Smart Antennas for Mobile Communications
The Importance of the Propagation Channel and Scenarios

João Gil
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What is this talk about?

- There is an ever growing need for capacity, in Mobile Communications.
- *Space* is another resource available for separating signals.
- *Smart Antennas* get into the picture, for this.
- But, their performance is highly dependent on the propagation channel and scenario.
- This talk provides an overview of the issues at stake, helping in understanding why and how such is so.
Outline

• Smart Antennas (SAs), id est,....
• The myriad of issues at stake:
  • Antenna array structures;
  • Adaptive algorithms;
  • Channel models;
  • Multi-user scenarios;
• Some research on channel characterisation for SAs/beamforming.
• Conclusions.
Searching for SAs?

- Googling:
  - “Smart Antenna” – 92 500 occurrences;
  - “Smart Antenna” + “Mobile” – 46 500;
  - “Propagation channel” – 22 200;
  - All phrases – 435;
  - “Harry Potter” – 18 600 000!
- There are many books, magazines, journals, papers, lectures, seminars, on SAs.
- SAs are not new, being used for much more than mobile comms.
Background and Motivation (1)

• Array processing is used for:
  • Sound Engineering;
  • Sound Navigation And Ranging (SONAR);
  • Radio Detection And Ranging (RADAR);
  • Communications;
  • Imaging;
  • Geophysical and Astrophysical Exploration;
  • Biomedicine;
  • etc.
Background and Motivation (2)

• Concerning mobile communications systems, evolution is permanent:
  • From being analogue to digital;
  • From targeting voice to data;
  • From using temporal, frequency, to code and/or spatial resources.

• For UMTS, the 3GPP Working Group 1, TSG-RAN, has considered the application of SAs, from the onset.
Background and Motivation (3)

- So, in the mobile communications case:
  - There is an increasing demand for capacity (bit/s/Hz/cell) and new services;
  - This requires more/new means of reducing intra- and inter-cell interference;
  - There is a large infrastructure already set;
  - TDMA/FDMA/CDMA are not enough.

One solution is the using of SAs, for Spatial Division Multiple Access!
What is the idea? (1)
What is the idea? (2)

The Phased Array Concept
(narrowband array assumption)
Analogies to Real-Life Common Situations (1)

- From our birth, we have always applied the principle behind SAs!
- There are simple analogies that show it:
  - *Blind animal/person, or Afraid in the dark situation* – nulling out interaural phase;
  - *The busy restaurant* – spatially separating channels.
- We make use of spatial filtering, for audio.
- It’s a problem of choosing the right signal, the wanted wave!
Analogies to Real-Life Common Situations (2)
Analogies to Real-Life Common Situations (3)
Deployment Benefits

• SAs may work on top of the current networks to improve:
  • Interference rejection ➔ Capacity
  • Multipath exploitation ➔ Diversity
  • Array signal gain ➔ Range/coverage
  • Power efficiency ➔ Expense
Smart Antennas!
Types of SA Structures

- SAs may be grouped into two large families, concerning the pattern generation structures.

  - **Switched-Beam Arrays:**
    - Simple, but stiff and limited performance in tracking a MT, and nulling out the others.

  - **Adaptive Arrays:**
    - Complex, but flexible and powerful performance.
Types of Array Processing (1)

- **Adaptive Arrays** may involve processing units for several objectives.
- These are related, may be complementary, but different:
  - **Direction Estimation** – determining the spatial spectrum, from uncorrelated sources;
  - **Beamforming** – capability to shape of the array pattern, following a criterion;
  - **Tracking** – following signal sources, accounting for channel changes.
Types of Array Processing (2)

- **Beamforming** will be *adaptive* if it involves the adjustment to signal/channel variations.
- Statistically Optimum are types of *Non-adaptive* beamforming, involving several methods/criteria:
  - Sidelobe Cancelling
  - Minimising Mean Squared Error
  - Maximising SNR
  - Reducing Variance
Types of Array Processing (3)

- For Adaptive Beamforming, some of these methods/criteria are implemented by Adaptive Algorithms, e.g.:
  - Steepest Descent (SD)
  - Least Mean-Square (LMS)
  - Recursive Least Squares (RLS)
  - Constant Modulus Algorithm (CMA)
  - Sample Matrix Inversion (SMI)
  - Conjugate Gradient (CG)
  - Neural Networks (NN) based.
Beamforming Structures (1)

• Narrowband array processing

\[
y(n) = \sum_{m=1}^{M} w_m^* x_m(n) = \mathbf{w}^H \mathbf{u}(n)
\]

Baseband and Digital!

