Air-Ground Channel Characterization

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ICAO

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Outline

• Introduction & Motivation
• Channel Characterization Basics & Significance
• AG Channel Measurements
• AG Channel Modeling
• Example Results
• Summary
Introduction & Motivation

• Since safety & reliability paramount, UAS CNPC systems being specified to meet rigorous performance requirements

• NASA project (UAS in the NAS) exploring & validating technologies for reliable CNPC
  – **U. South Carolina** working w/NASA on PHY/MAC
    • Air-ground (AG) channel
    • Radio mod/demod
    • Networking
• There exist NO comprehensive, validated, *wideband* models for time-varying AG channel

• Existing measurements
  - Sparse, & for different frequency bands in widely different environments
  - *Not parameterized* as function of
    - Elevation $\angle$
    - Ground site (GS) antenna height
    - GS local environment
  - Do *not* include airframe shadowing
“Classical” AG channel
- ~En-route, with continuous LOS
- Narrowband signals (only path loss required)
- GS in open, cleared areas, without obstructions

Modern AG channel (e.g., UAS) will NOT always satisfy these conditions!
Other organizations studying the AG channel

- German Aerospace Center
- NICT (Japan)
- Nanyang Tech. Univ. (Singapore), Czech Tech. Univ.
- IMST GmbH (Germany), Canadian Research Centre
- Also past/future
  - BYU
  - Boeing
  - ITT
  - UPM (Spain)
  - L3 Communications
  - Virginia Tech
  - USAF
  - Lockheed-Martin
Channel Characterization

- Characterization means

- Accurate, quantitative description of channel
  - $h(\tau,t)$ or $H(f,t)$

- Translating this description into simpler functions, features, models
  - For use in evaluation of signaling
  - “Classical” AG channel characterized only by path loss
Channel Characterization Importance

• If you don’t know your channel, system performance will be *sub*optimal, possibly very poor, with
  – Irreducible channel error rate, precluding reliable message transfer (e.g., *blurry* video!)
  – Severely limited data carrying capacity

... could require *co$t*ly re*€m€diation*
### Channel Char. Importance (2)

- AG channel can **strongly** affect performance

#### Channel Effect on Signaling (“101”)

- Delay Spread (multipath) $\Rightarrow$ Dispersion $\sim$ distortion
  - Requires compensation (equalization, multicarrier, diversity…)

- Doppler $\Rightarrow$ Time Variation
  - Requires compensation (carrier tracking, inter-carrier interference mitigation,…)

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If channel not quantified, signal design **suboptimal**
AG Literature Review Summary

• Some research begun in early 1960s (VHF)

• Common assumptions
  – Isolated GS in open area
  – Tall tower
  – Narrowband signals
  – Latency requirement moderate (voice)

⇒ simple channel models sufficient

<table>
<thead>
<tr>
<th>Environment</th>
<th>Since…</th>
<th># Papers (~2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle-to-Vehicle</td>
<td>2005</td>
<td>77</td>
</tr>
<tr>
<td>Cellular</td>
<td>1980</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Air-Ground</td>
<td>1960</td>
<td>27</td>
</tr>
</tbody>
</table>
# Measured RMS Delay Spreads

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Avg Delay Spread $\sigma_t$ (µs)</th>
<th>Max Delay Spread $\sigma_t$ (µs)</th>
<th>~Min Coherence Bandwidth (kHz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport</td>
<td>0.5-1</td>
<td>2.5</td>
<td>80</td>
<td>Miami, Cleveland, JFK airports</td>
</tr>
<tr>
<td>Surface</td>
<td>0.65</td>
<td>1.8</td>
<td>111</td>
<td>Munich airport</td>
</tr>
<tr>
<td>Air-Ground</td>
<td>0.07</td>
<td>—</td>
<td>—</td>
<td>Aero telemetry w/narrow beamwidth GS antenna, open desert, 2 GHz</td>
</tr>
<tr>
<td></td>
<td>3.8</td>
<td>7.2</td>
<td>27.7</td>
<td>VHF in Duluth, MN, Aspen, CO</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>3</td>
<td>67</td>
<td>L-band, Aspen, SIMULATED only</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>15</td>
<td>13</td>
<td>VHF, analytical + measured</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.55</td>
<td>200</td>
<td>2 GHz, college campus</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>0.5</td>
<td>400</td>
<td>C-band, over ocean, directional antenna</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>0.4</td>
<td>500</td>
<td>C-band, near mountains</td>
</tr>
<tr>
<td>Satellite</td>
<td>1.2</td>
<td>4.5</td>
<td>44.4</td>
<td>L-band, 15-70 degree elevation angle</td>
</tr>
</tbody>
</table>

