- Digital operation also offers considerable operational benefits to users.
- There was no digital standard in place when the rules were formed.
- P25 was an attempt to prevent a digital radio "Tower of Babel"
What is Project 25?

- Standards developed by a TIA/EIA-supported committee of manufacturers, system operators, and industry associations, guided by a steering committee of public safety and federal government radio system users. APCO = Association of Public Safety Communications Officials

- *Open* (public domain) standard for production and implementation of digital land mobile radio system infrastructure and subscriber equipment

- Defines a digital radio system technology that supports a wide range of advanced radio system features including:
  - Conventional and trunked radio system operation
  - Emergency status indication
  - Radio unit identification
  - Regrouping of fleets
  - Remote radio disable
Project 25 System Interfaces

- Subscriber Data Peripheral Interface (e.g., MDT)
- Fixed System Interface (FSI)
- Common Air Interface (CAI)
- P25 RF SubSystem (RFSS)
- Inter RF SubSystem Interface (ISSI)
- Other P25 Systems
- Console SubSystem Interface (CSSI)
- Data Interface (e.g., Databases)
- Telephone Interconnect (PSTN)
- Gateway
- Network Manager
- Consoles
- Repeaters
Who is using P25?

• > 1 million P25 subscriber radios from over 12 suppliers deployed nationwide
• > 31 states have deployed, or deploying, statewide networks

**Washington Users**

• Department of Fish and Wildlife
• TSA, FBI, Secret Service, GSA, Federal
• Spokane County, Benton County
Why P25 is here to stay...

- Functional Capabilities and Benefits
- Grant and Funding Source Requirement - PSIC
- Federal & State Purchasing Requirements – DHS, RCW 43.105.330
- Interoperability - CAI and Intersystem Interfaces
- Going with the 'flow' - "Everyone around me has P25...

(c) Coordinate the purchasing of all state wireless radio communications system equipment to ensure that:

(i) After the transition from a radio over internet protocol network, any new trunked system shall be, at a minimum, project-25;

(ii) Any new system that requires advanced digital features shall be, at a minimum, project-25; and

(iii) Any new system or equipment purchases shall be, at a minimum, upgradeable to project-25;

(d) Seek support, including possible federal or other funding, for state-sponsored wireless communications systems;

(e) Develop recommendations for legislation that may be required to promote interoperability of state wireless communications systems;

(f) Foster cooperation and coordination among public safety and emergency response organizations;

(g) Work with wireless communications groups and associations to ensure interoperability among all public safety and emergency response wireless communications systems;
Who manufactures P25 Radios?

- More than one dozen manufacturers, with more to follow:
P25 CAI (Common Air Interface)

- Consists of Modulation, Channel-Coding, and Vocoder standard
- Allows multi-vendor equipment to operate with equivalent functionality in a basic communications mode
- Defines conventional and trunked infrastructure access algorithms, replacing vendor-specific (*proprietary*) access methods
- Does not specify TX power, RX sensitivity, or other technical specifications; these are manufacturer and market-driven capabilities where other TIA, IEEE, or FCC standards may apply
C4FM Digital Modulation

- C4FM – Constant Envelope 4-carrier (level) FSK modulation, 12.5 kHz, 9600 bps
- Carrier is frequency-shifted at a particular rate to 4 deviation points around a center frequency.
- Each state represent a binary number (DiBit/Symbol - 2 bits of information).
- Each carrier has a fixed offset and *never returns to the center frequency* - each transition is encoded to start from its last position
- Mixed mode (analog/digital) operation
- FDMA bearer can provide voice, data, and network control

**Plots of C4FM**

<table>
<thead>
<tr>
<th>Information Bits</th>
<th>Symbol</th>
<th>C4FM Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>+3</td>
<td>+1.8 kHz</td>
</tr>
<tr>
<td>00</td>
<td>+1</td>
<td>+0.6 kHz</td>
</tr>
<tr>
<td>10</td>
<td>-1</td>
<td>-0.6 kHz</td>
</tr>
<tr>
<td>11</td>
<td>-3</td>
<td>-1.8 kHz</td>
</tr>
</tbody>
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*Display samples courtesy of Aeroflex*
P25 Transceiver Diagram

ANALOG SPEECH
- Input Gain & Filtering
- A/D Conversion
- A/D Conversion
- Output Gain & Filtering

