DEI Doctoral Research Seminars – A.Y. 2021/2022

Same power, longer range: estimating the Angle-of-Arrival for adaptive beamforming

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Feb 23rd, 2022

Introducing myself

- ❑ Antonello Florio
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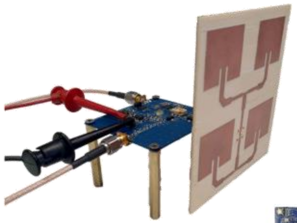
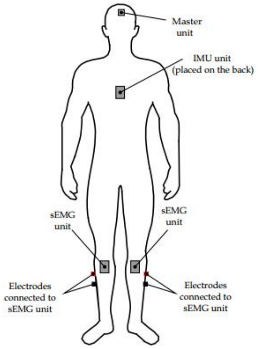
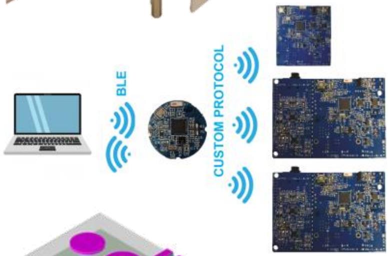
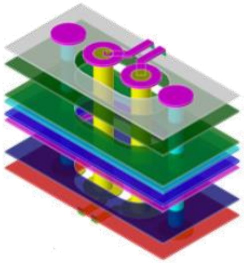
- ▪ Supervisors: Proff. Gianfranco Avitabile, Giuseppe Coviello
- ▪ Research fields: phased arrays, localization, green WSNs

- ❑ Electronics for Telecommunications (ETLC) Laboratory
- ▪ Indoor and outdoor positioning systems
- ▪ E-health
- ▪ RF electronics
- ▪ IoT and IoMT
- ▪ http://etlclab.poliba.it





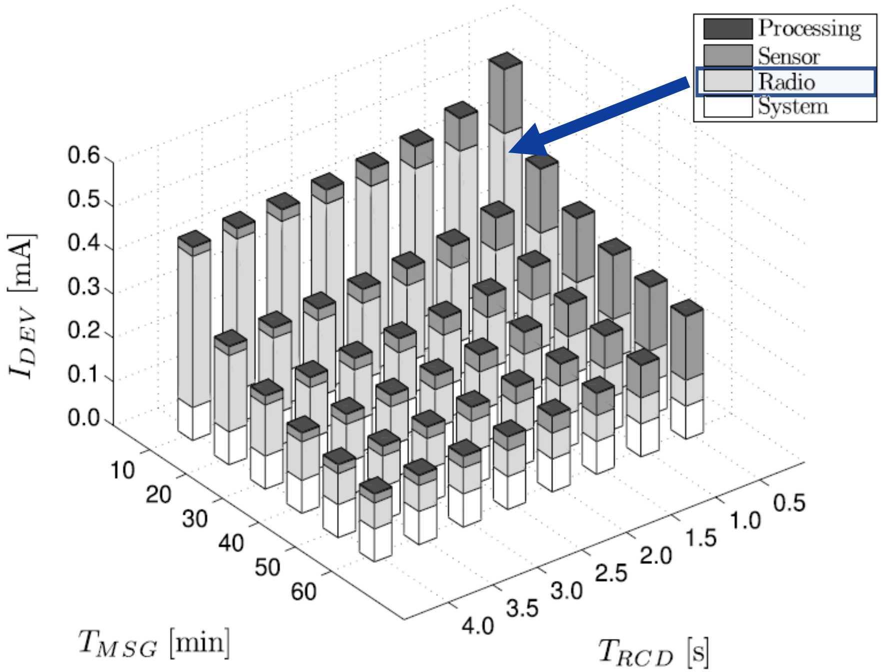




Outline

- Power consumption in IoT devices
- Same power, longer range: beamforming
- Localization for Telecommunications (TLC)
- Estimating the Angle of Arrival (AoA)
- A Full-Hardware approach to AoA estimation
- I/Q Low-Pass Mixing algorithm (1 and q sources)

Power consumption in IoT devices



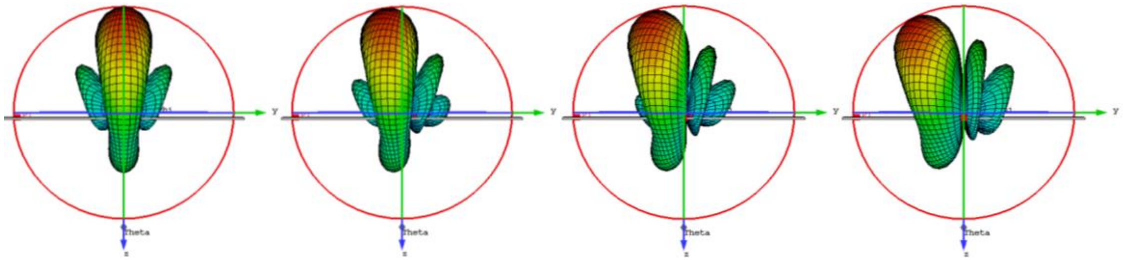
- According to the model proposed by *Martinez et al.* (2015) in an IoT device most of the power is spent in the transceiver section.
  - ✓ Reduce the number of the messages (→not today's subject).
  - ✓ Optimize the power employed for the transmission.

