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Breaking the Blockage for Big Data Transmission: Gigabit Road Communication in Autonomous Vehicles

Chaofeng Zhang, *Student Member, IEEE,* Kaoru Ota, Juncheng Jia and Mianxiong Dong, *Member, IEEE*

***Abstract*—Recently, the spectrum band beyond 60 GHz has attracted attentions with the growth of traffic demand. Previous studies assumed that these bands are not suitable for vehicle communications due to the short range and high rate of blockage. However, it also means there is no existing service or regulation designed for these bands, which makes this area free to apply. Therefore, in this paper, we draw a potential map of terahertz vehicle transmission for autonomous vehicles to break the blockage of short range and unstable links. Firstly, we give a brief overview of possible waveforms followed by the specific channel at 0.1-1 THz. Then, we propose an autonomous relay algorithm called ATLR for the gigabit level communication in the high-speed road environment. Finally, we discuss how the gigabit links help relieve interference problem and provide extra data to support various instructions in autonomous vehicles.**

***Index Terms*—Thz Communication, Vehicle Network, Autonomous Driving.**

I. INTRODUCTION

In recent years, the fast growing demand for vehicle communications has raised the importance of spectrum availability, which is used for data creation, sharing, and consumption. With this trend, each mobile cell has to keep 10-GBit transmission rate around the year of 2020 [1]. Some already well designed and researched communication systems applied in 60GHz may be theoretically compatible with more than 0.1-THz bandwidth. However, it is difficult to establish a stable and efficient link due to the greater attenuation in vehicle communications. A couple of research groups all around the world have started to investigate the abundant spectrum resource to be operated beyond 300-GHz, the so-called THz communication systems [2]. With the advanced physical layer solution realized in the future, the new spectral bands can be utilized on Internet of Vehicles (IoV) [3], which lays the foundation for the challenges due to the explosive growth of autonomous vehicles' data transmission, sharing and consumption.

There are many challenges in the realization of efficient and practical THz band communication networks, which is related to the development of innovative solutions in different layers. The solutions overcome the challenges in mm-Wave systems can also be utilized in terahertz band, which bring enough bandwidth for gigabit level transmission. However, the attenuation of transmission distance is much higher than longer waves and the antenna array is also not completely developed. The obstacles can easily block terahertz waves, which is similar with mm-Wave. Various sensors could be embedded into the new type of vehicles in order to monitor the space condition, which help them find suitable positions for communication and driving. The formed networks can bypass the obstacles such as barriers or constructions and extend the communication links to other vehicles which are out of the shorter terahertz communication range.

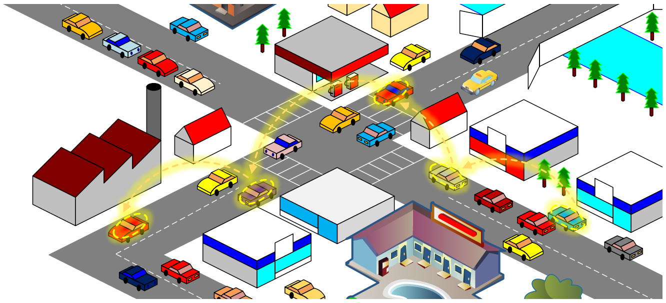

Fig. 1. No line of sight data sharing through terahertz vehicle networks

The purpose of this paper is to construct an applicable map of 0.1-1 THz supported autonomous vehicle system through the study of channel capacity, autonomous relaying and network establishment. Fig.1 is an example of data sharing scenario through terahertz band. For sending a large volume of data, the vehicles keep a gigabit level link through line of sight channels, which share information about traffic condition and captured videos for further processing. We believe the full use of this research can significantly improve the performance of autonomous driving.

The remaining part of this paper is organized as follows: In Section 2, the motivations from the existing technologies applied in autonomous vehicles are discussed. Section 3 gives a brief overview of possible waveforms followed by specific channel characteristics in 0.1-1 THz band. Discussions about the platform and throughput in developing technology and demonstrator are also given. An autonomous relay system for the gigabit road communication is presented in Section 4. In Section 5, we describe how the high-rate short-range communication helps provide extra data to support the advanced new self-driving technologies. Section 6 provides conclusions and an outlook to future research required in this area.

