Geolocalization of low complexity and low power consumption IoRT terminals

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10th Conasense workshop 2021, Oct. 4-5, Hybrid-Mode, fortiss, Research Institute of Free State of Bavaria, Munich Germany

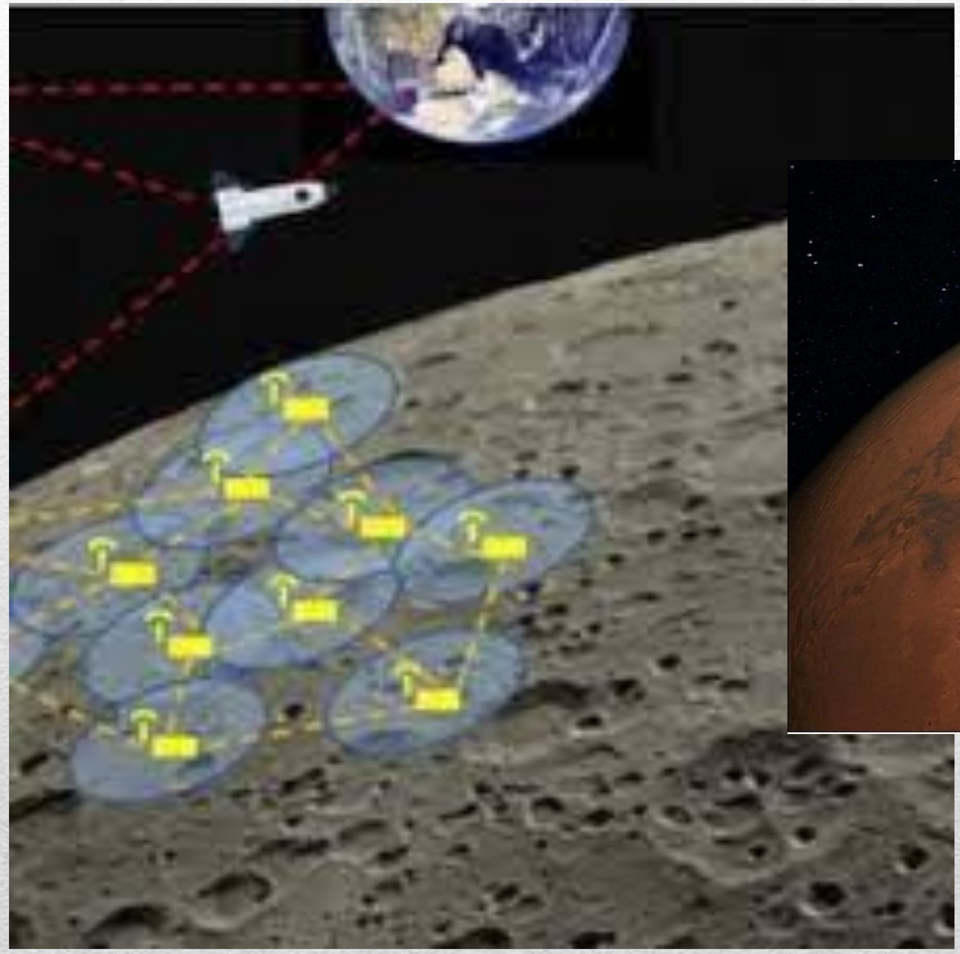
Internet of Remote Things (IoRT) scenarios

