MFEs 2023-2024

OPERA – Wireless Communications Group

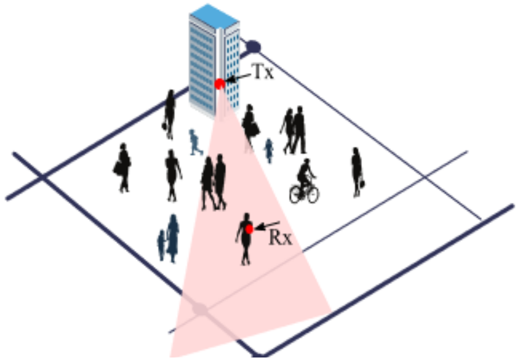
Ecole polytechnique de Bruxelles

Effect of Human-Blockage in Monostatic Radar Crowd Monitoring

Information: Philippe De Doncker, François Horlin, Quentin Gontier, Laurent Storrer
Students: ELEC, PHYS
Type: Theoretical, numerical and possibly experimental

MOTIVATION

Crowd monitoring systems are currently deployed in smart cities to optimize soft mobility while preserving crowd safety. Such a system was developed in our research group, based on the wireless sniffing of signals emitted by smartphones. It is currently being augmented with radar technologies to improve its accuracy and to make it able to measure people fluxes.



M. Gapeyenko *et al.*, *Proc. ICC*, Kuala Lumpur, Malaysia, 2016, pp. 1-7.

Crowd monitoring using radars is, however, a challenging task due to human blockage of the radar signal, leading to unreliable counting and tracking results. This Master Thesis will address this challenge by developing a realistic model of the radar signature of crowds.

OBJECTIVES

The objective of this thesis is to get a better modelling of radar systems when deployed in a crowded environment. In recent years, stochastic geometry (SG) has emerged as a very powerful approach for wireless performance analysis. We propose to use this SG framework for modelling the radar signature of crowds.

The student will have to:

1. Develop realistic crowd models based on stochastic geometry.
2. Evaluate the probability that a human target is illuminated and detected in a crowd using a monostatic radar. Deduce the radar signature of a crowd.
3. Evaluate the performance of radar systems for crowd counting and people fluxes estimation.
4. Investigate the effect of various parameters on the probability of detecting a human target, such as crowd density, target density, target size, and the radar system parameters.
5. Provide insights into the trade-offs between different radar system parameters and the detection probability, and to propose optimization strategies to improve the radar system performance in crowd counting scenarios.

The models will be compared to experimental results obtained in the lab.

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Monitoring the crowd dynamics with radars

Information: François Horlin, Philippe De Doncker, Laurent Storrer, Dejvi Cakoni
Students: ELEC, INFO
Type: Theoretical and/or experimental; can be coupled to an internship at Macq S.A.

MOTIVATION

Mass events are very important and symbolic events in the life of dynamic cities. Unfortunately, disasters occurring during such mass events are significantly increasing worldwide. Two risky behaviours have been identified when thousands of people are gathering in a limited area. First, stampede occurs typically in the case of panic caused by a sudden unpredicted event making the crowd start rushing massively towards a single point. Second, turbulence appears when the crowd density is too high, causing people movements several meters away in a totally uncontrolled way due to unintentional forces from the sides of the crowd.

There is therefore a lot of interest in understanding and measuring the dynamics of crowds. Many applications can benefit from this information, such as the prevention of disasters on mass events (security), or the monitoring of the daily commutes in the city centres (mobility).

Measuring crowd dynamics requires time-stamped position and speed information of the people. The goal of this thesis is to leverage the time variations of the Doppler frequency shifts in the signals gathered by a radar due to moving people in a crowd. This process is also known as micro-Doppler analysis and is widely used for movement analysis. The objective is to transpose that analysis at the scale of a crowd. It involves the simulation of crowd dynamics, the study of time-frequency transforms to analyse the Doppler frequency shifts evolution, and the definition of crowd-specific radar metrics as well as the use of machine learning classification techniques on the output of those transforms to estimate the main people flow among the crowd and detect critical situations like stampedes or turbulences.