Beamforming Structures (2)

- Wideband array processing

\[ y(n) = \sum_{m=1}^{M} \sum_{p=0}^{P_m-1} w_{m,p} \ast u_m(n - p) \]
These need testing – how? (1)

- *Just* go on the field and test!
- **But** to do that, we need:
  - An antenna array, processing structure, and all backing equipment;
  - These fully working, tested and calibrated;
  - Measurements, in different places, several times, with several terminal users;
  - To process all the acquired data;
  - Environmental protection;
  - People, time and money.
These need testing – how? (2)

- There are good research groups and/or consortiums deal with this, e.g., TUW, HUT, UBrís, COST273, or EC projects.
- It is very hard to extrapolate results, and very few include multi-user interference.
- One needs to keep in mind the practical side of system deployment.
- There is a way around it, sought by many people, involving time and money, providing important and contributive results.
Propagation Channel Models!
Channel Modelling (1)

- signal power level (attenuation+fading) and Doppler spectrum
- delay spread/Time-of-Arrival (ToA)
- angle spread/Angle-of-Arrival (AoA)

Spatial Channel Models (SCMs)!
Channel Modelling (2)

• Back in 1999/2000, out of 21 models:
  • Out of the 10 wide-band models, 8 had been conceived for spatial modelling;
  • Though the cluster effect had been proven, only 8 models accounted for it;
  • No model with true field validation;
  • Only 3 models revealed convergence of different models into one (the unification objective, was just arising).
Channel Modelling (3)

- The recent trends are to:
  - Support SCMs with measurements;
  - Unify SCMs into larger, more complete, but complex models, e.g., the COST259 case;
  - Implement *physical* or *non-physical* models;
  - Going into Multiple-Input-Multiple-Output (MIMO) channel modelling;
- Still, the model is chosen depending on its application.
- And, again, there is a plethora of SCMs.
Channel Modelling (4)

- From the most simple:
Channel Modelling (5)

• To more complex, physical:


Channel Modelling (6)

- To more complex, analytical:


Channel Characterisation (1)

• There is the issue of *Spatial Channel Characterisation*, providing properties of arriving/departing waves:
  • Temporal distributions (ToA);
  • Angular distributions (AoA);
  • Correlation properties;
  • Power clustering and diffuse scattering;
  • Eigenstructure properties;
  • Polarization-related issues.
Channel Characterisation (2)

- The focus is on the *Propagation Channel*:

![Diagram](image.png)

- BS Array
- Propagation Channel
- Radio Channel
- Modulation Channel
- Digital Channel
Measurements for Smart Antennas (1)

- There is also the issue/field of doing Measurements:

Arrays for Smart Antennas (2)

• And also the issue/field of building Antenna Arrays:


Multi-User Scenarios
Multi-User Scenarios (1)

• *Multi-user* means several distributed people.
• The most important parameters may be:
  • Environment, e.g., streets, plazas or crossroads scenes, macro-/micro-cells, in/outdoor;
  • Spatial distribution and number of MTs;
  • Number of array elements, location and type of array.
Multi-User Scenarios (2)
Multi-User Scenarios (3)
So, after all of this...
What is truly at stake, then?

Signal Processing

Mobile System

Propagation Channel

Antenna Arrays
Uhm…

Mix these.

Do research!

Contribute!

Say something useful!
Uhm...
Contributing with Research
The Questions

• What are the important Propagation Channel properties that condition SAs performance?

• How do those properties and performance relate, at the physical level?

• How do these vary between Micro- and Macro-cellular propagation channels?

• How do these depend on Multi-user scenarios?
The Channel Model (1)

- *Modified Geometrically Based Single Bounce Elliptical or Circular Models* were used.
- Scatterers are grouped into clusters.
- Each *l*\textsuperscript{th} MT-BS link defines a scattering area, defined by each *l*\textsuperscript{th} MT and BS.
The Channel Model (2)

- Model parameters have been assessed with measurements.
- It complies with the objectives:
  - It is physical and semi-statistical;
  - It is flexible;
  - It allows for multi-user application;
  - It is simple and effective.
MiCs and MaCs Scenarios (1)

\[ \phi_{MT1..L} = 0^\circ \]

\[ d_{MT} \]

\[ \phi_{MT1..L} \sim U(-\pi/2, \pi/2) \]
MiCs and MaCs Scenarios (2)

$$d_{MT}$$

$$\phi_{MT1} = \pi/4$$

$$\phi_{MT2..L} = -\pi/5$$

$$\phi_{MT1} \sim U(0, \pi/2)$$

$$\phi_{MT} \sim U(-\pi/2, 0)$$
# Channel Characteristics

<table>
<thead>
<tr>
<th>$d_{MT}$ [m]</th>
<th>$\sigma_\tau$ [$\mu$s]</th>
<th>$\sigma_{\phi, NB}$ [$^\circ$]</th>
<th>$A_{\text{scat. ellipse}}$ [km$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.39</td>
<td>44</td>
<td>0.182</td>
</tr>
<tr>
<td>500</td>
<td>0.18</td>
<td>32</td>
<td>0.261</td>
</tr>
<tr>
<td>1 000</td>
<td>0.10</td>
<td>23</td>
<td>0.418</td>
</tr>
</tbody>
</table>