II. MOTIVATIONS IN TERAHERTZ SELF-DRIVING

A. *Terahertz Communication Model*

Terahertz band communication is envisioned as a key wireless technology to satisfy the demand of data collection in autonomous vehicles, by alleviating the spectrum scarcity and capacity limitations of widely used 4G or future 5G networks. Meanwhile, it motivates the potential of existing applications in vehicle technologies. The THz band is generally considered as the spectral band that spans the frequencies between 0.1 and 10 THz. Frequency regions below and above this band have been fully investigated: Spectral band below 0.1 THz (known as the microwave) is not available to support gigabit level links [4] while the spectral band beyond 10 THz has too many constraints to realize a feasible optical approach for mobile wireless communications. Therefore, the THz band is still one of the least explored frequency bands for communication. Impulse waveforms are discussed in this paper due to the fine multipath and fading environments. It enables precise ranging and data transmission using IEEE 802.15.4a. These features are indispensable for autonomous system, which makes the motivation for us.

B. *Terahertz Autonomous Relay*

Autonomous relaying technologies can be discussed to solve the capacity and feasibility problem mentioned above, but there are still several disadvantages for the real application. First, the range of terahertz band is relatively shorter than existing wireless technologies such as Wi-Fi and 4G technologies. The attenuation of the signal becomes much higher. Furthermore, the molecular absorption such as water vapor molecules can affect the channel performance more significantly [5]. To overcome the disadvantage mentioned above, vehicle relays can be applied to form Ad hoc networks or delay tolerant networks (DTN) among autonomous vehicles, in order to bypass obstacles and extend the link distance. The autonomous vehicles are more suitable than man-driven vehicles since the minor position adjustment can be made to achieve better multi-hop performance. Here, we propose an autonomous terahertz relay (ATLR) algorithm to determine the relaying position. This algorithm helps to improve the quality of real-time multi-hop links, by using embedded sensors to monitor the whole candidate space. It handles the channel condition and road presentation accurately, and leverages the relative position efficiently. After the position adjustment of autonomous vehicles, the terahertz channel can approach optimized performance.

C. *Terahertz Autonomous Driving*

Autonomous driving in up-to-date studies mainly focuses on 'correctness', such as assuming driving operations are prescribed in advance as functions of time or state of the system, which can never be proven that autonomous vehicles are superior to human drivers [6]. Although predictive controls such as decision trees, partially observable Markov decision processes (POMDPs), and methods based on multi-policy decision-making are fully discussed, the lack of fully collected data prevents these control systems from the real deployment. For example, Line of sight (LOS) image data, self-positioning coordinates collected by one vehicle's sensors sometimes are inaccurate and needed further calibration. Instead, with the constant high-speed channels, the autonomous control system can make the decision depending on added invisible information, calibrated cooperative positioning and traffic condition of the whole city. Fig.2 is an example of autonomous driving supported by additional traffic information. Because of the huge truck ahead, our sports car cannot detect the truck which is changing lane in the front. A decision of left-handed rotation from the autonomous driving system may put our car into a dilemma due to the lack of road information.

Fig. 2. Supplement of NLOS (no line of sight) traffic information for autonomous decision-making system

Nowadays, image recognition is important for human-like driving systems, but researchers only use the image data collected by individual sensors. Terahertz band can satisfy the requirement of constant high-rate video data transmission. This mean provides the dead zone image data or even computation capability through cloud service linked RSUs (Road-Side Unit) [7]. Traffic information is captured by the onboard sensors or other vehicles. With the added data provided by other vehicles, we conduct and discuss the impact of terahertz band for autonomous driving systems.

III. COMMUNICATION MODEL

A. *Impulse radio waveform*

A few number of waveforms are considered for terahertz band communication as the key wireless technology to satisfy the constantly changing attenuation on the road. Impulse radio (IR) waveform is one of the suitable waveforms for vehicle communication, which takes the advantage of detecting traffic condition and certain resistance with NLOS transmission [8]. The short pulse can reduce the interference of other radio frequency systems, when the galloping vehicles have to cross by several static or mobile communication systems. In short range, the NLOS signal is obtained due to the relatively strong penetration of road obstacles. The distortion and spurious signal detection is also reduced due to the multipath propagation. In a word, the impulse radio waveform is suitable for

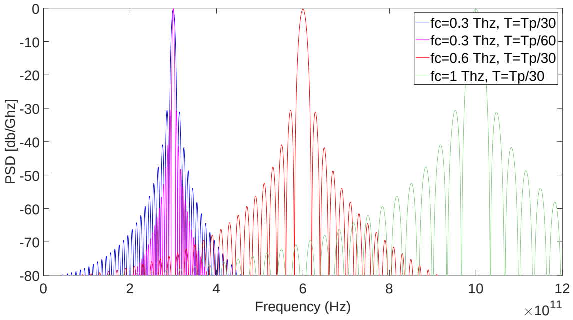

Fig. 3. The Hann pulse waveform for four values in THz Band

terahertz band communications either from capacity aspect or attenuation aspect.