Delay spreads (& coherence bandwidths) vary by more than an order of magnitude
Key Channel Parameters

• **Path loss** (attenuation)
  – \( L(d) \approx A + 10n\log(d/d_0) + X \); or “2-ray”

• **Delay dispersion**
  – RMS-delay spread \( \sigma_\tau \)
  – Coherence BW \( B_c \sim 1/\sigma_\tau \)

• **Time Variation**
  – Doppler spread \( f_D \) & coherence time \( t_c \sim 1/f_D \)

• **Inter-antenna/band correlation**
Channel Effects

• Current comm. systems: 3 main chan. effects

1. Large scale **path loss**: function of Tx-Rx distance \( d \); typically \( \sim d^n \), \( n \sim 2-7 \)
   • Attenuation, spreading or basic transmission loss

2. Small scale **fading**: “local” phenomenon, often nearly independent of Tx-Rx distance
   • Occurs on spatial scales \( \sim \lambda/2 \)—**multipath**

3. **Shadowing**: blockage or obstruction of LOS
   • Related to **diffraction**
Channel Attenuations

- Graphically (extension of plot in [Sklar]); with $P_t$, $G$’s constant

Received Power $P_r$ (log scale)

- Small Scale Fading (multipath)
- Shadowing (obstruction)
- Path loss (spreading)
- Medium (meso) –scale fading

$d$ (log scale)

$\sim \lambda / 2 \quad \gg \lambda$
Channel Models

- For communications (& radar, navigation, etc.), want model for what channel does to signals
- Simplest model is

\[ s(t) \stackrel{\text{Delay } \tau_0}{\rightarrow} s(t-\tau_0) \rightarrow \alpha s(t-\tau_0) \rightarrow r(t) \]

- \( s(t) \) = transmitted signal, bandpass
- \( \alpha \) = channel gain
- \( r(t) \) = received signal

Valid for AG channel (e.g., enroute) when GS in OPEN area, & surface reflection minimal/mitigated
Channel Models (2)

- Simplest model is **distortionless**

\[ h(\tau, t) = \alpha(t) \delta(\tau - \tau_0) \]

- **Channel impulse response (CIR)**

  - Transfer function \( H(f, t) = \alpha(t) \exp(-j2\pi f \tau_0) \)
  
  - Model can interchange order of delay & gain (linear)
  
  - In general, both \( \tau_0 \) and \( \alpha \) are **time varying**
Canonical Channel Model

- For digital comm., send symbol sequences $\{x_k\}$
- Linear, time-varying (LTV) channel modeled by FIR filter, “tapped-delay line” (TDL)

$$ y_k = \ell(t) \beta(t) \sum_{i=0}^{L-1} x_{k-i} h_i(t) $$

Delay dispersion $\Leftrightarrow$ Frequency selectivity
Time variation $\Leftrightarrow$ Spectral broadening
• Channel is *linear, time-varying* system

⇒ Completely characterized by *channel impulse response* (CIR) $h(\tau, t)$ (or $F\{h(\tau, t)\} = H(f, t)$)

$$h^{(c)}(\tau, t) = \sum_{k=0}^{L(t)-1} z_k(t) \alpha_k(t) \exp\{j[\omega_{D,k}(t)(t - \tau_k(t)) - \omega_c(t) \tau_k(t)]\} \delta[\tau - \tau_k(t)]$$

- “birth/death”
- amplitude of $k^{th}$ MPC
- phase of $k^{th}$ MPC
- Doppler of $k^{th}$ MPC
- Dirac delta
- delay of $k^{th}$ MPC
# Channel Parameters & Effects

<table>
<thead>
<tr>
<th>Channel Parameters</th>
<th>Affected Signal/System Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multipath delay spread $T_M$ &amp; coherence bandwidth $B_c$</td>
<td>Signal &amp; subcarrier bandwidths, symbol rate, cyclic prefix or equalizer length</td>
</tr>
<tr>
<td>Channel attenuation $\alpha$</td>
<td>Transmit power $P_t$, link range, modulation/FEC/detection, data rate $R_b$</td>
</tr>
<tr>
<td>Doppler spread $f_D$, &amp; coherence time $t_c$</td>
<td>Data block/packet size, signal &amp; subcarrier bandwidths, FEC type/strength, transceiver adaptation rates, duplexing method</td>
</tr>
<tr>
<td>Spatial/temporal correlations $\rho_s$, $\rho_t$</td>
<td>Diversity method, FEC type, multiplexing method, antenna design</td>
</tr>
</tbody>
</table>

