WC PROJECT

MODELLING AND PERFORMANCE ANALYSIS OF MMWAVE, WIFI AND 5G-BASED V2V COMMUNICATIONS USING MONTE CARLO SIMULATIONS

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ABSTRACT:

Vehicle-to-vehicle (V2V) communications are crucial for enhancing road network safety and efficiency. With the increasing demand for bandwidth in V2V services, exploring innovative solutions has become imperative. This study explores a comparative analysis of **mmWave and WiFi and 5G- Cellular** transmission technologies, with a specific focus on line-of-sight (LoS) and non-line-of-sight (NLoS) scenarios 3D modelling environments. The use of stochastic geometry tools allows a realistic modelling of the random positioning of vehicles within the V2V system framework, resulting in accurate expressions for the **successful transmission probability (STP) and average throughput (AT), Channel Capacity and Outage Probability** for **mmWave and WiFi Communication** and **successful transmission probability (STP) and average throughput (AT) for 5G Cellular Communication System.**

To validate our analytical findings, **Monte Carlo simulations** have been employed, offering a comprehensive evaluation of mmWave and WiFi and 5G Cellular System performance. Simulation results highlight that mmWave systems outperform in scenarios with short transmission distances and low vehicle density while WiFi systems demonstrate greater efficiency for longer transmission distances.

INTRODUCTION

Vehicular communication technologies play a vital role in enhancing road safety and traffic efficiency in Intelligent Transportation Systems (ITS). As the demand for reliable, high-speed data transmission in Vehicle-to-Vehicle (V2V) communication grows, traditional technologies such as WiFi (802.11p) and emerging mmWave and 5G bands have been at the forefront of research. WiFi offers stable performance in moderate scenarios, whereas mmWave is praised for its high bandwidth and low latency capabilities and 5G provides very high speed, bandwidth and low latency.

However, each technology faces limitations. WiFi struggles with bandwidth constraints under heavy loads, and mmWave encounters significant propagation challenges, such as signal attenuation over long distances and poor penetration through obstacles. The 5G Band faces issues like Limited Coverage, High cost and High-Power Consumption. These challenges have led to the need for a detailed analysis to identify the most effective communication protocols for specific scenarios in V2V networks.

In V2V communication systems, maintaining consistent and reliable connectivity is crucial, especially under varying conditions such as dense traffic, long-distance communication, or environments with numerous obstructions. Traditional evaluations often employ 1D or 2D models to assess system performance, but these models fail to account for the vertical dimensions, such as vehicle heights and elevation angles, which can significantly influence communication outcomes.

The integration of stochastic geometry-based modelling has allowed researchers to simulate the random spatial distribution of vehicles, providing a more realistic approach to system evaluation. By incorporating factors such as vehicle density, positions, and elevation, this methodology enables the derivation of key analytical performance metrics like Successful Transmission Probability (STP) and Average Throughput (AT), Outage Probability and Channel Capacity.

LITERATURE SURVEY

1). Modeling and Performance Analysis of mmWave and WiFi-Based Vehicle Communications*: MohamedRjab1,2, *, Aymen Omri 2, Seifeddine Bouallegue 3 1, Hela Chamkhia 4 and Ridha Bouallegue 1,2.*

Advantages

1. **Realistic Modeling**: The inclusion of 3D modeling with stochastic geometry provides more accurate results by considering vehicle altitude and obstacle heights.
2. **Comprehensive Performance Metrics**: Derives essential metrics like Successful Transmission Probability (STP) and Average Throughput (AT), validated through simulations.

Disadvantages

1. **Lack of Real-World Validation**: The study relies on simulations without experimental verification, which limits its practical applicability.
2. **Restricted Scope**: Focuses only on WiFi and mmWave technologies, excluding other advanced V2V communication options like 5G Systems.