Emerging IoRT satellite scenario

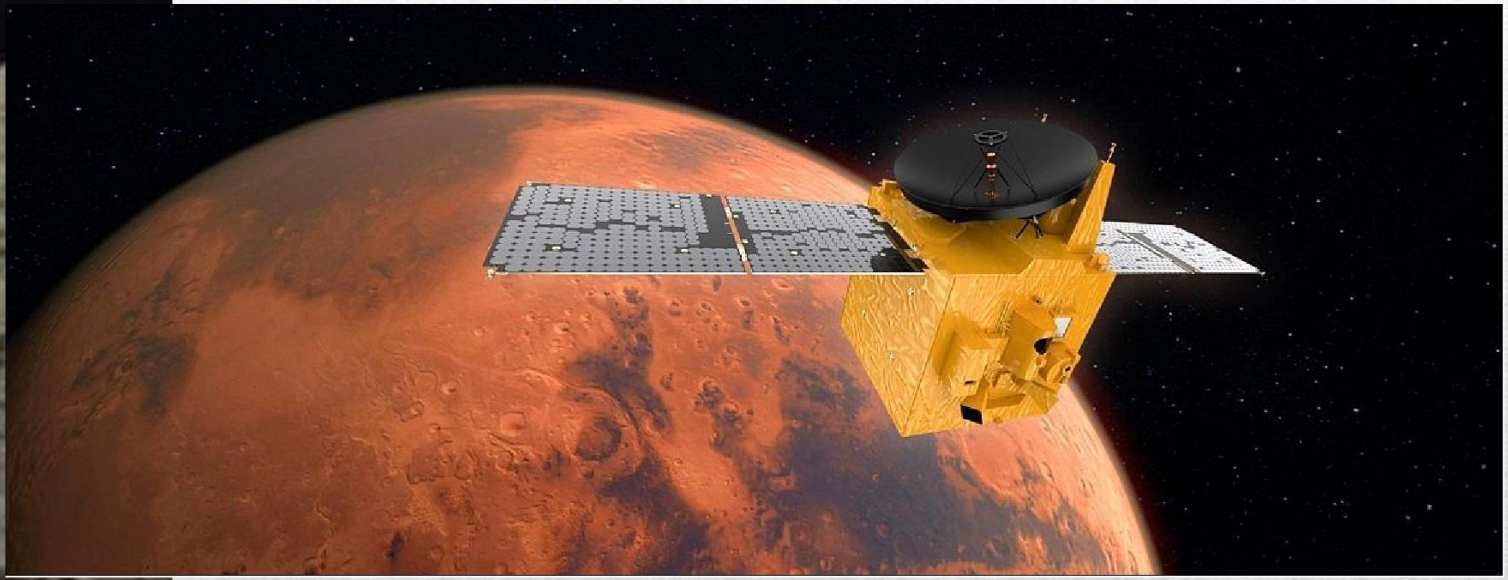
- ❑ Environmental monitoring
- ❑ Agriculture
- ❑ Critical infrastructure monitoring
- ❑ Automonous cars in rural areas



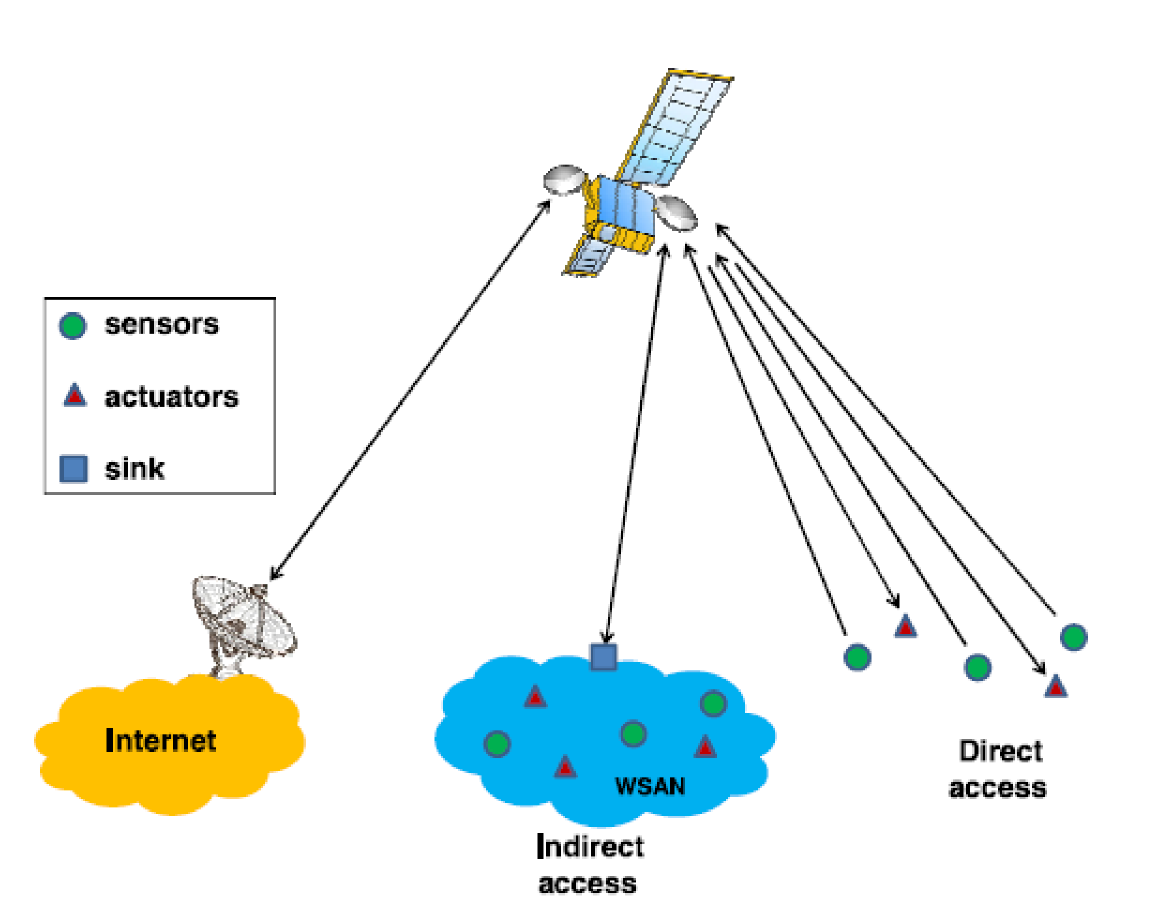

Not only Geo….localization



Lunar/Mars IoT scenarios



IoRT scenarios - Direct or Indirect access?