Image source: B. Martinez, M. Montón, I. Vilajosana and J. D. Prades, "The Power of Models: Modeling Power Consumption for IoT Devices," in IEEE Sensors Journal, vol. 15, no. 10, pp. 5777-5789, Oct. 2015.

- From **Friis transmission equation** the power (P_T) decreases as the square of the distance (R) according to:

$$p = \frac{P_T}{4\pi R^2}$$

- Thanks to **adaptive beamforming**, it is possible to focus the antenna pattern towards the wanted direction, even if this direction varies with time.



- **<u>What should we “*adapt*” to?</u>**

✓ As it happens in archery: nock the arrow, **<u>aim</u>**, hold, release!

✓ In order to aim, we must first localize the target.

Localization for TLC

- **What?**

Localization means to establish the position of a given target in the space thanks to a given TLC standard and/or e.m. properties of the signals or the medium employed for the communication.

- **Why?**

Localization allows a set of TLC improvements (energy saving, better interferer rejection, …)

- **How?** Many possible taxonomies:
  - Geometric vs non-geometric
  - Indoor vs outdoor
  - Collaborative vs non-collaborative

Localization for TLC

- **Non-geometric localization**
  - It is employed when there is high prevalence of NLoS conditions or heavy multipath propagation.
  - ✓ Localization relies on **fingerprinting** techniques

- **Geometric localization**
  - Mostly based on Radio Frequency localization (radiolocation).
  - They use measured distances (**trilateration**) and angles (**triangulation**) to known geographical markers (**anchor nodes**).

▪ Received Signal Strenght (RSS)

It is based on the received signal strength, linked to the **pathloss**:

$$\mathrm{FSPL}_{\mathrm{dB}}(r,f) = \boxed{20\log_{10} r} + 20\log_{10} f - 147.55$$

- Considered as the least complex positioning method
- Good estimation *iff* **good channel pathloss model**
- <u>Channel varies:</u> people and objects move in the space.

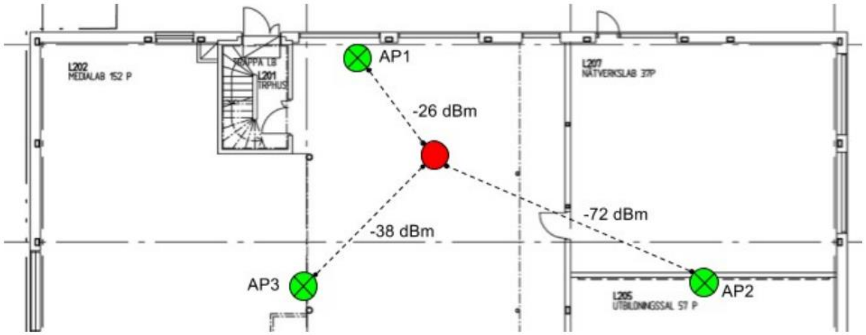


Image src: Christoffer Olsson & Tobias Öhrström. The precision of RSSI-fingerprinting based on connected Wi-Fi devices. Bachelor Thesis (2017).

▪ Phase (Difference) of Arrival (PoA/PDoA)

- We exploit the phase or phase difference of a carrier signal.
- *Hyp*: signals transmitted have known initial phase offset
- Possible applications in RFID and NFC (backscattered signal).