SYSTEM MODEL/ STATE OF THE ART

System Model

1. **3D Spatial Representation**: Vehicles are positioned in three dimensions, accounting for altitudes and obstacle heights to accurately model realistic vehicular environments.
2. **Communication Technologies**:
    - **WiFi (IEEE 802.11p)**: Robust for short to medium distances, modelled with Rice fading (LoS) and Rayleigh fading (NLoS).
    - **mmWave**: High bandwidth and directional communication but limited range and sensitivity to blockages.
    - **5G Network**: Introduced for 5G networks, it offers ultra-reliable low-latency and high throughput. Its STP and AP are modelled for comparison alongside WiFi and mmWave systems.
3. **Performance Metrics**: Successful Transmission Probability (STP) and Average Throughput (AP), Channel Capacity and Outage Probability are derived analytically and validated through simulations.

State of the Art

1. **Incorporation of 5G Systems**: The inclusion of 5G highlights its capability for handling high-density, high-speed vehicular communication scenarios.
2. **Advanced Stochastic Geometry**: Used to model the spatial distribution of vehicles and interference in urban settings.
3. **Comparative Analysis**: Highlights the trade-offs in STP and AP between WiFi, mmWave, and 5G systems, demonstrating the strengths of 5G in terms of latency and throughput in complex environments.

MATHEMATICAL ANALYSIS

1). WiFi Systems- PATHLOSS MODEL

$$PL_{WiFi}(r) = PL_{WiFi}(r_0) + \sum_{\xi=1}^{2} P_\xi \beta_\xi 10 \log_{10}\left(\frac{r}{r_0}\right),$$

where P1 and P2 present the LoS and NLoS probabilities, respectively, βξ is the path-loss exponent, r denotes the 3D spatial distance between Tx and Rx, and PL_WiFi (r0) indicates the path loss at the reference distance r0 (usually is equal to 1 m), which is presented as follows,

$$PL_{WiFi}(r_0) = 20 \log_{10}\left(\frac{4\pi f_{c_{WiFi}}}{C}\right),$$

here, fc_WiFi is the WiFi carrier frequency, and C denotes the speed of light. (2) Accordingly, the corresponding instantaneous received signal-to-noise ratio (SNR) can be expressed as follows

$$SNR_{WiFi} = \sum_{\xi=1}^{2} \frac{P_\xi \mathcal{P}_T \mathcal{H}_\xi A_W r^{-\beta_\xi}}{\mathcal{P}_N},$$

2). mmWave Systems- PATHLOSS MODEL

$$PL_{\xi(dB)} = FSPL_{\xi(dB)} + \mathcal{S}_{\xi(dB)} + \mathcal{F}_{\xi(dB)},$$

Where Sξ(dB) presents a random shadowing factor, Fξ(dB) indicates a small-scale fading factor, and FSPLξ(dB) stands for the free space path loss, which is expressed as follows

$$FSPL_{\xi(dB)} = 20\log_{10}\left(\frac{4\pi f_{c_{mmWave}}}{C}\right) + 10\alpha_{\xi}\log_{10}(r),$$

Where ξ is equal to1 and 2, respectively, for the LoS and NLoS cases, and α ξ stands for its associated path-loss exponent. By considering that, the expression of the corresponding SNR is given by

$$SNR_{mmWaves} = \sum_{\xi=1}^{2} \frac{P_{\xi}\mathcal{P}_{T}A\mathcal{S}_{\xi}\mathcal{F}_{\xi}r^{-\alpha_{\xi}}}{\mathcal{P}_{N}},$$

2). 5G Systems- PATHLOSS MODEL

The general **path loss model** includes a path loss exponent α to account for environmental factors (e.g., urban, suburban):

$$\mathrm{PL} = \mathrm{PL}_{\mathrm{FS}} \cdot d^{-\alpha}$$

Where:

- α: Path loss exponent (e.g., 2 for free space, $3.5 - 4.5$ for urban environments).

