Radio

Radio link design
Overview

• VDL Mode 4
• A (radio) communication system
• The radio channel
• Channel access
VDL Mode 4 Ground station

VHF Transceiver

Communication Processor

GNSS reference receiver
VDL Mode 4 Transponder

VHF Transceiver

Communication Processor

GNSS receiver
VDL Mode 4 Superframe - 1 minute - 4,500 slots = 75 slots/s

Slot 1 13.33 ms Current superframe  Slot 4500

Slot 4501 Current superframe + 1  Slot 9000
VDL-4 Summary

- Avionics data link
  - Communication, navigation and surveillance
- Based upon STDMA (By Håkan Lans)
- 108-137 MHz, 25 kHz channels
- 19200 bit/s, FSK
- ≈10 W Tx power
- 200 nmi range (≈370 km)
## Communication layers

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**Notes:**
- ADS-B: Automatic dependent surveillance broadcast
- TIS-B: Traffic information service broadcast
- DLS: Digital local service
- STDMA: Standard data mode automatic
Power level units

- dB: Logarithmic level ratio:
  - 3 dB ↔ double power
  - 10 dB ↔ 10 * power
- dBm: Power level, 0 dBm = 1 mW
- dBi: Antenna gain, 0 dBi => isotropic ant
- dBc: Power level, 0 dBc => carrier level
- dBμV: Voltage level, 0 dBμV = 1 μV
- dBμV/m: Field strength
The radio spectrum

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3 kHz to 300 GHz

FM radio | VDL-4 | GSM 900 | Bluetooth | NG W-LAN |
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Spectrum mask:

-1st: -45 dBm
-2nd: -28 dBm
-4th: -38 dBm
-32nd: -53 dBm
Frequency issues

• Attenuation $\sim f^2$ \(\frac{P_r}{P_t} = \frac{G_r G_t \lambda^2}{(4\pi r)^2}\)
  – 81 times more power required at 900MHz for same received power as at 100MHz

• Antenna size $\sim f$
  – Typically 70 cm for FM $\lambda/4$ antenna (100 Mhz)
  – $\approx 8$ cm for 900 MHz $\lambda/4$ antenna
  – Efficient (VHF) antenna can have $\approx 0$ dBi (typical aircraft antenna $\approx -4$ dBi)
Noise

- Thermal background noise
  - -174 dBm/Hz @ 290K (0 dB NF)
- Sky temperature
  - Significant (NF ≈ 5-10 dB) at low frequencies (< 200 MHz)
- Other systems (man made)
  - Impulse and continuous signal (CW)
- Noise figure \( NF = 10 \log(1 + T/290) \) 
  Temperature \( T \) in Kelvin
Noise

Typical sky temperature

Thermal noise floor (-174 dBm/Hz @ 290K)
Noise

• CCI: Co-channel interference
  – In-band interference
  – Typically 6-20 dB CCI rejection
  – Interference from other similar units using same channel
  – Low CCI ratio => more efficient frequency reuse
  – 10 dB CCI protection will be required for VDL-4
Digital modulation

- Symbol: Bit or collection of bits
- Modifying parameters of a carrier
  - Amplitude (ASK), 1 bit/symbol
  - Frequency (FSK), 1 bit/symbol
    - Constant envelope (no amplitude variations) can be implemented
  - Phase (PSK), 1-3 bit/symbol
  - Amplitude and phase (QAM), 4-8 bit/symbol
  - Multi-carrier (OFDM), 50-16000 bit/symbol
Metrics

• Power efficiency
  – Signal power to achieve a particular BER for a given modulation scheme
  – Signal energy per bit / noise spectral density: $E_b / N_0$

• Bandwidth (spectral) efficiency
  – Possible data rate for given bandwidth
  – Data rate typically 0.5-4 bit/s/Hz
  – Shannon limit: $C = B \times \log_2(1+s/n)$
Constellation: Vector notation

- Representing amplitude and phase using polar coordinates
  - $I = M\cos\theta$, $M$: Amplitude, $\theta$: Phase
  - $Q = M\sin\theta$
Using the vector notation

- "Detectability"
- Crest factor (amplitude variations)
- Power and bandwidth efficiency

Transitions: Indicates amplitude variations

Distance ~ detectability

Peak power

Log2(number of signals) = bits/symbol \sim bits/s/Hz
Transceiver structure
Analog design issues

• Filters
  – Attenuation
  – Phase linearity

• Mixers and amplifiers
  – Dynamic range
    • Spurious products
    • Noise

• Oscillators
  – Phase noise
Implementation issues

• For analog components:
  – Performance costs:
    • Money
    • Size
    • Power
Constant envelope modulation

- FSK, MSK (h=0.5)
- Features:
  - Frequency reuse (CCI)
  - Power efficient
  - Non-linear transmitter
Phase modulation

- D8PSK, QPSK
- Features
  - High throughput (1.5-3 bit/s/Hz)
Phase/Amplitude modulation