Channel affects availability, integrity, latency
• How channel model affects spectrum
  – Dispersion affects signal bandwidth (⇒data rates)
  – Path loss, shadowing affect link range
    • This affects frequency re-use distance⇒ capacity

– Rate of time variation affects packet size
  • Variation rate⇒“burst” length, which for given data rate, specifies signal bandwidth
Channel Modeling

- Channel modeling complexity ↑ over time
  - Increased accuracy for higher system reliability
  - Wider signal bandwidths

- Model types/examples
  - Free-space
  - 2-ray
  - MPCs (TDL)
  - Deterministic (HF, e.g., ray tracing)
  - Statistical
  - Hybrid/combination
Aeronautical Channels

• Types
  – Air-to-Ground (AG) ~ Ground-to-Air (GA) ×
  – Air-to-Air ~ ×

• Aircraft “phases of flight”
  – En route (✓ for conventional links)
  – Takeoff/Landing ~ × (✓ for conventional links)
  – Taxiing & Parking (GG)

• Done for airport surface area [DWM, DLR] ✓
NASA AG Chan. Measurements

- Simultaneous **dual-band** 1 x 2 measurements
- Six-seven distinct environments
- Power delay profiles for estimating
  - Path loss, small-scale fading
  - Delay dispersion
  - Doppler
  - Correlations

Telluride, CO
Measurement Equipment

GS

Transmitter

- L-band Tx
- C-band Tx
to Transmit Antennas

Receiver 1

- L-band Rx
- C-band Rx
from Receive Antennas

Receiver 2

- L-band Rx
- C-band Rx
from Receive Antennas

Band | Signal Bandwidth (MHz) | Frequency Span (MHz) |
-----|------------------------|----------------------|
L    | 5                      | 960-977              |
C    | 50                     | 5000-5100            |

- \( P_{Tx} \sim 10 \, W \) (40 dBm)
- C-band: HPA \( G \sim 7 \, dB \), LNAs \( G \sim 30 \, dB \)
- \( R_{rep,max} \sim 3 \, kHz \)

Band | DS-SS Sequence Length \( N \) | \( \tau_{\text{MAX}} \) (\( \mu s \)) |
-----|-------------------------------|-----------------------------------|
L    | 511                           | 102.2                             |
L    | 1023                          | 204.6                             |
C    | 511                           | 10.2                              |
C    | 1023                          | 20.4                              |
Dual-Band Channel Sounder

Each Rx chassis contains 1 L-band & 1 C-band Rx

Receivers (Qty 2)

Transmitter (at GS)
Measurement Equipment (cont’d)

- Transportable ground site (GS), S-3B aircraft

20 m extendable tower

Four receiver (Rx) antennas:
- 2 in C-band, 2 in L-band
Example Measurement Environment

- Desert, hilly/suburban, near Palmdale, CA
  - June 2013
  - $G_C=6$ dB, $G_L=5$ dB
  - $h_{GS} = 20$ m
  - El/Az beamwidths
    - $35^\circ/180^\circ$ for C
    - $60^\circ/120^\circ$ for L
  - Aircraft antennas omni monopoles ("blades")
  - Both straight & oval-shaped flight tracks (FTs)
  - Over 42 GB data (>106 million PDPs) gathered
$h_{\text{OverSea}}(\tau, t) = \alpha_0(t)e^{-j\phi_0(t)}\delta(\tau) + \alpha_s(t)e^{-j\phi_3(t)}\delta(\tau - \tau_s(t))$

$+ z_3(t)\alpha_3(t)e^{-j\phi_3(t)}\delta(\tau - \tau_s(t) - \Delta \tau_3(t))$
Channel Modeling → Radio → Network

1. AG Channel Modeling

- Measurements
- Data processing
- Validation

![Diagram of AG Channel Model](image)

**Example Input**

- Flight Paths & attitudes
- Frequency Band
- Geometry (d, θ, ...)
- Environment Type
- Desired Model Features
- Time Duration

**Example Output**

- LOS & Ground Ray Computations
- Obstruction Attenuation Model(s)
- MPC Model(s)
- AG Channel Model: Time-Domain Samples

![Variation of Ricean K-factor](image)


2. Channel Model Implementation

\[ \beta(t) = \text{shadowing} \]

from Tx \( x_k \) to Rx \( y_k \)