Direct access is more challenging: scalability issues, energy efficiency etc.

but

it offer more degrees of freedom in many application scenarios

Geolocalization of RF sources

N 41° 53' 24″ E 12° 29' 32″

Determining the position of a device that transmits RF signals from the Earth
is a topic that is gaining more and more attention,
NOT only for defence/military purposes

Why User Equipment (UE) Localization?

- Business perspective – accurate positioning will drive new business models and avenues
  - ✓ smart transportation (bike sharing, autonomous driving)
  - ✓ augmented reality
  - ✓ advirtisement push
- Mobility and Network/Resource Management

The knowledge of the position of the UE and/or BS

- ➢ It can be important in terrestrial system
- ➢ <u>It is CRUCIAL in satellite communication scenarios (and challenging in IoRT scenarios)</u>

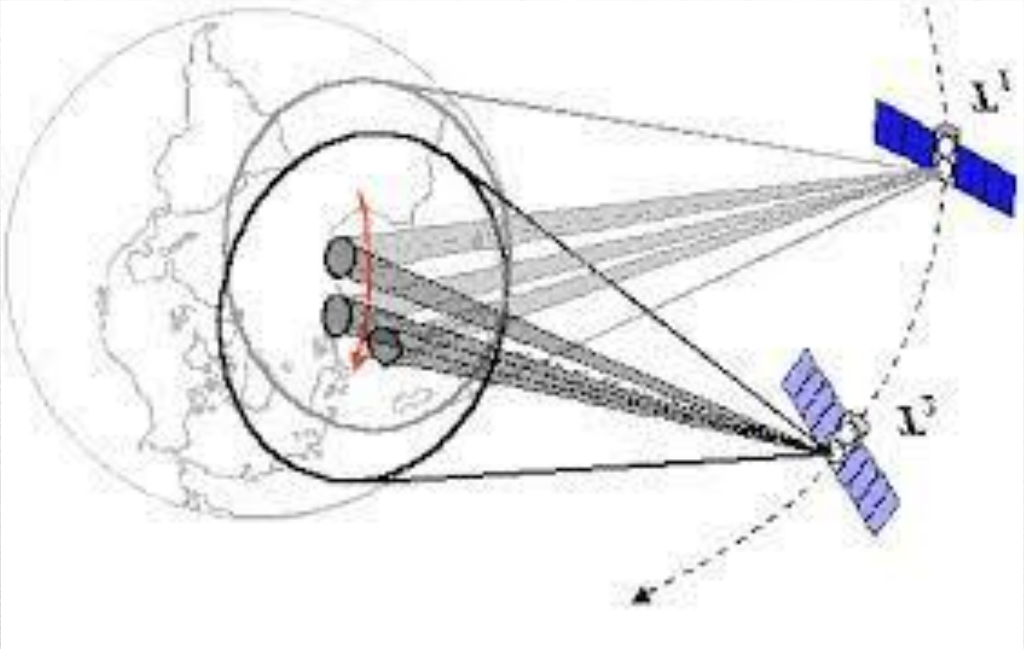
Some key characteristics of the LEO-based communications

- Coverage: Earth-fixed vs Satellite-fixed
- Propagation Delays
- High Doppler Shift and Doppler Rate

LEO satellite coverage

Earth fixed cells

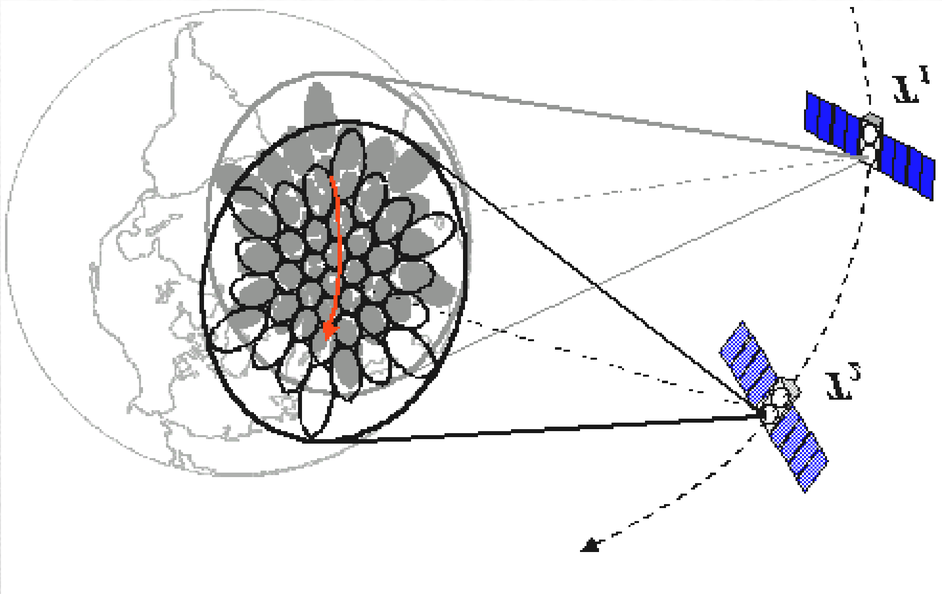
- The cells are fixed to a certain location on Earth from the time where the satellite (these cells belong to), is at a certain elevation angle over the horizon until the same satellite has reached the same elevation angle at the opposite horizon.
- At that point in time, another satellite takes over and all Connected UEs are handed over to a new cell at the new satellite. Only UEs in cells at the satellite coverage border are subject to the handover.
- Each satellite must have the capability to steer beams towards fixed points on Earth and this can be realized through a mechanically steerable beam or a beamforming (BF) technique.
- A LEO satellite spot-beam can serve a given UE for about 400/500 seconds.