**Micro-cells (MiCs)**

<table>
<thead>
<tr>
<th>$r$ [m]</th>
<th>$d_{MT}$ [m]</th>
<th>$\sigma_\tau$ [$\mu$s]</th>
<th>$\sigma_{\phi, NB}$ [$^\circ$]</th>
<th>$A_{\text{scat. circle}}$ [km$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1 500</td>
<td>0.10</td>
<td>$\approx$ 0.8</td>
<td>0.008</td>
</tr>
<tr>
<td>1 000</td>
<td>1 500</td>
<td>0.36</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>2 000</td>
<td>1 500</td>
<td>0.37</td>
<td>3.7</td>
<td>0.126</td>
</tr>
<tr>
<td>400</td>
<td>1 500</td>
<td>0.66</td>
<td>7.4</td>
<td>0.503</td>
</tr>
</tbody>
</table>

**Macro-cells (MaCs)**
New Channel Parameters (1)

- $\rho_\tau [\text{km}^2 / \mu s] = \frac{A_{\text{scat}} [\text{km}^2]}{\sigma_\tau [\mu s]}$, Temporal Density

- $\rho_\phi [\text{km}^2 / \text{rad}] = \frac{A_{\text{scat}} [\text{km}^2]}{\sigma_{\phi, NB} [\text{rad}]}$, Angular Density

- Multipath Frequency, $\omega_{DCIR} [\text{rad} / \mu s] = \frac{\rho_\tau}{\rho_\phi} = \frac{\sigma_{\phi, NB} [\text{rad}]}{\sigma_\tau [\mu s]}$

- These account for the spatio-temporal decorrelation and channel richness, in the multi-user/multi-link sense.
New Channel Parameters (2)

- Channel 2 results in components that are temporally more correlated, per link;
- But, between links, Channel 2 results in components that better retain decorrelation;
- Channel 2 will aid in temporal separation.
New Channel Parameters (3)

- Channel 2 results in components that are angularly more correlated, per link;
- Also among links, as function of the scenario!
- Channel 2 may not aid in angular separation.
The Adaptive Problem (1)

- In the Up-Link, at the Base Station, with a Uniform Linear Array, for TDD, UMTS.
- A Conjugate Gradient Normal Residual problem is solved:

\[ U^H U w_l = U^H c_d^{(l)} \iff R w_l = d_l \]

- The \( l \)th quadratic form is minimised.
- \( U \) is a Signal+AWGN matrix, \( N_s \times M \), taken at chip rate, within a TDD slot.
- \( c_d^{(l)} \) are the TDD codes, \( N_s \times 1 \).
The Adaptive Problem (2)

- SINR was calculated, for the $l^{th}$ link:

$$SINR^{(l)} = G_p \times P_{DesS}^{(l)} \times \left( \sum_{l=1}^{L_T} P_{NDesI}^{(l)} + N \right)^{-1}.$$

- Beamforming Gain was evaluated, for the $l^{th}$ link:

$$G_{bf}^{(l)} [\text{dB}] = SINR^{(l)}_{\text{beamformer [dB]}} - SINR^{(l)}_{\text{single [dB]}}.$$
Performance Results (1)
Array Patterns (examples)
Performance Results (2)
BG, function of $d_i$, $M$ (examples)
Performance Results (3)

SINR, function of $L$, $M$ (examples)
Performance Results (4)

Power & Matrix Components (example)

Macro-cell, $M=12$
Performance Results (5)  
Relating Several Parameters

• Comparing MiCs with MaCs, $\rho_\phi$, $\rho_\tau$, $\omega_{DCIR}$ and performances consistently agree:
  • $\rho_\phi \uparrow \Rightarrow$ worse performance;
  • $\rho_\tau \uparrow \Rightarrow$ better performance;
  • $\omega_{DCIR} \uparrow \Rightarrow$ better performance.

• Such consistency covers both the angular and temporal domains, at the physical level.

• The way that the channel is seen, characterised and studied was confirmed in several ways.
...The Answers

- $\rho_\phi$, $\rho_\tau$ and $\omega_{DCIR}$ are measures of channel richness.
- I.e., the freedom to spatially separate signals, in the angular and temporal domains.
- The channel in MiCs is richer than in MaCs.
- MiCs generally result in better beamforming performance and robustness.
- Future cellular planning must consider this.
Finally

Where *space* seems less available for us, that is where *space* is most available for adaptive antennas to perform best.

*The richness I achieve comes from Nature, the source of my inspiration.*

__—Claude Monet, 1840-1926.__

Public contributions in the ESTG or GROW webpages.
Thank You.