8 KHz SPEECH DATA
- ENCORDER
- IMBE
- VOCODER

COMPRESSED DATA (2.0 - 9.6 KBPS)
- Symbol mapping, TX Shaping Filters, FM Modulator
- Detector, Rx Filter, Symbol De-mapping

BINNARY DATA
- 4-Level to TX
- (C4FM)
- 4-Level From RX

MIC
- 8 KHz SPEECH DATA

SPKR
- 4-Level From RX
IMBE™ VOCODING

• IMBE™ (Improved Multi-Band Excitation) full-rate (7.2 kbps) DVSI vocoder
• Multiple vocoders in MOS tests, best voice quality in occupied bandwidth
• *Model-based* speech coder - provides a *synthetic equivalent* of human speech using 'model parameters'
• License agreement with royalties – high cost of entry
• Models audio segments as frequency-dependent *combination* of either *voiced* or *unvoiced* speech.
• Goal is high level of *perceptual* quality rather than waveform accuracy
P25 Channel Coding

Channel CODEC (coding/decoding)

• Provides Error Correction and Data Protection
• Counteract effects of noise, fading and interference
• Error Correction Techniques include
  – Interleaving & Linear block (Hamming, Golay, Reed-Soloman) codes
  – Primitive BCH (Bose & Ray-Chaudhuri) and shortened cyclic codes

Error Correction -119 dBm @ 5% BER
P25 Mixed Mode Operation

**Auto-Detect and Switching between analog & digital**

- A special sequence of 48 bits (5 msec) used for frame synchronization is sent at beginning of all P25 transmissions.
- Presence of frame sync implies digital mode - lack of frame sync implies analog information.
- Base station switches operational mode accordingly.
- Frame sync is re-inserted every 180 msec. during transmit for receiver detection (late entry) and to maintain digital operation.
P25 Performance Differences

Digital versus Analog characteristics

- Not immune to classic impairments to radio communications
- Increased effects of multipath distortion
- Differing system performance at the edge of coverage area
  - *Sudden* loss of intelligibility at the outer limit of system coverage.
  - *Gradual* loss of intelligibility with analog systems at fringe
- Phenomenon noticed when transitioning from analog to digital systems
- Some reduction in S/N ratio due to narrower BW (12.5 kHz)
- Error correction offsets some of this
- Improved usability in fringe areas not possible with analog
P25 and General Digital Radio Foes

Classic Enemies of Radio Communications

• Low signal strength
• Multipath distortion

Digital Radio Specific Phenomena

• BER > 5% - pushing the limits of error correction and recoverable data (and therefore understandable speech)
• ISI (Inter-Symbol Interference)

ISI

• Major issue
• Simulcast transmission
• Advanced Modulation
Analog vs. Digital (P25 C4FM/CAI) Radio Conceptual Coverage Comparison

Audio Quality (Analog SINAD)

Strong

Poor

2.5uV (-99dBm)
0.45uV (-114dBm)
0.19uV (-121dBm)
0.14uV (-124dBm)

Signal Strength

Off-air audio samples courtesy of Tait Communications
Vocoder Performance in Noise (Wind)

Off-air audio samples courtesy of Tait Communications
P25 Integrated Voice & Data Modes

• Use 2400 bps for signaling and control functions 
ex. SELCAL, TG ID, network (repeater) access codes (NAC)
• Each Logical Link Data Unit in a voice message contains the 16 bit Low Speed Data field - total capacity 88.9 bps.
• Intended for custom user applications 
  - GPS AVL ('APRS' style) 
  - SMS style text messaging 
  - Status & Telemetry 
  - Database query total capacity of 88.89 bps.
• Manufacturers offering open API's for development 
• Optimized for Digital Voice not Digital Data
P25 Phase II

Next Generation Technology Evolution – what and why?