- 16 QAM, 64 QAM, 256 QAM
- Features
  - High throughput (3-8 bit/s/Hz)

16 QAM

- Microwave links
Multi-carrier modulation

- OFDM, COFDM, MC-CDMA
- Multiple orthogonal carriers, typically PSK or QAM modulated
- Coding in the frequency dimension
- For N carriers, symbol time increases by N
  - Less ISI (intersymbol interference)
  - Less sensitive to multipath interference
DS-CDMA modulation

- Direct sequence CDMA
  - Spreading gain \( W/R \)
  - Rake receiver ("ISI-free")

\[
W/R = 10 \log(1.2288 \text{ MHz}/9600\text{Hz}) = 21 \text{ dB} \quad \text{(IS-95 CDMA)}
\]

\( W = \) Spreading bandwidth, \( R = \) data rate
Performance

• Spectrum use

Error rates

Typ. ≈ 1-1.5 * symbol rate

FEC gain ≈ 2-10 dB
Link budget

- Antenna gain: -2dBi (Tx and Rx)
- Cable loss: 3dB (Tx and RX)
- Thermal noise: -174dBm/Hz
- Sky temp: NF~4dB
- Man-made noise 16dB ENR
- \( U = 4.359 \times 10^6 \times Er \times \sqrt{GR} / f \)
- \( U = \sqrt{PR} \)
- Bandwidth: 25 kHz = 44 dB
- Rx Input NF: 12dB
- Rx SNR required: 12 dB
- Distance 200 nmi (370 km)
- Carrier frequency: 137 MHz
- Signal attenuation: 127dB
Link budget

Cascaded noise temperature: \( T_{\text{eq}} = T_1 + \frac{T}{G_1} + \frac{T_3}{G_1G_2} + \ldots + \frac{T_n}{G_1G_2\ldots G_{n-1}} \)

Cascaded noise factor: \( F_{\text{eq}} = F_1 + \frac{(F_2-1)}{G_1} + \frac{(F_3-1)}{G_1G_2} + \ldots + \frac{(F_n-1)}{G_1G_2\ldots G_{n-1}} \)

\[ T_e = (10^{\frac{\text{NF}}{10}} - 1) \cdot T_0 \quad \text{NF = Noise figure, } T_0 = 290K, \quad T_e = \text{equivalent noise temp} \]

\[ T_{\text{enr}} = (10^{\frac{\text{ENR}}{10}+1}) \cdot T_0 \]

**Noise into RX antenna:** Man-made + Sky temp: \( T_{\text{enr}} = 11835K, \quad T_{\text{sky}} = 1018K, \quad \text{Tot: } 12853K \Rightarrow 4064K \text{ at LNA} \)

LNA NF (12 dB) \( \Rightarrow T_{\text{eq}} = (10^{\frac{12}{10}-1}) \cdot 290 = 4306K \)

Total T at LNA: 4306+4064=8370K \( \Rightarrow F=30 \text{ (NF=15dB)} \)

\[ \text{PA power: } 29+2+3=34\text{dBm (2.5W)} \]

\[ \text{Transmitted power: } -98+127=29\text{dBm} \]

\[ \text{Noise power at LNA = } -174+44+15= -115\text{dBm} \]

\[ \text{Signal level at LNA: } -115+12= -103\text{dBm} \text{ for 12 dB SNR} \]

**PA:**
- \( G_t: -2 \text{ dB} \)
- \( A = -3 \text{ dB} \)

**LNA:**
- \( G_r: -2 \text{ dB} \)
- \( A = -3 \text{ dB} \)

**Noise into RX antenna:**
- \( T_{\text{enr}} = 11835K, \quad T_{\text{sky}} = 1018K, \quad \text{Tot: } 12853K \Rightarrow 4064K \text{ at LNA} \)

\[ T_{\text{enr}} = \frac{T}{G_1} + \frac{T}{G_1G_2} + \ldots + \frac{T}{G_1G_2\ldots G_{n-1}} \]

\[ T_{\text{eq}} = \left(10^{\frac{\text{NF}}{10}} - 1\right) \cdot T_0 \]

\[ T_{\text{enr}} = \left(10^{\frac{\text{ENR}}{10}+1}\right) \cdot T_0 \]
Multi-access system FDMA

- Central coordination
- Analog systems
- POTS, FM-radio, VHF

Frequency

Time
Multi-access system “Aloha”

- No coordination
- Low channel utilization
- Mode-S, UAT
Multi-access system CSMA

- No central coordination
- Medium channel utilization

- Ethernet, VDL mode 2,3
Multi-access system TDMA

- Coordination of slots
- GSM, DECT...
- VDL4 (STDMA)
Multi-access system FH-CDMA

- Coordination by codes
- Bluetooth, Radio-LAN
- Military systems
Multi-access system DS-CDMA

- Users use different spreading sequences with low cross-correlation
- Coordination by codes
- IS-95 (US CDMA), GPS
Make it simple...