Terrestrial communication in the X/ K bands aided by hybrid antenna arrays and precoding techniques

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Outline

- **Background**: terrestrial & satellite-ground communications (H2020 Project SANSA)
- **Objectives** & focus
- **Channel** modelling
- **Antenna technology**: hybrid analog / digital antenna arrays
- **Single-RF** solutions
- **Multiple-RF** solutions
- **Interference mitigation techniques**
- **Summary / conclusions**
The aim of H2020 project SANSA is to improve the capacity, resilience, and coverage of mobile backhaul networks while maximizing, at the same time, their spectral and energy efficiency, in order to meet the Digital Agenda 2020 for the European Union requirements.

Project partners:
CTTC (Spain), Thales Alenia Space (Spain), ULUX (Luxembourg), AIT (Greece), Avanti (UK), OTE (Greece), Fraunhofer IIS (Germany), ViaSat (Switzerland)
SANSA Objectives

The SANSA paradigm promotes the development of self-organizing hybrid terrestrial – satellite backhaul networks that are capable of reconfiguring the terrestrial topology and jointly exploit the terrestrial and satellite links depending on the traffic demands.

The main SANSA objectives are to:

1. Increase the mobile backhaul network’s capacity in view of the predicted traffic demands.
2. Drastically improve backhaul network resilience against link failures and congestion.
3. Facilitate the deployment of mobile networks both in sparsely and densely populated areas.
4. Improve the spectral efficiency in the extended K/Ka-bands for backhaul operations.
5. Reduce the energy consumption of mobile backhaul networks.
6. Strengthen the terrestrial and satellite operators’ market and their related industries.
Ground-satellite interference in SANSA
Our focus in SANSA

- **Interference mitigation techniques** applied on P2MP and MP2MP networks (e.g. via precoder and beamforming designs).
- **Power allocation** of multi-antenna links under an interfered power constraint.
- **Antenna arrays** (e.g. phased, hybrid and parasitic) designs.
- **Coordinated MIMO techniques**

For these, we have developed a channel simulator that is suitable for the modelling of the corresponding links.
Channel Simulator Architecture

- **Input (GUI)**: Scenario, topology, frequency, etc.
- **Nodes / Links Configuration**: Topology filename, N of links, link connectivity, etc.
- **Build Clusters / MPCs**: Selected scenario, N clusters, M sub-paths
- **Scattering Environment**: Antenna file, azimuthal/elevation angles
- **Antenna RPs Configuration**: File (topology.xls)
- **SIMULATOR**: File (Radiation_pattern.xls)
- **Plots**: H Data

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SANSA Channel Model structure

We pursue a semi-deterministic approach wherein the node topology is given, whereas the clusters of scatterers are drawn from a statistical distribution [1][3].

The driving factors behind the development of the SANSA channel model simulator were:

1. The use of topologies such as the “Helsinki” or “Vienna” (geometry based) for benchmarking without the need of exhaustive sets of measurement data.

2. The need to include steerable, narrow beam antennas (smart antennas), hence the incorporation of the angular (spatial) dimension.

3. The desire to address a variety of propagation environments.
Channel Model Configuration

Inputs:

- Placement / Locations of the nodes (for site-specific topologies)
- Number of nodes and link configuration (Active links per network)
- Type of scenario (rural, suburban, urban, etc.)
- Link parameters (frequency, Tx power, rain rate [7][8], BW, speed, number of iterations, etc.)
- Antenna parameters (type, angles, simulated or measured radiation pattern data)

Outputs:

- Channel Coefficients (for all links, including interfering links)
- Power Delay Profile (RMS Delay) per link and composite for given radiation patterns
- Doppler Effect
- Estimation of multipath component parameters (MPCs), such as AoD/AoA, path loss, phase, delay, etc.
- Exported file and plots with all simulated data
Channel model software GUI screenshot

19/28 GHz mmWAVE CHANNEL MODEL SIMULATOR

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<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Mode</th>
<th>Scenario</th>
<th>BW (MHz)</th>
<th>Samples (FFT)</th>
<th>N iterations</th>
<th>Rain rate (mm/hr)</th>
<th>Power (dBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Topology</td>
<td>6</td>
<td>Rural</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Number of Links
8

Load Clusters from File

Link | Tx | Rx | Tx_RP | Tx(phi) | Tx(theta) | RP Rx | Rx(phi) | Rx(theta) |
1    | Node_01 | Node_02 | bowtie.mat | 274.03 | 92.83 | bowtie.mat | 94.03 | 87.17 |
2    | Node_01 | Node_03 | bowtie.mat | 348.36 | 90.82 | bowtie.mat | 168.36 | 80.18 |
3    | Node_01 | Node_05 | bowtie.mat | 330.05 | 95.11 | bowtie.mat | 150.05 | 84.69 |
4    | Node_01 | Node_08 | bowtie.mat | 39.38  | 91.75 | bowtie.mat | 219.38 | 88.25 |
5    | Node_10 | Node_02 | bowtie.mat | 217.53 | 90.39 | bowtie.mat | 37.53  | 80.61 |
6    | Node_10 | Node_03 | bowtie.mat | 203.00 | 88.83 | bowtie.mat | 103.00 | 90.17 |
7    | Node_10 | Node_05 | bowtie.mat | 205.41 | 90.63 | bowtie.mat | 26.41  | 88.37 |
8    | Node_10 | Node_08 | bowtie.mat | 140.93 | 90.89 | bowtie.mat | 320.93 | 89.11 |