LEO satellite coverage

Satellite fixed cells (Earth moving cells)

- The cells follow the satellite projection on ground as the satellite antenna system continuously points at the center of the Earth, and gradually move with the **speed of the satellite, e.g. 7 km/s.**
- The satellite beams are constantly moving along with the satellite, and a satellite spot-beam is expected to provide coverage for a given UE for just a few seconds.



Satellite Propagation Delays

		LEO at 600 km		LEO at 1500 km		MEO at 10000 km	
Elevation angle	Path	Distance D (km)	Delay (ms)	Distance D (km)	Delay (ms)	Distance D (km)	Delay (ms)
UE: 10°	satellite - UE	1932.24	6,440	3647.5	12,158	14018.16	46.727
GW: 5°	satellite - gateway	2329.01	7.763	4101.6	13.672	14539.4	48.464
90°	satellite - UE	600	2	1500	5	10000	33.333
Bent pipe satellite							
One way delay	Gateway-satellite_UE	4261.2	14.204	7749.2	25.83	28557.6	95.192
Round Trip Delay	Twice	8522.5	**28.408**	15498.4	**51.661**	57115.2	**190.38**
Regenerative satellite							
One way delay	Satellite -UE	1932.24	6.44	3647.5	12.16	14018.16	46.73
Round Trip Delay	Satellite-UE-Satellite	3864.48	**12.88**	7295	**24.32**	28036.32	**93.45**

Satellite Differential Propagation Delays

	LEO 600 km		LEO 1500 km		MEO 10000 km	
	Delta Distance	Delta Delay	Delta Distance	Delta Delay	Delta Distance	Delta Delay
Differential One way delay between nadir and EOC paths	1332.2 km	4.44 ms	2147.5 km	7.158 ms	4018.16 km	13.4 ms
Percentage of the maximum delay (bent pipe)		31.26 %		27.8 %		14.1 %
Percentage of the maximum delay (regenerative satellite)		67 %		58.9 %		28.7 %

Satellite Doppler Shift and Doppler Rate

Frequency (GHz)	Max doppler	Relative Doppler	Max Doppler shift variation	
2	+/- 48 kHz	0.0024 %	- 544 Hz/s	LEO at 600 km altitude
20	+/- 480 kHz	0.0024 %	-5.44 kHz/s	
30	+/- 720 kHz	0.0024 %	-8.16 kHz/s	
2	+/- 40 kHz	0.002 %	-180 Hz/s	LEO at 1500 km altitude
20	+/- 400 kHz	0.002 %	-1.8 kHZ/s	
30	+/- 600 kHz	0.002 %	-2.7 kHz/s	
2	+/- 15 kHz	0.00075 %	-6 Hz/s	MEO at 10000 km altitude
20	+/- 150 kHz	0.00075 %	-60 Hz/s	
30	+/- 225 kHz	0.00075 %	-90 Hz/s	