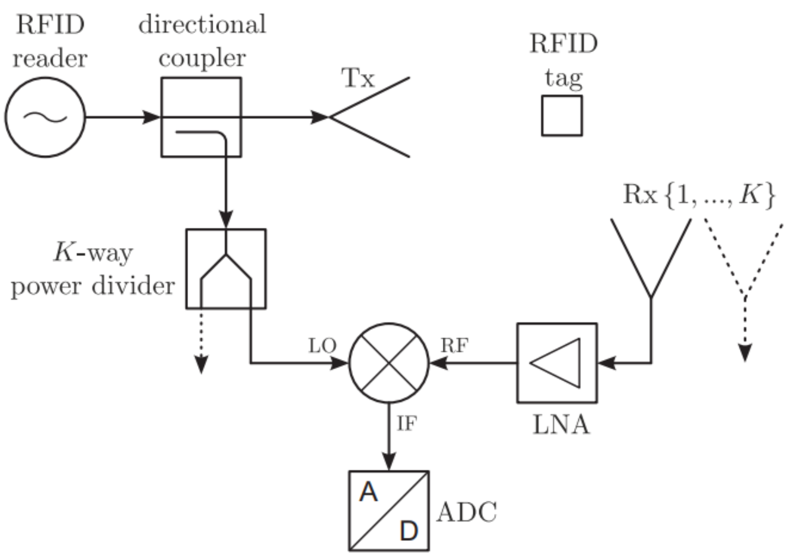


Image src: M. Scherhäufl et al., "Phase-of-arrival-based localization of passive UHF RFID tags," 2013 IEEE MTT-S International Microwave Symposium, pp.1-3

- **Time (Difference) of Arrival (ToA/TDoA)**

- ToA exploits the signal propagation time.

$$d = c \cdot \tau$$

- ToA requires **strict synchronization** between TX and RX.
- Sometimes, timestamps must be transmitted with the signal.
- TDoA does requires instead synchronization between RXs.

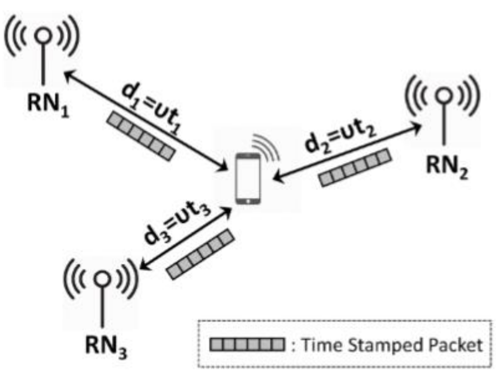


Fig. 3. ToF based user equipment (UE) localization.

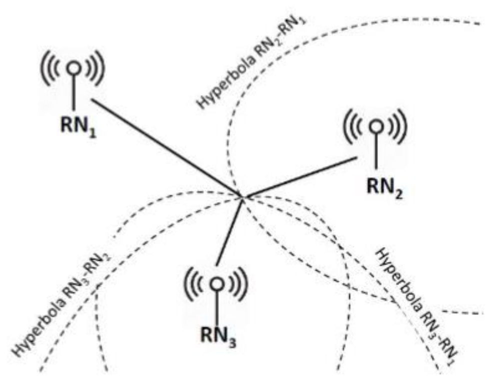


Fig. 4. TDoA based localization and proximity detection.

Image src: F. Zafari, A. Gkelias and K. K. Leung, "A Survey of Indoor Localization Systems and Technologies," in IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2568-2599, thirdquarter 2019

- **Direction or Angle of Arrival (DoA, AoA)**

  - AoA is the angle between the perpendicular to the receiving array and the direction of the incoming wave.
  - In far field, we can suppose the wavefront to be plane.
  - Geometrical relationships can be applied to determine the AoA from the phase difference measured between two receiving antennas.
  - For a M-ULA with spacing d:

$$\Delta\varphi_{i,j}(\vartheta) = \frac{2\pi}{\lambda} d(j-i)\sin\vartheta, \quad i,j = \{0,\cdots,M-1\}$$

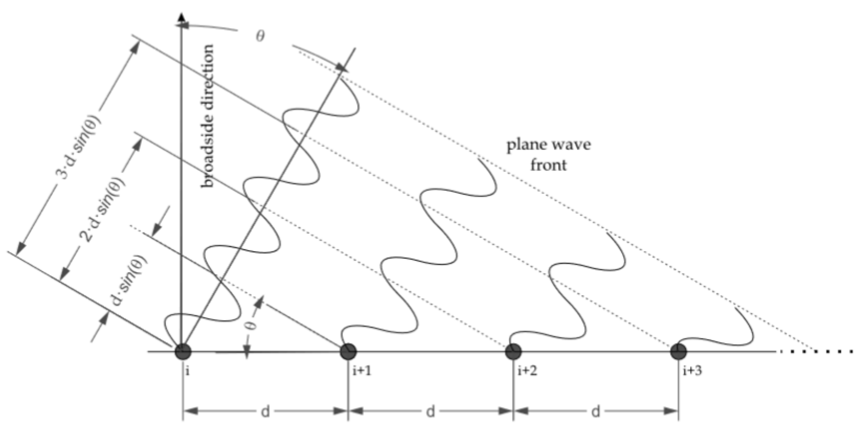


Image src: G. Avitabile, A. Florio and G. Coviello, "Angle of Arrival Estimation Through a Full-Hardware Approach for Adaptive Beamforming," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 67, no. 12, pp. 3033-3037, Dec. 2020.