In dB:

$$\mathrm{PL(dB)} = 10 \cdot \alpha \cdot \log_{10}(d)$$

The FSPL formula models the attenuation of signal strength over distance in free space:

$$\mathrm{PL}_{\mathrm{FS}} = \left(\frac{\lambda}{4\pi d}\right)^2$$

- $\lambda = \frac{c}{f_c}$: Wavelength (m), where c is the speed of light ($3 \times 10^8\ \mathrm{m/s}$) and f_c is the carrier frequency (Hz).
- d: Transmission distance (m).
- $\mathrm{PL}_{\mathrm{FS}}$: Free-space path loss factor (unitless).

In decibel form (dB):

$$\mathrm{PL}_{\mathrm{FS}}(\mathrm{dB}) = 20\log_{10}(d) + 20\log_{10}(f_c) - 147.55$$

The SNR at the receiver is given by:

$$\mathrm{SNR} = \frac{P_r}{P_n}$$

In decibel (dB) form:

$$\mathrm{SNR(dB)} = P_r(\mathrm{dBm}) - P_n(\mathrm{dBm})$$

Where:

- $P_n = k \cdot T \cdot B$: Noise power (Watts).
  - k: Boltzmann constant ($1.38 \times 10^{-23}\ \mathrm{J/K}$).
  - T: Noise temperature (Kelvin, often $290\ \mathrm{K}$).
  - B: Bandwidth (Hz).

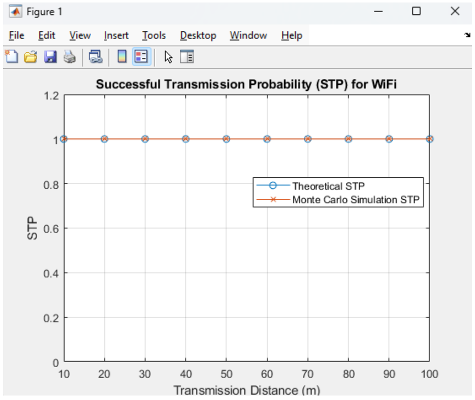
In dBm:

$$P_n(\mathrm{dBm}) = 10 \cdot \log_{10}(k \cdot T \cdot B) + 30$$

MONTE CARLO SIMULATION RESULTS

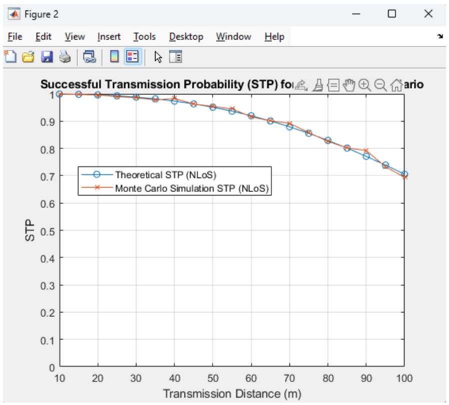
1). WiFi Systems-

a) STP in LoS Scenario



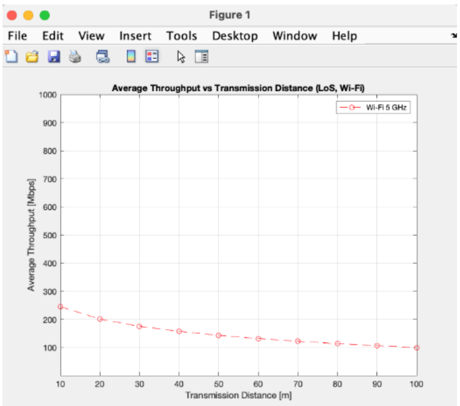
As we can see here, when the distance between vehicles increases, the STP value is constant around 1, which shows the great efficiency of using WiFi for Communication.

b) STP in NLoS Scenario



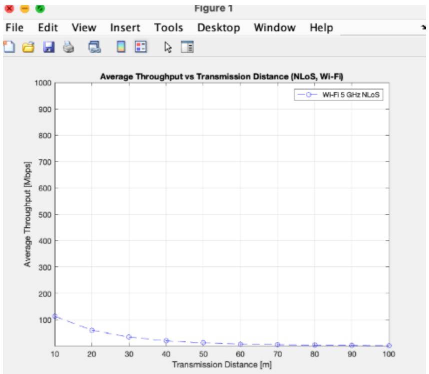
When the distance between Tx & Rx increases, the STP value is almost constant till 40m and then gradually decreases.