Satellite Doppler Shift and Doppler Rate

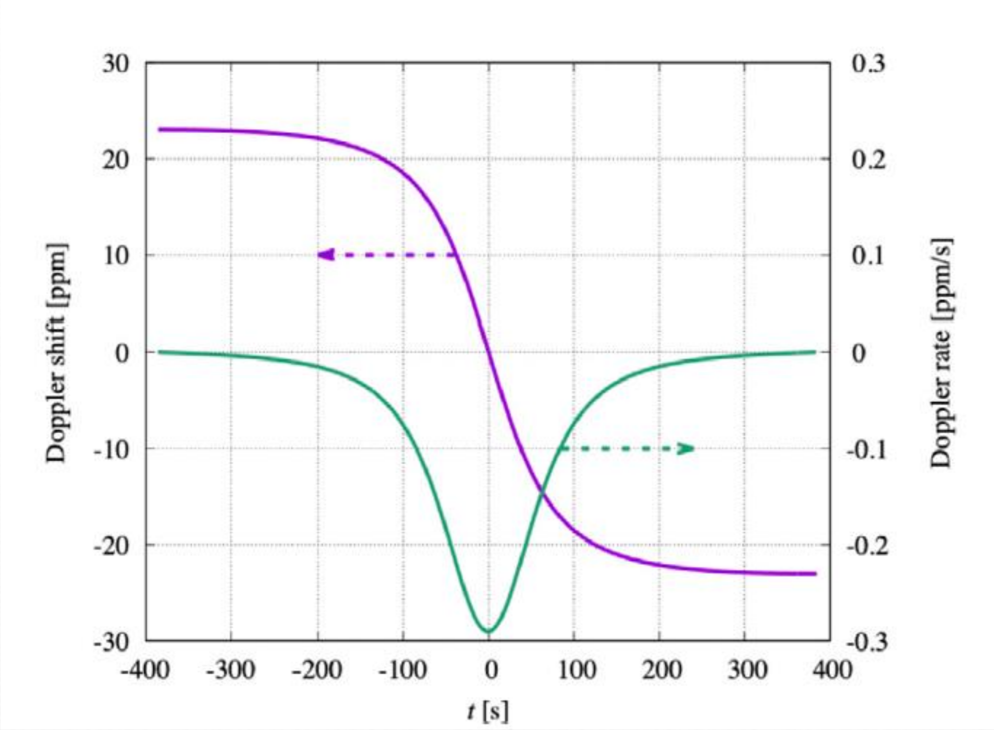
Doppler shifts

❑ Without compensation, the doppler shift can be as high as 20 or 24ppm and the Doppler rate can reach 0.09 and 0.27ppm/s
In terrestrial communications, the Doppler shift is mainly related to the UE crystal accuracy which is 10ppm

Pre/post-compensation ARE needed.

Currenlty, the proposed compensation techniques assume:

- ephemeris knowledge at UE
- equipped with a GNSS receiver to know their own position



Need for UE Geolocalization

Solutions for UE geolocation are required to:

- To simplify handover and paging procedures
  - To determine the belonging beam (satellite)
  - To determine the belonging time, and the next-to-switch beam (satellite)
- To reduce modifications to the 5G-NR standard in NTN scenarios
- ??????

Need for UE Geolocalization – 5G NR context

- Based on the outcome of the Rel-16 study, 3GPP decided to start a work item on NTNs in NR Rel-17;
- The objective is to specify enhancements necessary for LEO and GEO based NTNs while also targeting implicit support for HAPS and air-to-ground networks.
- The focus is on transparent payload architecture with earth fixed tracking areas and frequency-division duplexing (FDD) systems where <u>all UEs are assumed to have (GNSS) capabilities.</u>

The paging issue

NR based terrestrial networks

- a UE camps on a cell.
- A cell belongs to a Tracking area and a Registration Area.
- As long as the UE stays within a Registration Area, no location update is needed.
- The UE in the CM-IDLE state will perform a Registration Area update when it moves out of a Tracking Area.

LEO satellite access networks

- a UE camps on a beam of a satellite, but as beams move, it ends up camping on different beams and different satellites over time even though UE may not have moved.
- the same cell on the ground is covered by different satellites and different beams over time,
- for the initial Registration, the Satellite based radio access network will not be able to provide the Tracking Area information to Access & Mobility Management Function (AMF) based on which beam and which satellite the Registration Request was received.

The paging issue

NR based terrestrial networks

- The AMF only needs to be aware of the UE location to the granularity of the Registration Area when a UE is in the CM-IDLE state.

- If a packet for a UE in CM-IDLE state arrives from the Internet, the AMF attempts to page the UE on all cells belonging to the Registration Area in order to notify the arrival of packets to it.

- All RANs that receive the page transmits a page in the corresponding cells to reach UE that may be anywhere in the Registration Area.

LEO satellite access networks

- Given that tracking areas are defined on the ground and LEO beams are moving, there is no one-to-one correspondence between moving beams and fixed tracking areas or registration areas on the ground.

