

Surveillance de foule à l'aide d'une antenne à ondes de fuite dans une communication et détection intégrées

Leaky-wave antenna-based crowd monitoring in Integrate Sensing and Communications

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Résumé/Abstract

Radar systems utilize electromagnetic signals to detect and track multiple human targets. This study focuses on multi-target tracking using range, Doppler, and Angle-of-Arrival (AoA) measurements from a monostatic radar system. Human crowds are modeled as dielectric cylindrical shells interacting with an incident electromagnetic field. The scattered field generated by the targets is processed to extract channel transfer function coefficients, enabling the derivation of range and Doppler profiles. A key novelty of this work is the use of a leaky-wave antenna at the receiver, which enables AoA estimation with a single-port antenna, therefore reducing system complexity, cost and eliminating the potential phase shift discrepancies inherent to multi-receiver configurations.

Les systèmes radar utilisent des signaux électromagnétiques pour détecter et suivre plusieurs cibles humaines. Cette étude se concentre sur le suivi de cibles multiples par une estimation de distance, d'effet Doppler et d'angle d'arrivée provenant d'un système radar monostatique. Une foule humaine est modélisée par des cylindres diélectriques interagissant avec un champ électromagnétique incident. Le champ diffusé généré par les cibles est traité pour extraire les coefficients de la fonction de transfert du canal, ce qui permet d'obtenir la distance et l'effet Doppler. La principale nouveauté de ce travail est l'utilisation d'une antenne à ondes de fuite comme récepteur, qui permet d'estimer l'angle d'arrivée avec une antenne à port unique, réduisant ainsi la complexité et le coût du système et éliminant les divergences potentielles de déphasage inhérentes aux configurations multirécepteurs.

1 Introduction

The rapid deployment of wireless communication networks has created new opportunities for Integrated Sensing and Communication (ISAC), where the same infrastructure can be leveraged for both data transmission and environmental sensing. By repurposing existing communication signals for radar-like applications, ISAC enables sensing without requiring dedicated transmitters. This approach is particularly promising in the context of 5G and beyond, as the increased bandwidth availability and the flexible numerology of modern communication waveforms such as Orthogonal Frequency-Division Multiplexing (OFDM) facilitate advanced sensing capabilities, including fine-grained motion tracking and environmental awareness [1]. Traditional radar setups exploit these ambient communication signals to track movement but typically require multiple receivers for Angle-of-Arrival (AoA) estimation, while range and Doppler measurements can be obtained with a single receiver. These configurations introduce hardware complexity and potential issues due to phase shift discrepancies between receiver channels.

This study proposes an alternative approach using a single leaky-wave antenna (LWA) as the receiver, operating at 27 GHz with a 400 MHz bandwidth, to achieve comparable performance in range and Doppler estimation while eliminating the phase shift issues inherent in multi-receiver setups. We use OFDM signals based on 5G standards for radar sensing, leveraging their wide bandwidth flexible numerology. The unique frequency-dependent radiation properties of the LWA enable AoA estimation using the MUSIC (Multiple Signal Classification) algorithm without requiring multiple antennas, significantly simplifying hardware requirements. This novel approach takes advantage of ISAC to reduce system complexity while maintaining high-resolution human sensing capabilities, with potential applications in indoor monitoring, crowd behavior analysis, and smart environment interaction.

2 Crowd Monitoring Scenario Description

Crowd monitoring is a crucial aspect of public safety and event management. Tragic incidents, such as the Hillsborough disaster (UK, 1989) and the Astroworld festival tragedy (USA, 2021), highlight the need for real-time

crowd tracking to prevent dangerous levels of congestion [2]. A key factor in crowd management is crowd counting, which allows security personnel to assess density levels and take proactive measures before critical thresholds are exceeded. Additionally, sensing applications gain increasing attention for indoor people tracking and object detection, with use cases including movement classification, intruder detection, and security monitoring in public spaces. However, crowd monitoring must also respect privacy concerns, making non-intrusive solutions that do not rely on cameras particularly desirable. Radar-based sensing offers a viable alternative, enabling real-time tracking while preserving anonymity and mitigating ethical concerns related to visual surveillance.

We explore the feasibility of a radar system for crowd monitoring using a monostatic radar channel, where the transmitter (TX) and receiver (RX) are collocated. The physical medium is free space. TX is modeled as a y-directed lossless $\lambda/2$ dipole, while RX is a leaky-wave antenna receiving signals in the XZ plane. This configuration has been chosen to simplify calculations while remaining consistent with LWA equations, the scan is performed along θ , the elevation angle, within the XZ plane, with $\varphi = 0^\circ$. This 2D plane can be rotated accordingly to match the desired orientation. The system operates using OFDM waveforms inspired by 5G standards like Sounding Reference Signals (SRS) generally used for channel estimation. This waveform choice supports precise range and Doppler estimation, making it particularly suited for tracking human movement in crowded environments.