**Encapsulated PHY-MAC Model**

- Radio Tx Model(s) PHY/MAC
- Radio Rx Model(s) PHY/MAC
- Environment Type
- Flight Path
- Geometry
- Frame
- Demod Alg
- Sync

3. Network Model Integration

OpNet Network Model

University of South Carolina
Measurement Results: Path Loss

- Over-water best model: CE2R + Ricean

CE2R approximates shape vs. range better than log-distance models
- Ricean models surface scattering
Airframe Shadowing

- Example shadowing events, statistics

### Over-Freshwater Statistics

<table>
<thead>
<tr>
<th></th>
<th>C-band</th>
<th>L-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadow Duration (s)</td>
<td>Rx1</td>
<td>Rx2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>36.5</td>
<td>37.3</td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>4.2</td>
</tr>
<tr>
<td>Mean</td>
<td>9.1</td>
<td>17.2</td>
</tr>
<tr>
<td>Median</td>
<td>6.3</td>
<td>16.9</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>7.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Distance (km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>21.8</td>
<td>21.8</td>
</tr>
<tr>
<td>Min</td>
<td>20.5</td>
<td>20.5</td>
</tr>
</tbody>
</table>

- Example shadowing events, statistics
Example: Hilly Terrain RMS-DS

- RMS-DS vs. distance

- “Spikes” not anomalies/noise: *intermittent MPCs* due to terrain, buildings, etc.
Hilly Terrain PDPs, RMD-DS Stats

<table>
<thead>
<tr>
<th>RMS Delay Spread</th>
<th>Mean (ns)</th>
<th>Median (ns)</th>
<th>Max (ns)</th>
<th>Standard Deviation (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FT1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original</td>
<td></td>
<td>10.9</td>
<td>267.2</td>
<td>9.8</td>
</tr>
<tr>
<td>Moving Averaged, 100 PDPs</td>
<td>12.9</td>
<td>11.1</td>
<td>87.0</td>
<td>6.6</td>
</tr>
<tr>
<td>Moving Averaged, 1000 PDPs</td>
<td></td>
<td>11.2</td>
<td>57.0</td>
<td>5.7</td>
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<tr>
<td><strong>FT6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original</td>
<td></td>
<td>10.9</td>
<td>995.7</td>
<td>55.7</td>
</tr>
<tr>
<td>Moving Averaged, 100 PDPs</td>
<td>35.7</td>
<td>18.6</td>
<td>371.8</td>
<td>42.9</td>
</tr>
<tr>
<td>Moving Averaged, 1000 PDPs</td>
<td></td>
<td>19.3</td>
<td>349.2</td>
<td>40.4</td>
</tr>
</tbody>
</table>
Wideband Modeling

- **Traditional TDL**
  - For *over-water*
    - component 1 = LOS
    - component 2 = surface reflection
    - component 3 = *intermittent* 3rd ray

![Diagram showing the relationship between link distance, probability of 3rd ray present, duration, and delay](image)

**OxnardCA***06-11-2013**

- **Empirical Probability**
- **Exponential** ($a=0.17$, $b=-0.25$)

**Pr[“on”]**

**Duration**

**Delay**

**Link Distance (km)**

<table>
<thead>
<tr>
<th>Probability of 3rd Ray Present</th>
<th>10^{-1}</th>
<th>10^{0}</th>
<th>10^{1}</th>
<th>10^{2}</th>
<th>10^{3}</th>
<th>10^{4}</th>
<th>10^{5}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Distance (km)</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

- **Excess Delay (ns)**
  - max(Delay)
  - mean(Delay)
  - median(Delay)
  - Fit of max
  - Fit of mean
  - Fit of median

**University of South Carolina**
Additional Models, TBPdeveloped

- Hilly & mountainous terrain
- Suburban & near-urban
- Airframe shadowing

- Small UAS!
Summary

• Mobile radio—AG—communications requires **accurate channel characterization for high reliability**

• Complete channel characterization/modeling
  – CIR $h(\tau,t)$ or CTF $H(f,t)$
  – Path loss, small-scale fading, shadowing, # MPCs, correlations...
Summary (2)

• AG channel investigated much less than other channels (narrowband signals, high GS in open area...)

• Setting (GS) & flight path significantly affects
  – Presence/absence of LoS (range, fading severity)
  – Density of scatterers (dispersion, distortion)
  – Rate of time variation (Doppler)

• Channel modeling work ongoing!
Questions?

Thank You!