- <u>This information is necessary for UE to determine if it needs to perform a registration area update with AMF in NR.</u>

The paging issue

LEO satellite access networks

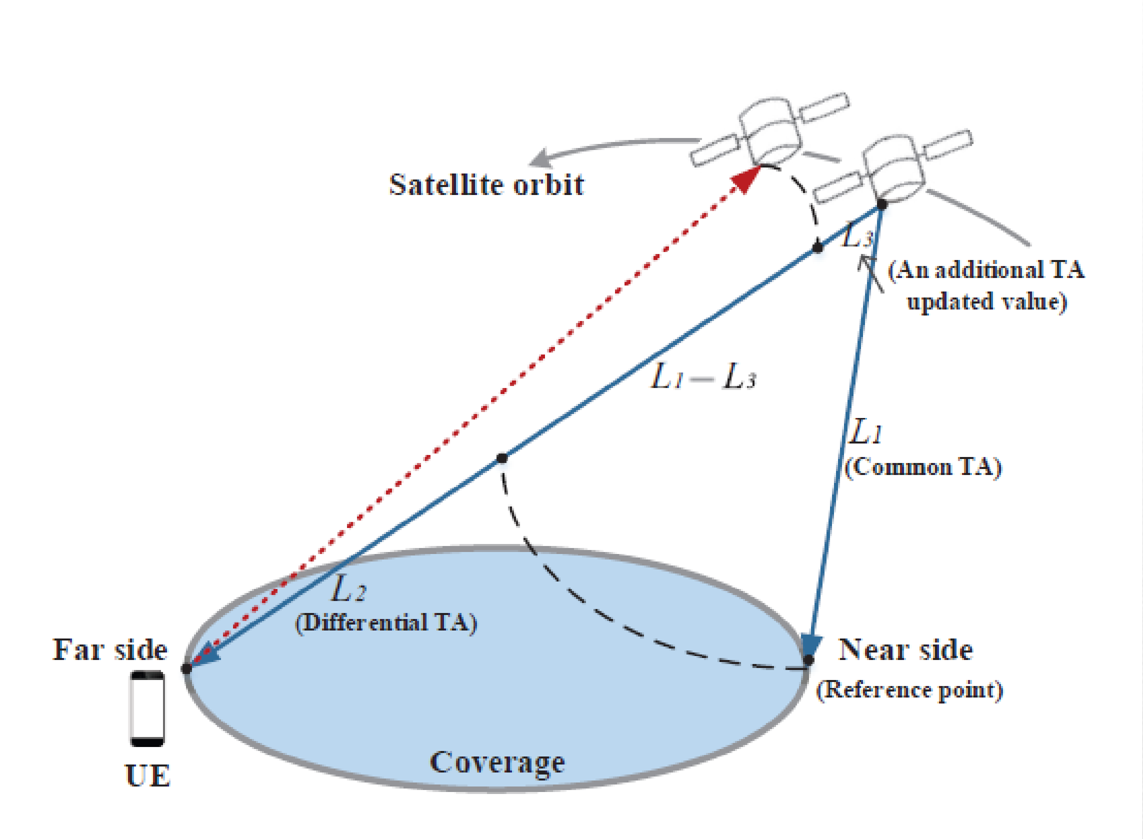
Assuming that:

- The satellite RAN knows UE position
- The ephemeris information of the NGSO satellites can be used to determine their footprints of each of the beams, and its velocity all the time.
- Therefore, for a given UE location at any given time, the network has information as to which beam of which satellite covers that location best.
- It also knows the duration that UE location would remain to be covered by the beam and which beam on the same satellite, or a different satellite will be the best candidate to switch over next, and at what time.

Timing Advance (TA) Issue in NB-IoT Random Access

- CP-OFDMA requires that the signals transmitted from different UEs are time-aligned when reaching the BS to keep the uplink intra-cell orthogonality i.e any timing misalignment across the received signals should fall within the range of one CP.
- In 5G NR the BS first estimated the uplink TA for the UE through the PRACH preamble and then sends adjustment information to the UE by the random access response message
- The UE adjusts its uplink transmission time based on the received TA values combined with the acquired downlink timing synchronization information.

Timing Advance Issue in NB-IoT Random Access



The total TA can be divided into:

1) beam/cell specific common TA L1, which is used to compensate for the round-trip delay at a reference point within the cell/beam, e.g., the nearest point to the satellite
2) A user-specific differential TA L2, which is used to represent the difference between the common TA and the actual TA for a specific user.

The second component of the TA must be calculated frequently as it changes over time due to the movement of the satellite

GNSS on the UE?

- Reduced battery lifetime for the UEs due to the frequency estimation of Doppler and delay along with their compensation, thus requiring substantial additional signal processing