OBJECTIVES

- Develop a simulation environment to emulate crowd dynamics
- Design metrics of crowd dynamics
- Implement time-frequency transforms on the radar signal (micro-Doppler analysis)
- Apply feature extraction and classification techniques based on machine learning (support vector machines, deep convolutional neural networks…) to identify the main crowd dynamics and to detect critical situations.

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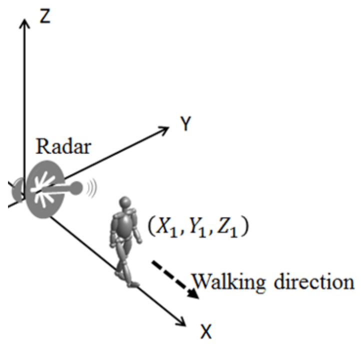
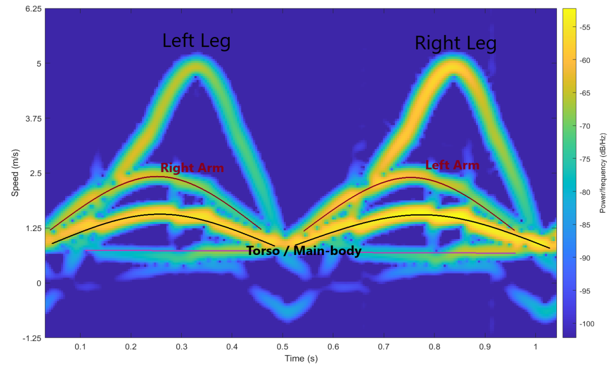
Radars for human gait analysis

Information: François Horlin, Jean-François Determe, Evert Pocoma Copa
Students: ELEC, BIOMED, PHYS
Type: Theoretical and/or experimental; collaboration with the Motors Sciences faculty and moveUP





MOTIVATION

There is considerable interest in developing reliable and cost-effective technologies enabling healthy living. When people are active (walk, run, spring, etc.), their limbs follow repetitive instantaneous speed patterns containing unique discriminative features useful for healthcare applications, such as assisted living (fall detection, activity classification), intensive training (running monitoring), and bio-medical applications (illness detection, rehabilitation).

Motion capture (MoCap) and Kinect sensors have been often considered for such applications. They provide 3D-position of skeleton joints that can be used to analyze the movement of limbs. However, MoCap sensors require expensive equipment and laborious/tedious calibrations processes. Kinect cameras suffer from low light conditions and are subject to privacy concerns. On the contrary, mm-wave radars are less invasive and provide clear representation of the movements (see the instantaneous speeds in the figure above). In addition, radars powered by Artificial Intelligence (AI) algorithms are used more and more in several domains.

Therefore, the goal of the master thesis is to build a radar capable of capturing the frequency variations known as micro-Doppler due to the motions of the limbs. This is done by performing a time-frequency analysis of the received signal. By inspecting the resulting Doppler spectrum and applying AI-algorithms, the gait parameters will be estimated and abnormal patterns will be detected.

OBJECTIVES

- Model typical and abnormal human gaits when walking
- Understand the radar principles, implement the Doppler spectrum estimation
- Validate the algorithms experimentally with a radar platform
- Compare the results to other technologies such as Kinect
- Apply gait parameter estimation and anomaly classification algorithms

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Communication modelling for K-band Low Earth Orbit satellites

Information: Philippe De Doncker, François Quitin
Students: ELEC, PHYS
Type: Modelling

MOTIVATION

Low Earth Orbit satellites are rapidly developing either to provide universal internet access (Starlink,..), or to monitor the environment and/or human activities (Earth-observation satellites). Satellite data are typically sent to the Earth on radio links working below 10GHz, i.e. in the X-band. However, the need for wider bandwidths and interference-free propagation conditions motivates the shift to higher frequencies, especially to the K-band, around 26GHz.