TABLE II

ADVANTAGES AND DISADVANTAGES OF DIFFERENT LOCALIZATION TECHNIQUES

Technique	**Advantages**	**Disadvantages**
RSSI	Easy to implement, cost efficient, can be used with a number of technologies	Prone to multipath fading and environmental noise, lower localization accuracy, can require fingerprinting
AoA	Can provide high localization accuracy, does not require any fingerprinting	Might require directional antennas and complex hardware, requires comparatively complex algorithms and performance deteriorates with increase in distance between the transmitter and receiver
ToF	Provides high localization accuracy, does not require any fingerprinting	Requires time synchronization between the transmitters and receivers, might require time stamps and multiple antennas at the transmitter and receiver. Line of Sight is mandatory for accurate performance.
TDoA	Does not require any fingerprinting, does not require clock synchronization among the device and RN	Requires clock synchronization among the RNs, might require time stamps, requires larger bandwidth
PoA	Can be used in conjunction with RSS, ToA, TDoA to improve the overall localization accuracy	Degraded performance in the absence of line of sight
Fingerprinting	Fairly easy to use	New fingerprints are required even when there is a minor variation in the space

Image src: F. Zafari, A. Gkelias and K. K. Leung, "A Survey of Indoor Localization Systems and Technologies," in IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2568-2599, thirdquarter 2019

Estimating the AoA

- In literature there are any established methods that can be divided in parametric and space-spectral function computation techniques.

- In the latter category we find algorithms like MUSIC, ESPRIT and root-MUSIC, the so-called **subspace separation techniques**.

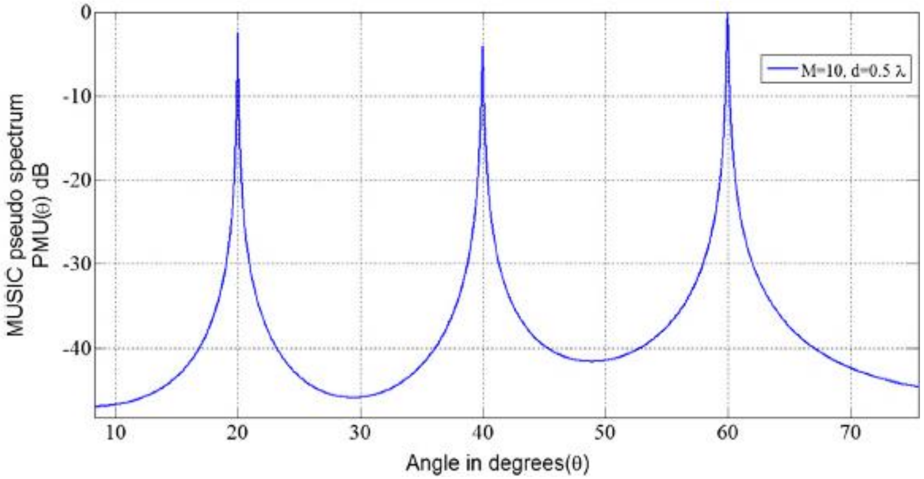
- Let us focus on MUSIC algorithm in order to understand steps that are almost the same between al these techniques.

MUSIC* Algorithm (in a nutshell)

- Let us consider D received signals at a M-ULA. MUSIC estimates the AoA computing the **pseudospectrum**:

$$PMU(\theta) = \frac{1}{\mathbf{a}(\theta)^H \mathbf{E_N} \mathbf{E_N}^H \mathbf{a}(\theta)}$$

being $\mathbf{a}(\theta)$ the steering vector and $\mathbf{E_N}$ the noise eigenvectors



$$\lim_{\theta \to (\theta_1 \cdots \theta_D)} PMU(\theta) \to +\infty$$

* R. Schmidt, "Multiple emitter location and signal parameter estimation," in IEEE Transactions on Antennas and Propagation, vol. 34, no. 3, pp. 276-280, March 1986

MUSIC Algorithm (in a nutshell)

- **MUSIC Algorithm**:
  1. Compute the autocorrelation matrix of the received signal;
  2. Eigenvalue decomposition (EVD) and re-ordering;
  3. Pseudospectrum function computation;
  4. Peak search on the function.

✓ Adv: Accuracy, possibility of managing multiple signals

✓ Dis: The algorithm operates with complex numbers; eigenvalue and eigenvector decomposition and peak search is computationally greedy.

- What happens when considering FPGA implementation?