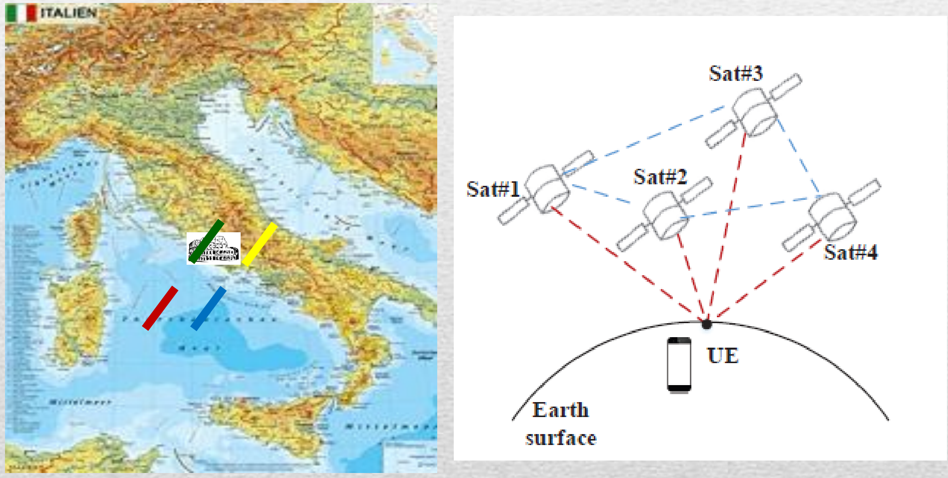
- Unclear update procedure for the satellite ephemeris at the UE level

UE Geolocalization - Challenges

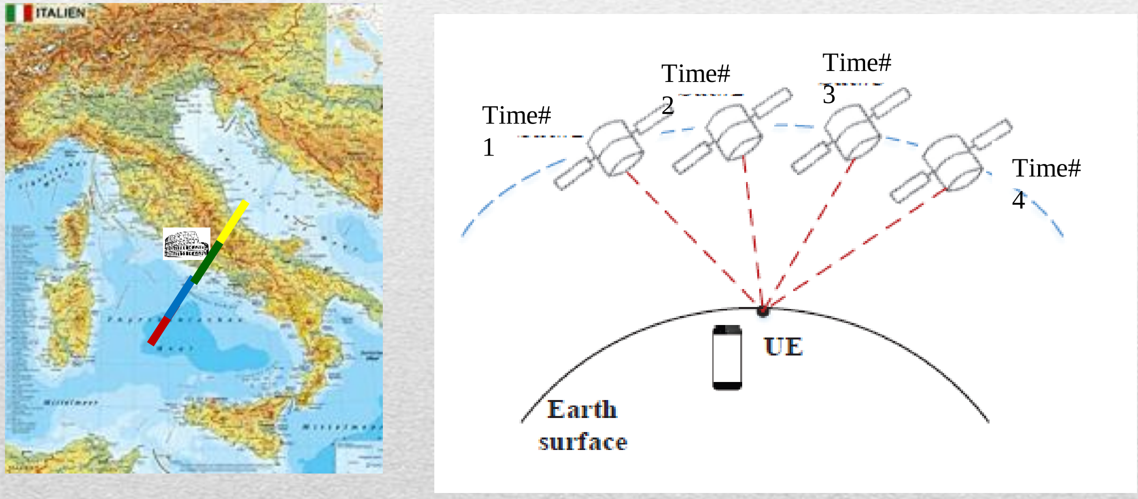
Geolocalization is a WELL studied topic

New challenges

- ❑ Single Satellite (not formation)



Formation



Single Satellite

- ❑ Using the same antenna system for localization and communications (no MUSIC or monopulse)
- ❑ Need for fast localization (beam visibility few seconds, satellite visibility few minutes)

Geolocalization from single satellite – TDoA/FDoA

$\mathbf{r}$=[x, y, z]^T posision of the UE in ECEF

$\mathbf{r}_i$=[x_i , y_i , z_i]^T position of the satellite in the time I

$\mathbf{v}_i$=[x_i, y_i , z_i]^T velocity of the satellite at the time i

Time Of Arrival (TOA) T_i

Transmission time instant T

$$||\mathbf{r}_i - \mathbf{r}|| = c(T_i - T)$$

TDoA

$$||\mathbf{r}_i - \mathbf{r}|| - ||\mathbf{r}_j - \mathbf{r}|| = c(T_i - T_j)$$

$$\begin{cases} ||\mathbf{r}_1 - \mathbf{r}|| - ||\mathbf{r}_2 - \mathbf{r}|| - c(T_1 - T_2) = 0 \\ \dots \\ ||\mathbf{r}_1 - \mathbf{r}|| - ||\mathbf{r}_N - \mathbf{r}|| - c(T_1 - T_N) = 0 \end{cases}$$