• Phase 2 embarked upon in 2006 - 2007
• Meets future FCC spectral efficiencies for one voice path in 6.25 kHz bandwidth or 6.25 kHz 'e' (efficiency)
• 12 kbps gross channel rate, 2 time-slot TDMA channel access
• New modulation and channel access schemes for greater performance & control of subscriber radios
• Improved VOCODER efficiency and voice quality
• Backward compatible with Phase 1

@ 6.25 kHz BW now!
P25 Phase II

6.25e kHz Spectral Efficiency FCC Regulatory Overview

**Definition**
- Voice Channel – one (1) voice path in 6.25 kHz BW
- Data/Control Channel – 4800 bps in 6.25 kHz BW

**Radio Manufacturers**
- New radios must be certified for compliance
- V/U – 1/1/2011 700 MHz – 1/12/2015

**Users/Operators**
Phase 2 operational (6.25 kHz 'e') by:
- V/U – date not set only encouraged
- 700 MHz – 1/12/2017 as per FCC
Time Division Multiple (channel) Access

TDMA History - Not new technology
- 2G cellular such as GSM, IS-54/136 (D-AMPS) 30 kHz/3 slots
- iDEN (Nextel) 25 kHz/3 slots

TDMA vs. FDMA Graphical Comparison
P25 Phase 2 Migration Issues

Significant Problems
• Financial
• Existing user's equipment
• Force obsolescence or upgrade

Interoperability
• Neighboring systems
• Roaming, conventional & trunked, mixed Phase 1 & Phase 2 system – how ?
• Direct mode operation – TDMA problem

Technical / Manufacturing
• Circuit and component design (linear Class A or AB)
• Power management (FDMA vs. TDMA, Class C vs. Class"A or AB)
• Tool-up, market, quantities
• Market barriers, multi-vendors, cost of entry (licensing for IMBE™/AMBE™)
P25 Phase 2 Core Technology

Asymmetric Uplink & Downlink

- **H-CPM on Uplink (Harmonized Continuous Phase Modulation)**
  - Constant envelope for easier subscriber RF PA design
  - Coherent (FM) receiver in the base station for good sensitivity

- **H-DQPSK on Downlink (Harmonized Differential Quadrature PSK)**
  - Linear 4-level for non-coherent (AM) subscriber receiver
  - Excellent simulcast delay spread

- **Backwards Compatible with Phase 1**
  - Migration of Phase 1 radio subscribers
  - Interoperability between Phase 1 & 2 users (ex. roaming)
  - Talk-around mode / TDMA requires synch from BS
  - Trunked dual-mode functionality
  - Control channel always Phase 1 mode

QPSK simultaneously modulates the phase and carrier amplitude to minimize occupied bandwidth - which generates an AM waveform. Implications for new Base Station transmitter and receiver design – linear PA's
P25 Digital Modulation Terms

C4FM – constant amplitude FM IQ diagram identifies four equally spaced states on a constant amplitude circle. The carrier power is constant but the modulation scheme specifies a phase accuracy

QPSK (Quadrature Phase Shift Keying) - PSK where there are four possible states allowed, determined by two data bits

CQPSK - a QPSK scheme used in P25 Phase 1 simulcast where the transmit filter is a raised cosine (rather than a root raised cosine) to ensure compatibility with C4FM

Note - Subscriber radio units use a common receiver for decoding/detecting both C4FM and CQPSK to ensure full interoperability
Detector design in demodulator allows receiving analog FM, C4FM, and CQPSK.

**Ex. - Phase 2 Base Stations**

- **Motorola GTR8000**
- **Harris MASTR 5**

  - Linear Class A/AB amplifier design
  - Increased size, power and cooling
  - Expensive
  - Additional standby power req. (-48 VDC)
P25 Phase 2

Vocoder Technology Evolution

• Voice quality and comparable to P25 Phase I
• Slightly reduced coverage compared to Phase 1
• Dual Rate Vocoder –
  Phase 1 *full-rate* IMBE™ or AMBE™ vocoder (7.2 kb/s)
  Phase 2 *enhanced dual-rate* AMBE™ vocoder (3.6 kb/s)
VOCODER Technology Trends

Technology Advancing Rapidly

Transition to new low-rate (IMBE™-Equivalent) AMBE+™ Vocoder
Early VOCODER problems - History

Background Noise and Radio Performance

• 2006: fire service noted P25 voice unintelligible with background noise (K-12 and chain saws, air mask low air alarm, etc.)
• 2007: IAFC forms investigative committees
• April 2008: Nationwide media exposure – line of duty death?
• 2008: NIST report findings: over 45,000 test results - inconclusive

Don't blame the VOCODER 100%
- Pre-VOCODER noise reduction algorithm "solves' much of audio problem
- Significant improvements in radio ergonomic design, better training of personnel