c) Average Throughput in LoS Scenario



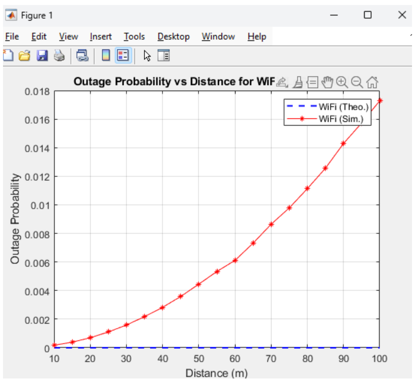
As the distance between vehicles increases, the AT value decreases very slightly.

d) Average Throughput in NLoS Scenario



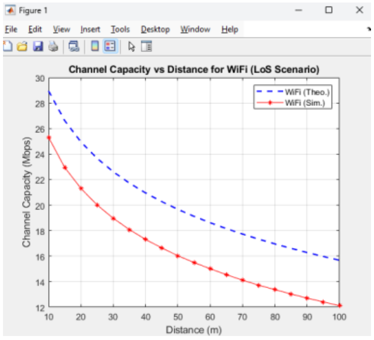
As the distance between Tx & Rx increases, the AT value gradually decreases and then reaches 0.

e) Outage Probability



As the distance between Tx & Rx increases, the Outage Probability increases exponentially.

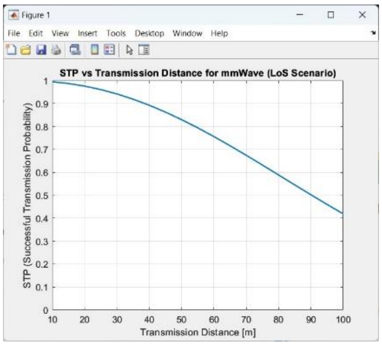
f) Channel Capacity



As the distance between Tx & Rx increases, the Channel Capacity gradually decreases.

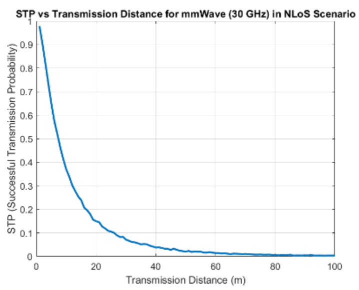
2). mmWave Systems-

a) STP in LoS Scenario



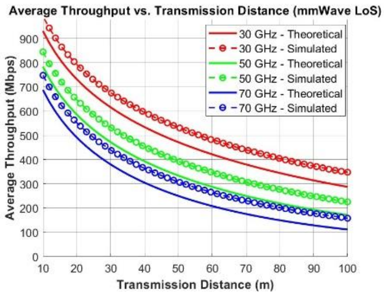
As the distance between vehicles increases, the STP value significantly decreases.

b) STP in NLoS Scenario



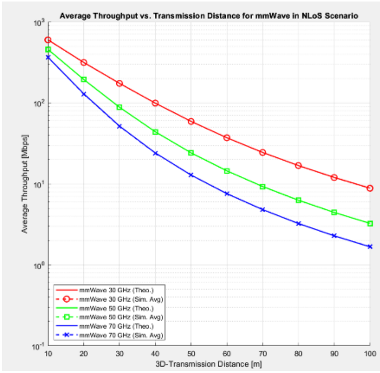
As we can see here, when the distance between vehicles increases, the STP value significantly decreases even when compared to LOS scenario.