Antenna Alignment
AUTO USER

www.sansa-h2020.eu
Indicative antenna radiation patterns for given links

Link Setup (19GHz Bowtie Parasitic Antennas)

Network Setup (multiple P2P links)
Indicative results for a P2P Link

Scattering Environments (MPC rays)

Clusters and Link Terminals - 2D Map Plot

PDP Plot

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Parasitic antenna arrays

The well-known baseband model of antenna arrays can be adopted as:

\[ y = Hi + n \]

where:

\[ i = (Z_T + Z_G)^{-1} v_T \]

\[ v_T = [v_{T1} \ 0 \ \ldots \ \ 0]^T \]

Design methodology:

First compute the desired currents

Then compute the loads that generate them

Arbitrary precoding schemes


Circular, i.e. 3D geometry

Planar, i.e. 2D geometry

active element

passive element

Tunable passive loads
19.25GHz: Single-RF Parasitic antenna design

- Bowtie-like elements.
- 1 active element at the center and 10 parasitic elements around it, resonates at 19.25GHz.
- Overall dimensions: 13x13mm.
Single-RF parameters & radiation patterns

- 3D far field radiation pattern, 4.88dBi gain.
- Azimuth plane.
- Elevation plane.
- Used for coordinated MIMO simulations.
Multi-Active / Multi-Pasive (MAMP) Array @ 19.25GHz

- 4 clusters of the initial parasitic antenna are used. Total of 4 active and 40 parasitic elements.
- Scattering parameters show good resonance at 19.25GHz and sufficient isolation between ports.
- Active inter-element distance is λ/2. Overall dimensions: 13x39mm.
MAMP parameters & radiation patterns

- 0deg rotation using weights in the baseband.
- 3D far field radiation pattern, 10.47dBi gain.
- Azimuth plane.
- Elevation plane.
MAMP parameters & radiation patterns (2)

- +45deg rotation using weights in the baseband.
- 3D far field radiation pattern, 9.38dBi gain.
- Azimuth plane.
- Elevation plane.
Precoding: Cooperative MIMO and switching based on Parasitic Antenna Arrays

Selected beam pair: Option 12

2 TX-RX pairs, 4 beams per TX node (16 beam combinations in total)
Precoding & power allocation

Zero Forcing:

\[ F^{(ZF)} = H^+ = H^\dagger (HH^\dagger)^{-1}. \]
\[ W^{(ZF)} = \frac{F^{(ZF)}(:, k)}{\|F^{(ZF)}(:, k)\|}, \quad k = 1, 2, \ldots, K. \]

Regularized ZF:

\[ v^{(RZF)}_k = H^\dagger \left( \frac{1}{p_k} I_K + HH^\dagger \right)^{-1}, \quad k = 1, 2, \ldots, K. \]
\[ w^{(RZF)}_k = \frac{v^{(RZF)}_k}{\|v^{(RZF)}_k\|}, \quad k = 1, 2, \ldots, K. \]

Power Allocation:

\[
\begin{align*}
\text{maximize} \quad & R = \sum_{k=1}^{K} \log_2 (1 + \text{SINR}_k) \\
\text{subject to} \quad & p_k \leq P. \\
\text{subject to} \quad & p_k = \left[ u_k - \frac{\sigma_n^2}{h_k} \right]^+ 
\end{align*}
\]
Spectral Efficiencies

Coordinated MIMO (19.25 GHz): Joint Transmission over Beams

- RZF: CSI-based beam pair selection
- ZFBF: CSI-based beam pair selection
- ZFBF: SINR-based beam pair selection

Average Sum Rate [bit/channel use] vs. Average SNR [dB]

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Spatial multiplexing under an interfered receiver constraint

Maximization of the mutual information according to the decomposition of:
\[ H_s^\dagger R_z^{-1} H_s = U \Lambda U^\dagger \]

Convex Optimization Task:
\[
\max_{d_i} \sum_{i=1}^{r} \log_2 (1 + \lambda_i d_i), \\
\text{s.t.} \quad d_i \geq 0, \\
\sum_{i=1}^{r} d_i \leq P, \\
\sum_{i=1}^{r} \alpha_i d_i \leq P_l.
\]

\[
y_s = H_s s + H_{ps} x + \eta \\
y_p = H_p x + H_{sp} s + \nu
\]
Capacity gains

Achieved Capacity and capacity loss %

Empirical CDF’s for various capacities achieved with different interference constraint values
Summary / conclusions

• Ground / satellite co-existence is a challenging yet promising paradigm for future 5G networks

• Antenna arrays of low complexity can be used in order to reduce the complexity and cost of ground station transceivers

• Hybrid analog / digital antenna arrays based on parasitic (single or multiple-RF) designs have been explored in this direction

• A combination of the derived hybrid antenna arrays and interference mitigation techniques shows a promising low-complexity approach in mitigating the interference in the corresponding setups
References

Thank You!