The quality of satellite-to-Earth communication links is heavily dependent on frequency due to atmospheric propagation conditions. On the other hand, to combat adverse propagation conditions, higher frequencies allow one to use more directive antennas which could combine analog and digital beamforming.

In this thesis, we propose a full analysis of the satellite K-Band channel including beamforming capabilities in order to compare satellite performance in both the K-band and the X-band. Realistic Low-Earth Orbit (LEO) scenarios will be considered.

OBJECTIVES

- Identify and compare the main propagation mechanisms for space communications in the X-band and the K-band.
- Develop a propagation model for satellites orbiting on a Low-Earth Orbit.
- Compare X-band and K-band performances taking into account beamforming capabilities.

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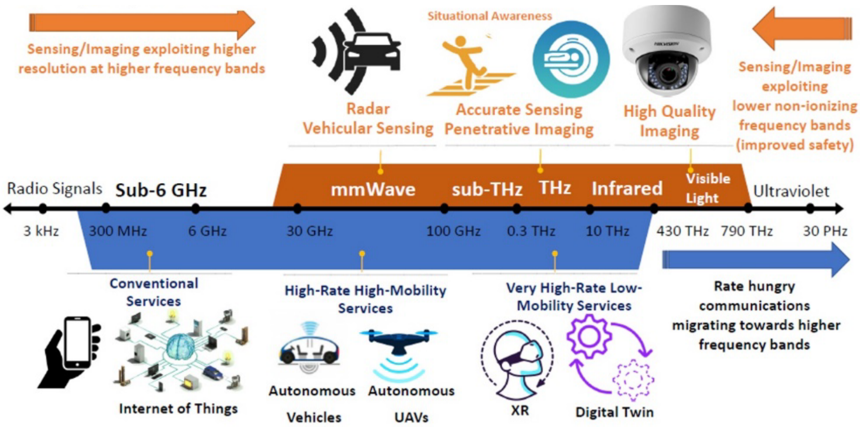
Analysis of TeraHertz communication systems

Information: Philippe De Doncker, Quentin Gontier
Students: ELEC, PHYS
Type: Modelling

MOTIVATION

THz waves, which lie between microwaves and infrared light in the electromagnetic spectrum, have the potential to revolutionize wireless communications by enabling ultra-high-speed data transfer that are orders of magnitude faster than current systems. However, the use of THz technology also poses major challenges, including limited range, sensitivity to blockage and to complex propagation environments.

To address these challenges, and to realize the full potential of THz communication systems, new simulation tools and design techniques are needed that can optimize network performance and improve their reliability.



C. Chaccour, *et al*., "Seven Defining Features of Terahertz (THz) Wireless Systems: A Fellowship of Communication and Sensing," in *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 967-993, 2022.

OBJECTIVES

The work will focus on one of the following challenges of THz systems:

- Develop a model for THz communication networks that incorporates the effects of atmospheric attenuation, network heterogeneity, and mobility patterns.
- Develop a framework for jointly optimizing the location of THz base stations and user devices to minimize energy consumption and maximize network coverage.
- Investigate the feasibility of using THz frequencies for sensing applications, such as detecting and localizing obstacles in outdoor environments.