c) AT in LoS Scenario



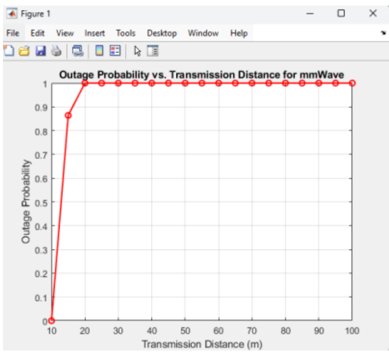
As we can see here, when the distance between vehicles increases, the AT value decreases gradually.

d) AT in NLoS Scenario



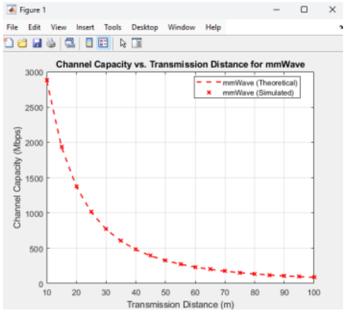
As we can see here, when the distance between Tx & Rx increases, the AT value rapidly decreases.

e) Outage Probability



As we can see here, when the distance between Tx & Rx increases, the Outage Probability increases exponentially, then becomes a constant beyond 20m.

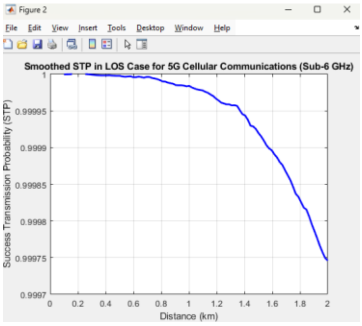
f) Channel Capacity



When the distance between Tx & Rx increases, the Channel Capacity exponentially decreases.

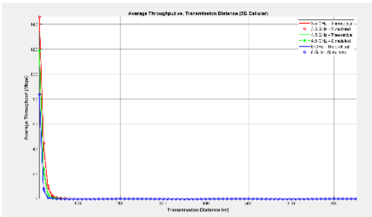
3). 5G Cellular Systems-

a) STP in LoS Scenario



As we can see here, when the distance between vehicles increases, the STP value gradually decreases and also the range is very high.

b) AT in LoS Scenario



As we can see here, when the distance between vehicles increases, the AT value rapidly decreases and also the range is very low.

CONCLUSION

This project provides an efficient comparative analysis of WiFi, mmWave, and 5G Cellular communication technologies in the context of Vehicle-to-Vehicle (V2V) communication. By using stochastic geometry and 3D modeling, the research accurately evaluates system performance under LoS and NLoS scenarios. The simulation results show that mmWave technology excels in scenarios with short distances and low vehicle density due to its high bandwidth and low latency, while WiFi is more reliable for longer distances and higher densities, offering stability despite bandwidth limitations. 5G Cellular systems stand out with superior data rates and low latency but face challenges such as higher power consumption and limited coverage in practical scenarios.

The derived metrics, including Successful Transmission Probability (STP), Average Throughput (AT), Channel Capacity, and Outage Probability, provide deep insights into the trade-offs and suitability of each technology for specific V2V applications. Simulation results validate the theoretical findings and highlight the importance of 3D modeling for realistic performance evaluations. This research underscores the need for tailored communication strategies that integrate the strengths of these technologies to meet the diverse demands of intelligent transportation systems.

INDIVIDUAL CONTRIBUTIONS

- Khader Zaahid Umar
    - WiFi- STP in NLoS Scenario
    - WiFi- AT in NLoS Scenario

EXTRA TASKS (Not in Base Paper)

- WiFi- Outage Probability
- WiFi- Channel Capacity
- 5G- STP
- PPT and this Report

- Sharan Karthick BL
    - mmWave- STP in NLoS Scenario
    - mmWave - AT in LoS Scenario

EXTRA TASKS (Not in Base Paper)

- mmWave - Outage Probability
- mmWave - Channel Capacity
- 5G- AT

- Vasavi Suma Bala
    - mmWave- STP in LoS Scenario
    - mmWave - AT in NLoS Scenario
    - This Report

- Sushanth Bansode
    - WiFi- STP in LoS Scenario
    - WiFi- AT in LoS Scenario

THANK YOU!