MUSIC Algorithm (in a nutshell)

- Devendra et al. → study on the correlation between the number of array elements, the committed error and the execution time.
    - When doubling the array elements (from 7 to 14) RMSE has 285% drop but the execution time increases of about the +230% (~ tens of ms).

- Minseok et al. → Implementation with fixed point integers
    - accuracy of about 2°.

- Zou et al. → skip the autocorrelation matrix decomposition and approximating it with a high-speed parallel iterative method.
    - 4 times faster, accuracy degradation.

Estimating the AoA

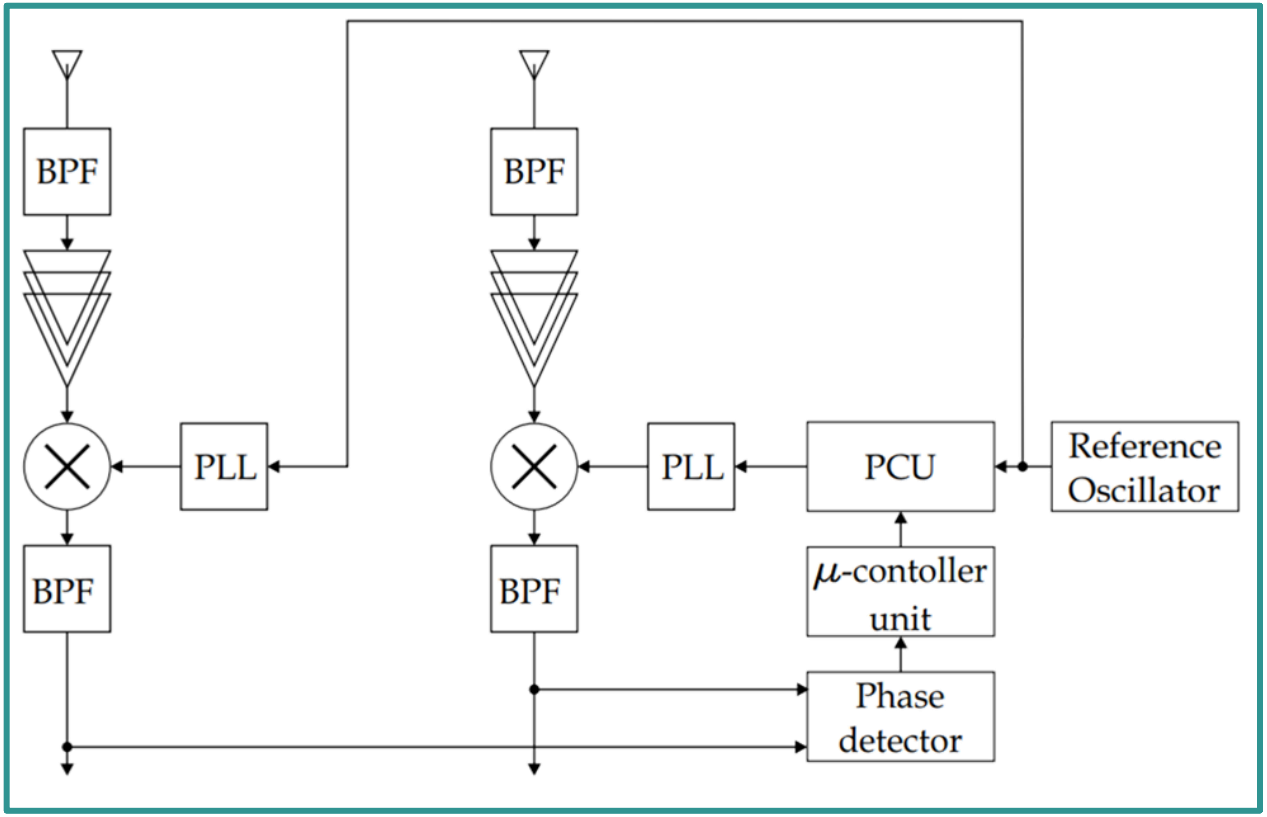
- Why implementing MUSIC in FPGAs (hardware)?

- Localization steals computational resources from other tasks
  - ✓ Implement localization mechanisms in order to make the operations transparent to upper layers of IoT stack.

- Idea: a protocol-agnostic reconfigurable full-hardware AoA estimation technique based on closed-loop estimation that can be implemented in specialized hardware (FPGA/DSP/µC).

  - We aim to seek not for the *best*, but the fastest AoA estimation, that can be refined in as many steps as needed from the given application (“*best subject to*”).

Full-Hardware AoA Estimation



- <u>How to lighten AoA estimation?</u>

Image source: G. Avitabile, A. Florio and G. Coviello, "Angle of Arrival Estimation Through a Full-Hardware Approach for Adaptive Beamforming," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 67, no. 12, pp. 3033-3037, Dec. 2020.