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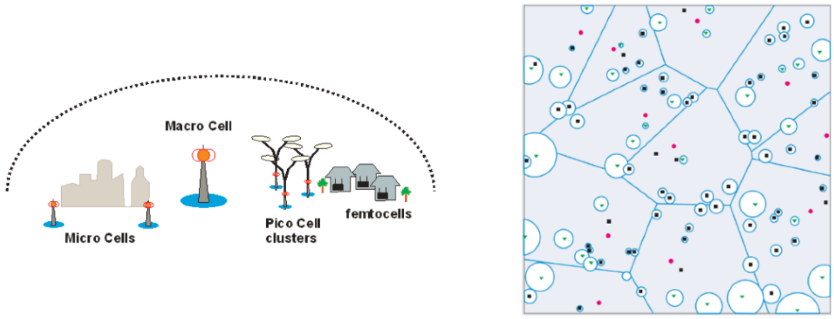
Stochastic geometry for mmWave networks

Information: Philippe De Doncker, Quentin Gontier
Students: ELEC, PHYS
Type: Modelling

MOTIVATION

Development of millimeter-wave (mmWave) technologies has paved the way for next-generation wireless networks that can support ultra-high data rates and low-latency communications. However, the deployment of mmWave networks poses unique challenges, including coverage, EMF exposure, and capacity analysis. By tackling these challenges head-on, this master thesis will contribute to the development of more efficient and effective mmWave networks that can meet the growing demand for high-speed wireless communications. This thesis will focus on heterogeneous network (HetNets) architectures, exploring their potential to improve network performance and capacity. The analysis will be done using the stochastic geometry (SG) framework, a powerful approach for generic network performance analysis at the communication or network layers.



(a) (b)

Heterogeneous Cellular Network (HetNet) (**a**) multiple-standard radio access HetNet; (**b**) 3-tier HetNet coverage with blue lines as service zones' boundaries, and red spots, green triangles, and black squares as macro-cells, pico-cells, and femto-cells, respectively. [Musovic, J. et al. 2021. "Stochastic Geometry-Based Analysis of Heterogeneous Wireless Network Spectral, Energy and Deployment Efficiency" *Electronics* 10, no. 7: 786.]

OBJECTIVES

- To evaluate the coverage of mmWave networks in urban and suburban environments, taking into account the effects of obstacles, blockages, and reflections.
- To analyze the electromagnetic field (EMF) exposure levels of mmWave networks and propose mitigation techniques to reduce exposure levels while maintaining network performance.
- To study the capacity of mmWave networks under different traffic loads and network topologies.
- To conduct Monte-Carlo-like simulations to validate the proposed models.

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Cartography of EMF exposure and network coverage in Brussels

Information: Philippe De Doncker, Quentin Gontier
Students: ELEC, PHYS
Type: Numerical and experimental

MOTIVATION

With the ever-growing number of wireless devices, the electromagnetic field (EMF) exposure has become a major public concern. Obtaining an accurate cartography of EMF exposure due to cellular networks is crucial, but network providers must balance emitting power to meet legal exposure thresholds while ensuring sufficiently high Signal-to-Interference-plus-Noise ratio at the user equipment.

To achieve EMF exposure cartography, we propose a master thesis that will explore the use of Open Street Map libraries and propagation models to map the EMF exposure and the network coverage in Brussels. Real-world measurements will be used to validate the model and calibrate its parameters. In 2021, the Wireless Communications Group deployed a large network of sensors through a $4km^2$ area in Brussels in order to measure total exposure caused by cellular networks and radio emitters. This infrastructure is the second largest network of sensors dedicated to EMF exposure deployed in a single city. Besides, for several years, measurement campaigns are being done in Brussels using a car (drive-tests). This provides additional information, giving more samples in one area, but at a specific time instant.

OBJECTIVES

The main objective of this master thesis is to obtain a cartography of the EMF exposure and of the cellular network coverage in Brussels. To achieve this objective, the student will have to:

1. Develop a propagation model that takes into account the physical characteristics of the environment, such as building height and density, to estimate the EMF exposure and network coverage. The model will be based on existing models and will be adapted to the specific characteristics of Brussels.
2. Analyze the simulation results, and extract statistics of the data.
3. Use extrapolation techniques, such as Kriging or graph neural networks, to extrapolate the measurements to streets where no data was collected by sensors and/or drive-tests and so obtain a full cartography of the area under test.