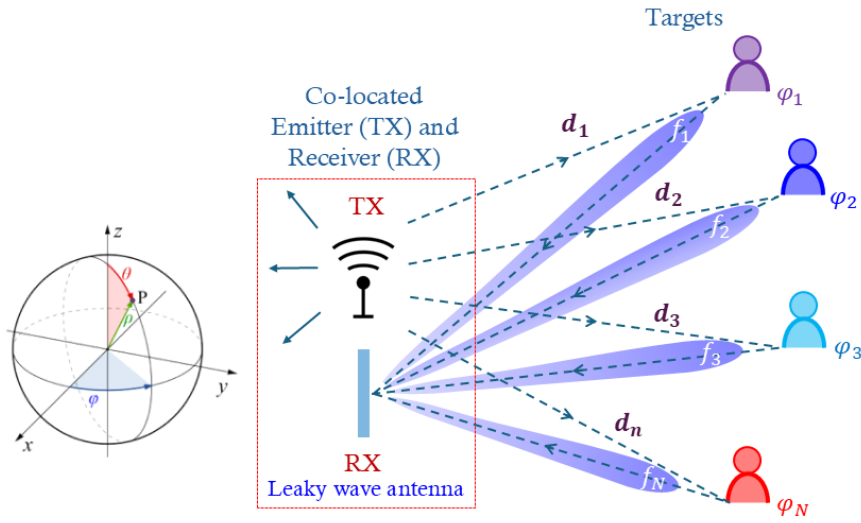


Figure 1: Scenario Description

3 Leaky-Wave Antenna

LWA unique property is its frequency-dependent radiation pattern. Unlike conventional antennas, LWA exploits a dispersive leaky-wave propagation mode, leading to an angle-dependent frequency relationship given by:

$$\cos \theta = \frac{\beta_z}{k_0}$$

Where θ is the receive beam orientation, β_z is the phase constant along the antenna and $k_0 = \frac{2\pi}{\lambda}$ is the free-space wavenumber. This property enables the LWA to act as a natural spatial filter, where different frequency components of the received signal correspond to different angles of arrival. Humans are represented by an infinite cylinder, serving as a target positioned at a random distance d from TX/RX. This simplification is useful to determine the radar cross section of a human and derive the scattered electric field on a target.

To derive the LWA radiation pattern, an air-filled rectangular waveguide with a longitudinal slot is considered. From the equivalence principle and image theory [3][4], the radiation from this structure in region $x > 0$ is approximately due to a z-directed magnetic line current flowing along the z-axis. To simplify, the radiation pattern is assimilated to the Array Factor (AF) of the LWA. The term "Array Factor" in the context of LWAs does not represent an array factor in the traditional sense used for antenna arrays. Instead, it is a mathematical construction used to quantify the contribution of the leaky-wave structure to the overall radiation pattern. Specifically, it describes the factor by which the electric field of an infinitesimal element along the waveguide is multiplied to account for the radiative properties of the LWA. Fig.2 illustrates frequencies responses for different AoAs.

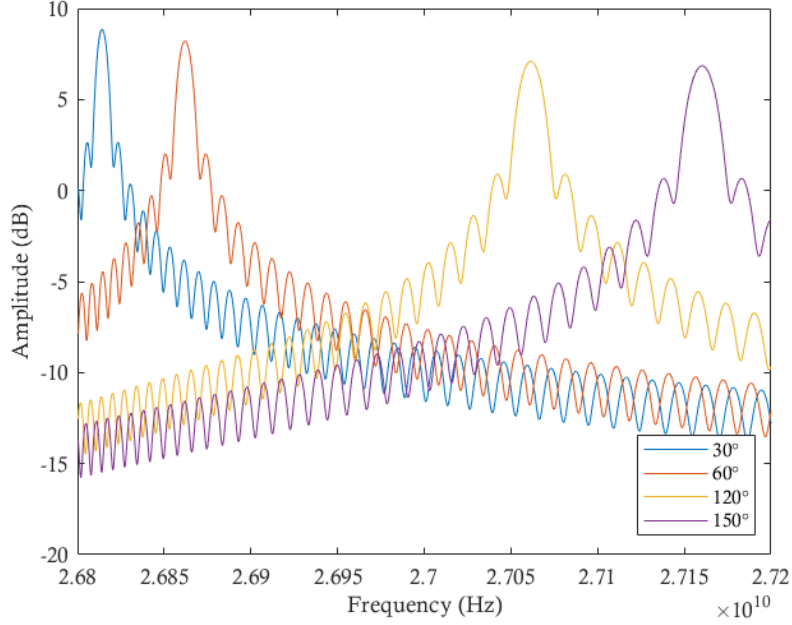


Figure 2: LWA Radiation Pattern

4 Aim of the study

The outlined scenario is well-suited for the Geometry-Based Single Bounce Model (GBSBM), which is commonly employed in radar applications. This model considers only the direct path between the transmitter (TX) and receiver (RX), as well as the first-order reflections from the target, which contribute significantly to the received signal. In the case of a monostatic radar configuration, where the TX and RX are collocated, there is no direct line-of-sight (LOS) path between them. Instead, the primary propagation path is defined by the first-order reflection from the target, which forms a TX-Target-RX path. In this context, the system operates similarly to a classical monostatic radar setup, where the primary goal is to derive the Channel Transfer Function (CTF). The CTF captures the key characteristics of the radar channel, including propagation delays and Doppler shifts that are induced by the motion of the target. These parameters are critical for accurately estimating the range and speed of the target.