Estimating the AoA

- **Phase interferometry approach**: it consists of simply invert the AoA computation formula.

$$\vartheta = \arcsin\left(\frac{\lambda\,\Delta\varphi_{i,j}(\vartheta)}{2\pi d\,(j-i)}\right)$$

- Now it is necessary to estimate the <u>phase difference</u> between the signals received at two given elements, since the other information is available.

✓ **Algorithmic approach to phase difference estimation**.

- <u>What if more than one source are present?</u>

I/Q Low-Pass Mixing (*1* source)

- Let us consider two signals $s_a[k], s_b[k]$ with same frequency and different amplitudes K_a, K_b and phases φ_a, φ_b respectively.

- Their phase difference is obtained by a beating and low-pass filtering (LPF) operation:

$$\varphi_b - \varphi_a = \arccos\left[\frac{2}{K_a \cdot K_b}\ \mathrm{LPF}\{s_a[k] \cdot s_b[k]\}\right]$$

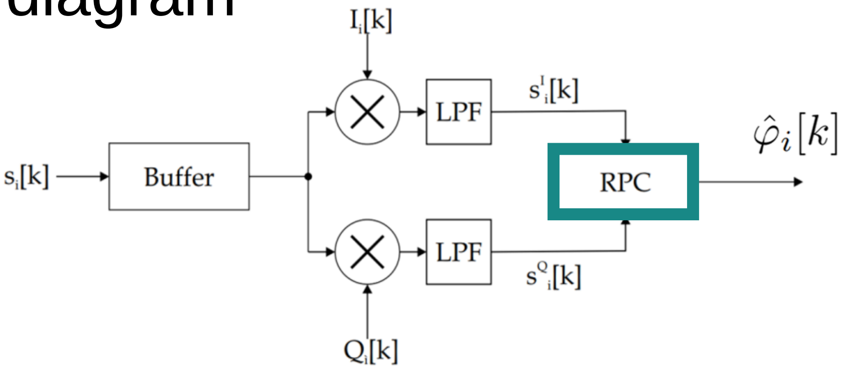
- The baseband term is proportional to the phase difference.
  - ❑ However, two angles have the same cosine value:

$$\cos(x) = \cos(2\pi - x), \forall x \in [0, 2\pi]$$

  - ❑ We need a way to discriminate the quadrant
  - ✓ **Intuition**: *Exploit the sine information*

I/Q Low-Pass Mixing (*1* source)

- The algorithm operations are sketched in the following block diagram



$$s_i^I[k] = \mathrm{LPF}\{s_i[k] \cdot I_i[k]\} \overset{!}{=} \frac{1}{2}\cos(\hat{\varphi}_i[k])$$

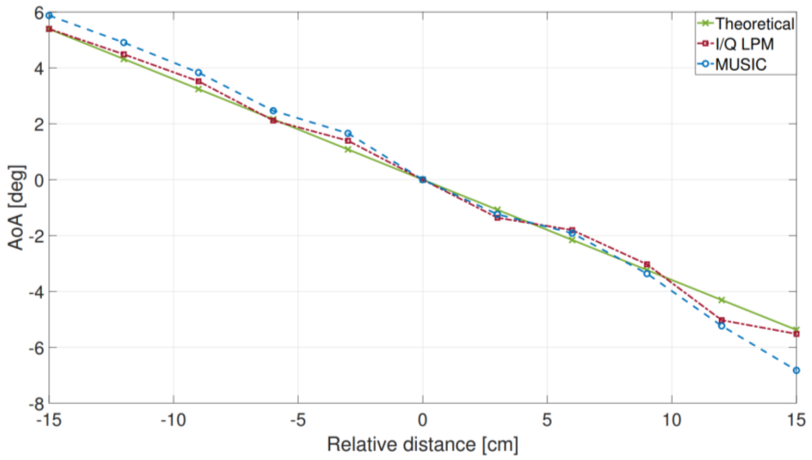
$$\hat{\varphi}_i[k] = \arccos(2 \cdot s_i^I[k]) = \arccos(\xi_i[k])$$

- The MSB $\psi_i[k]$ of the samples allows to identify the quadrant.