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Leaky-wave antennas for high efficiency mmWave base stations

Information: Philippe De Doncker
Students: ELEC, PHYS
Type: Numerical and experimental

MOTIVATION

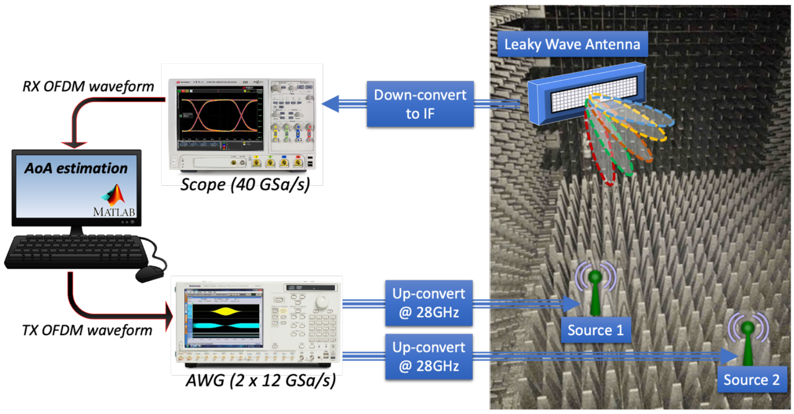
To meet the requirements of new use cases of wireless communications (autonomous vehicle, real-time augmented reality...), one key technology is millimeter-wave (mmWave) multi-antenna transceivers. However, operating at mmWaves remains challenging, especially in mobile scenarios. Indeed, multi-antenna mmWave operation includes a beam training process to align the directional beams radiated by the antennas at the base station and the user equipment. This procedure introduces large signaling overhead as well as latency, which could jeopardise mmWave effectiveness: beam training relies on the tedious sequential scanning of the beam space obtained by multi-antenna beamforming. The use of leaky-wave antennas at base stations could revolutionize this process: leaky-wave antennas are able to simultaneously radiate multiple beams and to estimate the user equipment direction by using only one single antenna, so replacing the traditional beam scanning process by one single operation.

This thesis is done in partnership with Sorbonne Université, Paris, were the experimental part will take place.

OBJECTIVES

This thesis investigates numerically and experimentally the potential of leaky-wave antennas to estimate in real-time Directions of Arrival of incoming signals at mmWave base stations. To achieve this goal, the student will have to

1. Adapt estimation algorithm such as MUSIC to leaky-wave antennas instead of classical linear uniform arrays.
2. Assess the impact of channel on the estimation performance.
3. Conduct experimental validations with the wireless setup available at Sorbonne Université in Paris.



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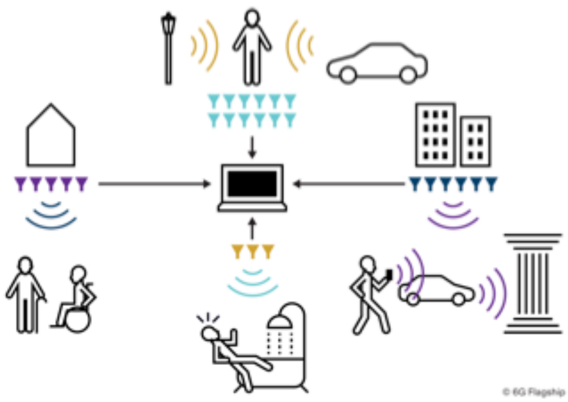
Joint communications and sensing (JC&S) for 6G networks

Information: François Horlin, Hasan Can Yildirim
Students: ELEC, INFO
Type: Theoretical and/or experimental



MOTIVATION

As the deployment of 5G networks progresses, wireless system designers are already working on advanced functionalities for 6G. Cellular networks have originally been designed to only meet the ever-increasing demand for communication capacity. Today, the positioning of active communication devices has further become an integral part of the network. However the sensing of passive objects has not yet been included in standards. Sensing can be seen as a radar designed to work based on communication signals. As such, when enabled with the sensing functionality, the future outdoor and indoor networks could image and measure the surrounding environment to improve the communication and offer advanced environment and location-aware services.