This study evaluates the performance of a leaky-wave antenna (LWA) as a receiver compared to classic monostatic radar systems. The LWA radiation pattern might be seen as a windowing effect in the CTF, leading to a spread in the Channel Impulse Response (CIR). Finally, the Doppler-FFT is applied to the CIR to obtain the Range-Doppler Map (RDM). The results demonstrate that the LWA maintains accuracy in target localization while reducing hardware complexity. An example is shown in Fig. 2 for a single target located at 10m with a speed of 4m/s moving away from TX/RX with $\theta = 30^\circ$ and a SNR of 10 dB.

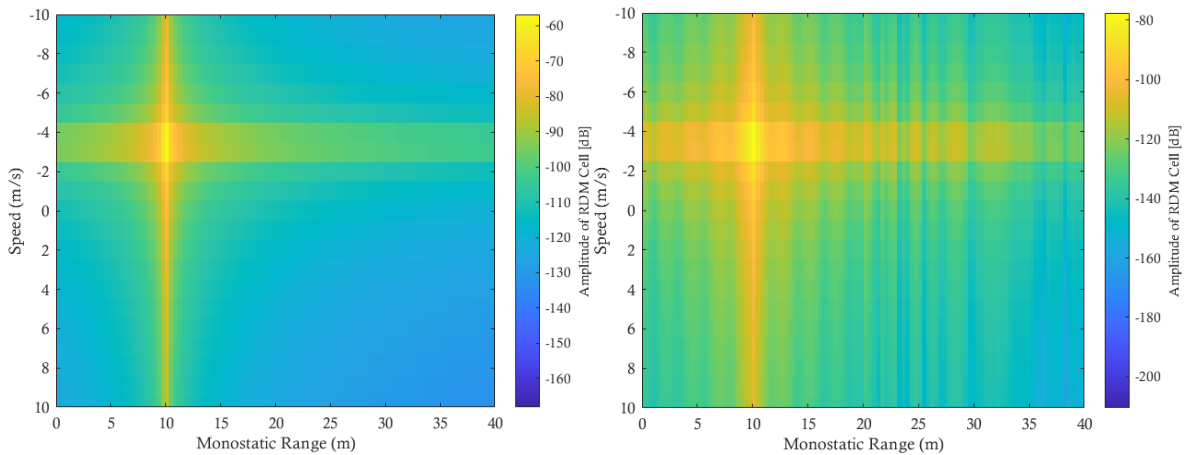


Figure 2: Range Doppler Map with a classic monostatic radar system (left) and with the LWA (right)

While the range and speed are accurately estimated in both cases, the use of the LWA introduces a spread and attenuation effect on the Range-Doppler Map (RDM). This effect arises because the LWA acts as a spatial filter, selectively receiving different frequency components at different angles. Consequently, unlike a conventional omnidirectional receiver that captures the full bandwidth uniformly, the LWA inherently modifies the received signal spectrum based on the angular distribution, leading to a spread and attenuation in the RDM representation. Nevertheless, the LWA provides the significant advantage of providing AoA estimation shown in Fig. 3, which is not possible with a traditional monostatic radar setup.

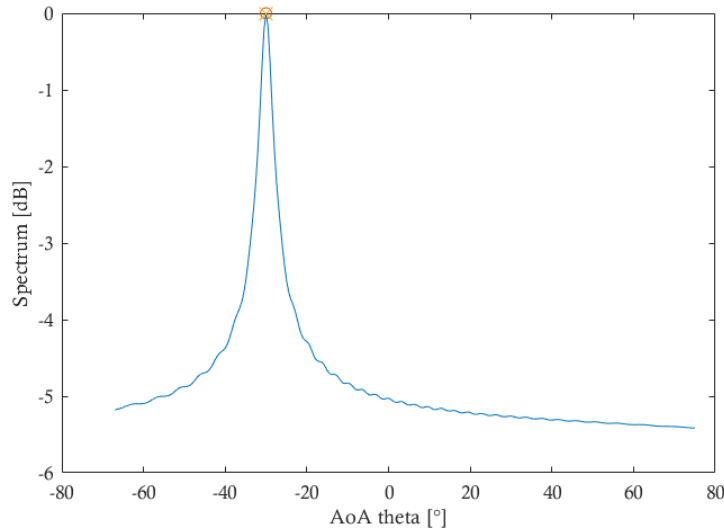


Figure 3: MUSIC Pseudospectrum

Future work will explore multi-receiver configurations to enable triangulation, enhancing real-time tracking capabilities in dynamic environments with minimal receiver infrastructure. This will simplify the radar system and make it more efficient, while still providing accurate localization and tracking of multiple targets, even in complex environments with limited receiver hardware.

5 References

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