Algorithm 1 Phase value adjustment algorithm, with $\varphi_i[k]$ the estimated phase value for channel i at discrete time instant $[k]$

Require: $\xi_i[k] = 2 \cdot s_i^I[k] \in \mathbb{R}$, $\psi_i[k] = \mathrm{MSB}(s_i^Q[k])$
  if $\psi_i(k) = 0$ **then**
    $\varphi_i[k] \leftarrow \arccos(\xi_i[k])$
  end if
  if $\psi_i(k) = 1$ **then**
    $\varphi_i[k] \leftarrow 2\pi - \arccos(\xi_i[k])$
  end if
  return $\varphi_i[k]$

I/Q Low-Pass Mixing (*1* source)



Theoretical AoA values vs Estimated at the distance of 1.6m

Theoretical AoA values vs Estimated at the distance of 2.2m

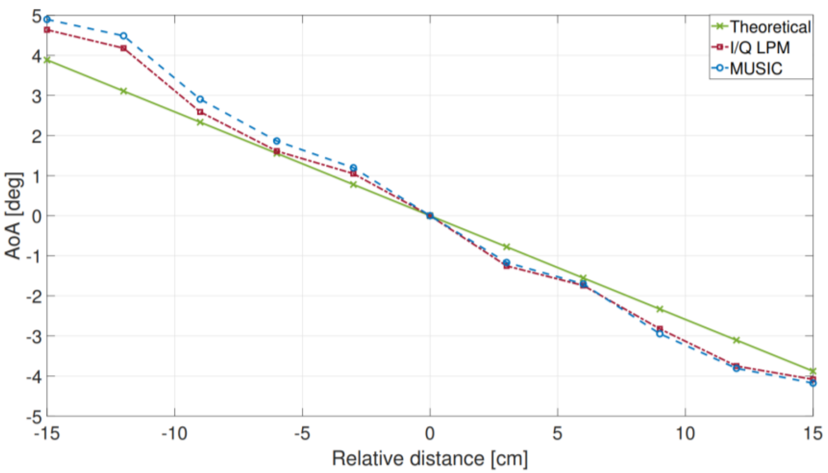


Image source: A. Florio, G. Avitabile and G. Coviello, "Digital Phase Estimation through an I/Q Approach for Angle of Arrival Full-Hardware Localization," 2020 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS), 2020, pp. 106-109.

I/Q Low-Pass Mixing (*1* source)

- The averages and maximum values for both metrics are extracted as average and maximum on the datasets coming from both measurements (i.e. the two broadside distances).

Distance	Max Error [deg]	Avg Error [deg]
I/Q LPM	1.2961	0.3409
MUSIC	1.4484	0.4277

Algorithm	Avg Exec time [s]	Max Exec time [s]
I/Q LPM	0.1081	0.1572
MUSIC	0.9015	0.9969

Image source: A. Florio, G. Avitabile and G. Coviello, "Digital Phase Estimation through an I/Q Approach for Angle of Arrival Full-Hardware Localization," 2020 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS), 2020, pp. 106-109.

I/Q Low-Pass Mixing (*q* sources)

- Hyp:
  - Each source transmits in a spectrum slice $B(p),\ p = 1, \cdots, q.$
  - The devices operate on different slice carriers.
  - Guardbands (GB) separate each spectrum slice.

$$TB = \sum_{p=1}^{q} (2 * \mathrm{GB} + \mathrm{B(p)}) = 2q * \mathrm{GB} + \sum_{p=1}^{q} \mathrm{B(p)} \ = q * (2\,\mathrm{GB} + \mathrm{B})$$

- Let us define suitable digital bandpass filters. Changing digital filters parameters consists of just updating filter coefficients.

- Once those different coefficients have been stored in memory, it is simple to recall the ones which are necessary and make a kind of spectral polling.

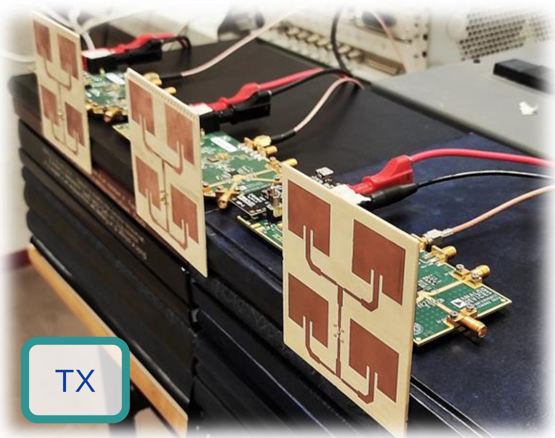
- Here the most and time-consuming operations are the filter itself with a delay that is function of the number of taps, *N*