Positioning and sensing are expected to be integrated with communications into the 6G system from the start and are becoming a key design target. Instead of just looking for a mutually enhanced performance, a real co-design approach will be followed where the three functionalities optimally share the spectrum, the hardware and the signal processing. Advances in theoretical understanding of the performance and limitations, and new algorithmic solutions are still needed to make that vision come true. Three master theses are proposed in this context.

MFE 1 - OBJECTIVES: Waveform selection for 6G JC&S in vehicular scenarios

The transmitted waveform itself should carefully be selected. Starting from the communication functionality, orthogonal frequency-division multiplexing (OFDM) is the commonly used modulation technique in current wireless communications systems as it can efficiently cope with the frequency selective channel by dividing it in a set of orthogonal subchannels. Even if OFDM has shown strong advantages in terms of communications performance, it is still unclear if it can efficiently support the sensing functionality. When dealing with the sensing of high mobility targets especially, the performance of OFDM may significantly be degraded by the interference caused among the observed OFDM subchannels. Other waveforms like orthogonal time frequency Space (OTFS) could be better suited in that case. The goal of this master thesis is to compare the performance of OFDM and OTFS in vehicular JCS scenarios considering both communications and sensing.

It will consist in:

- Understanding the OFDM and OTFS principles
- Building signal processing algorithms for both communications and sensing

- Designing the transmitted frame, including the preamble and pilot symbols besides the data symbols
- Assessing the impact of high mobility on the performance and designing solutions to cope with the performance degradation
- Assess the performance based on a simulation in Matlab

MFE 2 - OBJECTIVES: Impact of front-end impairments on JC&S in 6G networks

It is expected that the communications and sensing functionalities will be implemented with the same analog hardware. The super-heterodyne and zero-intermediate frequency (IF) architectures are commonly considered to down-convert the signal from RF to baseband. Unfortunately, their components always come with a set of impairments that may degrade the performance of both functionalities. Regarding the communication, the impact of the analog front-end on the performance is rather well understood. However, if the same hardware is used for sensing, its impact on the sensing performance should also be carefully assessed. It is expected that sensing is more sensitive to the non-ideal hardware than communication because the sensing requires the estimation of continuous parameters while the communication requires the estimation of discrete symbols. The goal of the master thesis is to understand how imperfect hardware can be shared between the two functionalities by comparing its impact on their performance.

It will consist in:
- Understanding the principles of the super-heterodyne and zero-IF front-end architectures
- Modelling the hardware impairments caused by the different hardware components
- Assessing the impact of the hardware impairments on the two functionalities, both analytically and by numerical simulations in Matlab
- Drawing general conclusions about the possibility of share hardware among the two functionalities

MFE 3 - OBJECTIVES: Experimental validation of the JC&S with USRP radios

The joint communications and sensing system can experimentally be validated. A prototype can be built by using the recent USRP radio platforms. Their interest lies in the fact that they can be interfaced with Matlab where the signals are usually generated and processed. In a quasi-static configuration, the system is composed of a transmitter collocated with a sensing receiver that analyses the scene, and communicating with devices in its neighbourhood. In that case, the self-interference caused by the transmitter on the sensing receiver should carefully be managed. In a bi-static configuration, the sensing receiver is at the location further away from the transmitter. The self-interference is weaker, but the sensing receiver should properly be synchronized to the transmitter. The goal of the master thesis is to practically analyse the performance of the two system configurations by using USRP radios.

It will consist in :
- Building a reference joint communication and sensing chain in Matlab
- Separately validating the communication and sensing functionalities with USRP radios
- Implementing the joint communication and sensing system with USRP radios, assuming both the mono-static and bi-static configurations
- Comparing the implementation complexity and achievable performance of the two configurations

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