History
IMBE – original vocoder selected 1993
AMBE+2 (v1.4) improved audio quality, better tones 2005
AMBE+2 (v1.6) improved noise suppression for fire service 2009
Other Digital Radio Technology

Multiple VOCODER and Channel Access Technologies
Domestic and International Markets

- TETRA (ETSI European Open Standard)
- D-Star (ICOM) 6.25 kHz GMSK
- Motorola TRBO (TDMA, 2-slot, 12.5 kHz)
- Kenwood/ICOM NXDN (FDMA C4FM 6.25 kHz)
TETRA

- Suite of *open* digital trunked radio standards
- Public Safety and professional radio market
- Interoperability standard, multiple vendors
- Supports trunked and conventional, cell hand-off
- Private and Public Systems (Carriers)
- Typically cellular-style networks, small coverage, low sites, low power, in-building cells
TETRA

- 4 slot TDMA in 25 kHz channels (6.25 kHz 'e')
- $\pi/4$ DQPSK Modulation, Gross Data Rate 36 kbps, Net Data Rate 28 kbps
- Circuit and packet mode data, Simultaneous Voice and Data
- Low bit rate ACELP codec @ 4.6 kbps
- 35 mile site range limit - propagation delays causing overlap of TDMA slots
- Data calls can use up to 4 ch. (multi-slot data)

EVM Plot of TETRA signal

![Diagram of TETRA signal with 4 channels multiplexed into 1 x 25 kHz carrier]
NXDN

- Two manufacturers: ICOM – IDAS™ and Kenwood – Nexedge™
- 6.25 kHz FDMA, C4FM, mixed mode, 4800 bps transmission rate
- IP backhaul for simple site linking
- Conventional and Trunked modes of operation
- AAR/Association of American Railroads recommended bypassing upgrade from 25 kHz to 12.5 kHz directly to 6.25 kHz and NXDN compliance for 6.25 kHz Very Narrowband (VNB) operation.

Targeted for Professional and Utility Markets
DMR

- ETSI standard supports 3 "Tiers" of operation:
  - Tier 1 - license-free (FRS equivalent), 6.25 kHz FDMA
  - Tier 2 - licensed conventional
  - Tier 3 - licensed trunked
- 12.5 kHz, 2-slot TDMA for 6.25 kHz equivalence
- IP backhaul for simple site linking
- Available from Motorola (MotoTRBO™) and Hytera
- Direct mode (conventional) falls back to 12.5 kHz efficiency

Targeted for Professional and Utility Markets
dPMR

• **Very narrow** bandwidth version of DMR
  - Channel BW: 6.25 kHz
  - Access Method: FDMA
  - Transmission Rate: 4800 bps
  - Modulation: 4-level FSK
  - Vocoder: AMBE+2™

• 4 Modes of Operation
  - dPMR446 – license free @ 446 MHz
  - dPMR Mode1 – simplex licensed
  - dPMR Mode2 – repeater licensed
  - dPMR Mode3 – trunked licensed
How do I learn more about digital radio technology?

- Wealth of open source information
  - Yahoo users groups
  - Industry websites
  - Professional organizations
  - Local and regional conferences and trade shows

Recommended Reads / Downloads

- www.nxdn-forum.com
- www.dmrassociation.com
- www.tetramou.com
- www.p25.com
- www.project25.org
- www.apco911.org
- www.p25ham.com
- www.radioreference.com
- Daniels Electronics Ltd. P25 Guide
- Aeroflex P25 and digital radio Application Notes
How do I find and buy P25 digital radios?

• Research, research, research
  – Decide your needs and budget
  – Validate the radio's legitimacy and DSP/Flash/Firmware
  – Seek local support from other hams, groups
  – Ebay and Eham.net offer 'fair-good' deals on used equipment
  – Dealer demo samples offer good deals
  – New prices are continually decreasing
  – P25 now sub-$1000, NXDN & TRBO now sub-$700 for new equipment
  – Expect to pay 40% ~ 50% of above prices for quality used
  – As P25 Phase 2 systems roll out, used Phase 1 equipment availability will rise

Recommended Reads / Downloads

Google the following:

- A Guide to ASTRO Digital Radio, authored by r0f
THANK YOU!

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