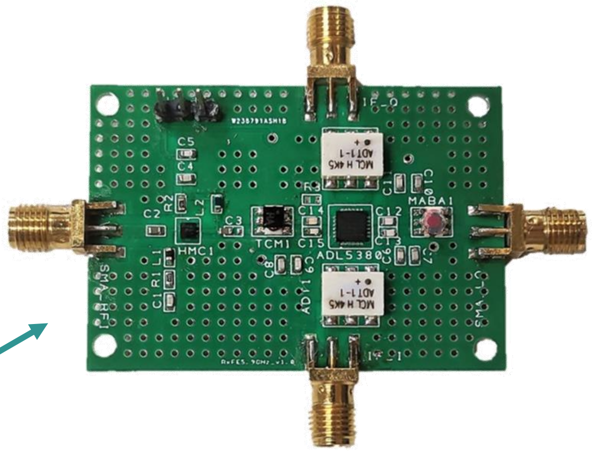
Experiments setup

- Transmitting section with N separate units, radiating +5dBm with frequency $f_{RF}(q) = [3.30 + 0.01\,(q-1)]$ GHz.

- The receiver had 4-ULA and it was connected to a RF front-end for the amplification, filtering and demodulation of the signal to the IF $f_{IF}(q) = [150 + 10\,(q-1)]$ MHz. The IF was then filtered and sampled at 10 GS/s.

- MATLAB implementations of ESPIRT and RMUSIC.





Experiments setup

- Ground Truth (GT) AoA was computed as

$$\vartheta_i(j,l) = \arctan\left(\frac{x_j(i)}{l}\right) \cdot \frac{180}{\pi}$$

- The evaluated statistical metrics were relative to the absolute error committed with respect to the GT AoA. The average error committed was computed as

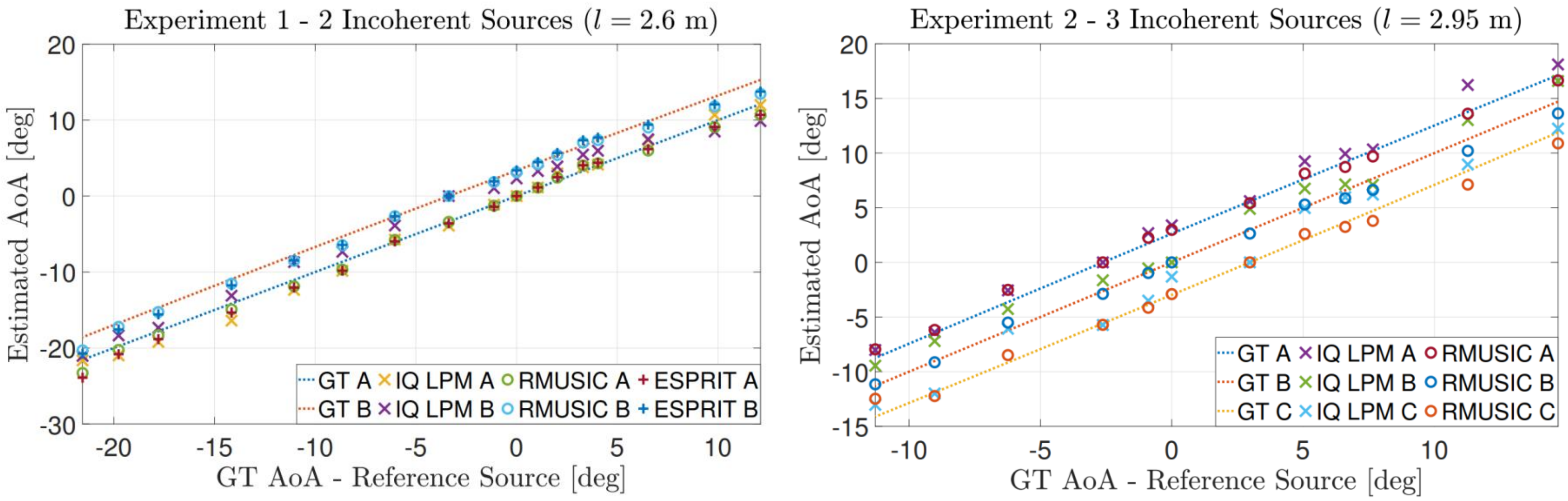
$$\epsilon_k = \frac{1}{Q}\sum_q \left[\frac{1}{|B(l)|}\sum_i^{|B(j,l)|} \left|\tilde{\vartheta}_{i,k} - \vartheta_i\right|\right]$$

with $Q = \max_{(j,l)} q$.

Results

	I/Q LPM [deg]	RMUSIC [deg]	ESPRIT [deg]
Exp #1	1.31–0.98	1.29–0.93	1.30–0.82
Exp #2	1.03–0.72	0.59–0.52	/

TABLE I: Statistics on the absolute estimation errors achieved by the three algorithms (mean value – standard deviation).



(a) **(b)**

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Thanks for your attention!

Question Time 🧐