FDoA

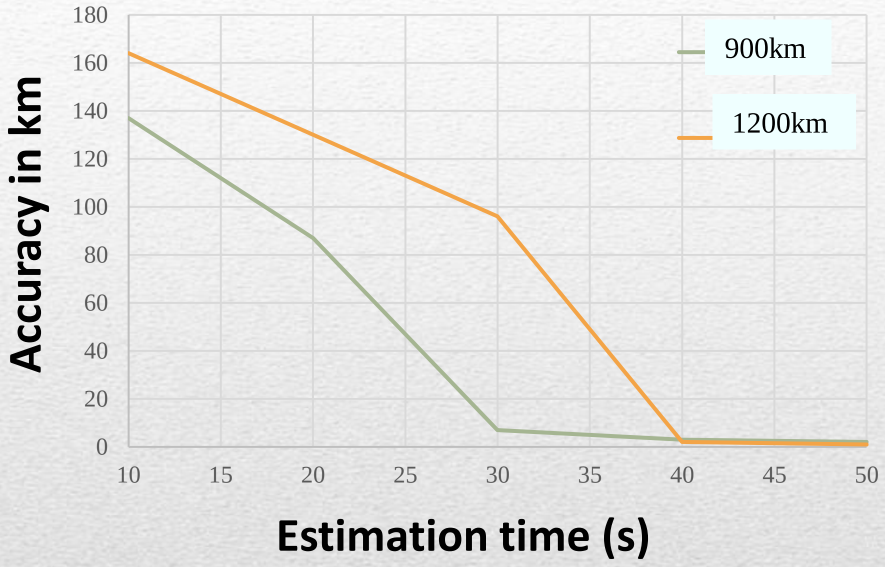
$$\begin{cases} f_0 \left[\mathbf{v}_1^T \dfrac{\mathbf{r}_1 - \mathbf{r}}{||\mathbf{r}_1 - \mathbf{r}||} - \mathbf{v}_2^T \dfrac{\mathbf{r}_2 - \mathbf{r}}{||\mathbf{r}_2 - \mathbf{r}||} \right] + c(f_1 - f_2) = 0 \\ \dots \\ f_0 \left[\mathbf{v}_1^T \dfrac{\mathbf{r}_1 - \mathbf{r}}{||\mathbf{r}_1 - \mathbf{r}||} - \mathbf{v}_N^T \dfrac{\mathbf{r}_N - \mathbf{r}}{||\mathbf{r}_N - \mathbf{r}||} \right] + c(f_1 - f_N) = 0 \end{cases}$$

Geolocalization from single satellite – TDoA/FDoA

Considered Sources of Errors

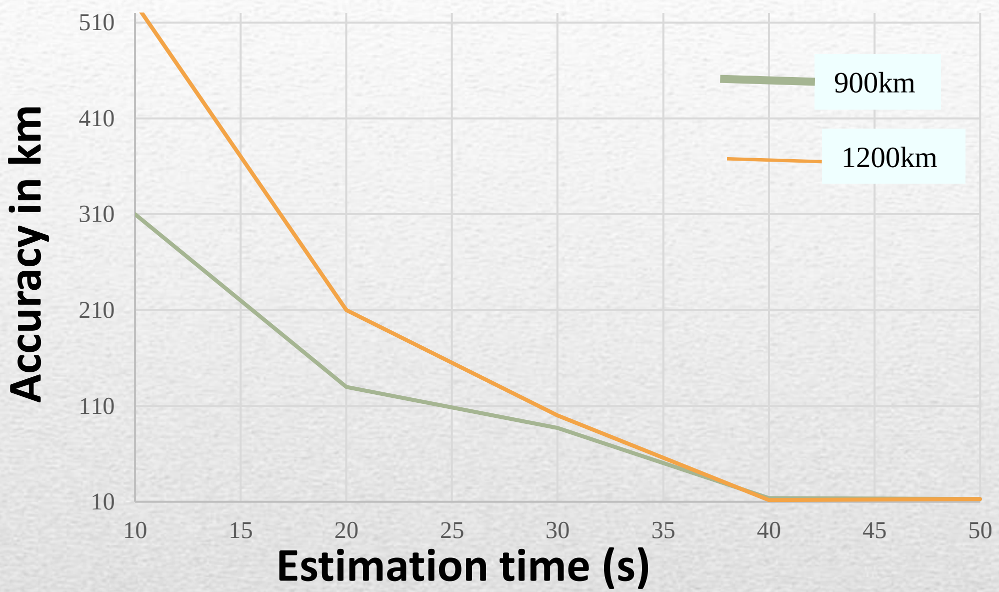
Standard deviation of the timing measurements (TDoA error)	⇨ 35ns
standard deviation of known position of satellite in x/y/z (error)	⇨ 10m
standard deviation of the frequency measurements (FDOA error)	⇨ 0.1Hz
standard deviation of known velocity of satellite in vx/vy/vz (error)	⇨ 10m/s

Geolocalization from single satellite –TDoA



Satellite passing above the target

Geolocalization from single satellite –TDoA



Satellite NOT passing above the target

Future Perspective and Conclusions

- Optimization of the TDoA/FDoA algorithm (use of Doppler Rate?)
- More deep studies are needed to understand the trade-off involved depending from the specific radio access technilogy and MAC (5G NR? A radio interface specifically designed for IoRT scenarios)

- A better understanding of what the "**space component**" of the 6G network can offer, will help in reaching the key objective of **6G**, such as
  - Convergent communication, localization and sensing systems
  - Integration of the terrestrial network with NTNs

- CONASENSE initiative has much to say!