Generally, carrierless waveforms such as IFFT pulse are used to realize vehicle positioning technology or other traffic detecting technologies. Carrier waveforms such as raised-cosine pulse (RCP) shape are used for data transmission. The basic shape is $p(t) = h(t)cos(2\pi ft)$, when $h(t)$ could be Rectangular, Gaussian, Hann or Hamming pulse. In order to calculate the capacity of this channel model, we analyze the frequency domain for this pulse first. Fig. 3 is the PSD (Power Spectral Density) of Hann pulse waveform using four different settings. The frequency of the carrier wave f_c is set as 0.3, 0.6, and 1 THz. The PSD of this pulse is

$$W(f) = T_p[\frac{1}{1-(2fT_p)^2}]sinc 2\pi T_p \tag{1}$$

where the duration T_p of pulse is 0.1 ns. From the figure we can observe that the available bandwidth increases with the frequency of carrier wave. It is noticed that with the increase of frequency, the width of the main lobe is also increasing. It broadens the analytical band and frequency resolution becomes worse. Therefore, Higher frequencies are suitable for less interference communication environments.

B. Channel Capacity

After the spectral analysis, we discuss the possible throughput of our proposed terahertz model. Generally, the total pass loss model $A(f,d)$ includes the sum of spreading loss and molecular absorption [9]. The noise includes system noise created by the electronic devices, antenna noise created by the Omni-antenna and molecular absorption noise depending on different humidity and air quality. For simply discussing the potential, we consider an omni-antenna situation. Notice that the main challenge and decisive factor to improve the link performance is still the real deployment of directional antennas.

The capacity can be calculated by the sum of each sub-bands' capacity, noted as Δf. In each sub-band, we consider the PSD of each transmission wave and the noise are locally flat, therefore the channel capacity is

$$C(d) = \sum_i \Delta f log2[1 + \frac{S(f_i)}{A(f_i,d)N(f_i,d)}] \tag{2}$$

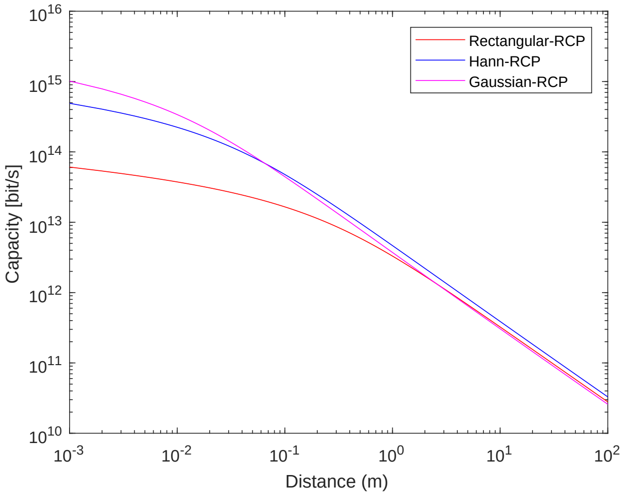

Fig. 4. Capacity as a function of the distance for three different power spectral densities

where d is the distance between Rx and Tx, S is the PSD function, A is the total pass loss function and N is the noise function. The capacity mainly depends on the distance and the SNR (Signal to Noise Ratio). The attenuation can be independently solved by relaying technology we introduced later. Meanwhile, the path loss and system noise increase with the frequency, and we can choose different pulses to achieve suitable PSD to improve the capacity.

In Fig.4, it shows the capacity as a function decreases with the distance. Generally, the molecular absorption noise becomes extremely high at several specific narrow bandwidth [5], which divides the whole THz band into 4 windows (0.38-0.44, 0.45-0.52, 0.62-0.72, 0.77-0.92 THz). In this figure, we set the transmission window with 0.62-0.79 THz, 170 GHz wide. Three common power allocation pulses are proposed here, rectangular-RCP, Hann-RCP, and Gaussian RCP. Rectangular-RCP is a flat pulse and cannot resist the path loss and noise efficiently. The Hann-RCP mentioned above performs better in short range than Gaussian-RCP. The Gaussian-RCP is not as sensitive as the others when the distance increases. Other pulses such as Sinc-RCP and carrierless IFFT pulse also have specific applicable systems of terahertz vehicle communications.

IV. TERAHERTZ AUTONOMOUS RELAY

Similar to the study result in recent paper [5], we observe the propagation of THz level signal at 1 and 10 meter decreases by 80 dBm and 110 dBm, respectively. THz communcation systems are proposed to achieve a 100 m link with directional antennas and shorter than 10 m link with omnidirectional antenna [10]. In order to extend the available transmission distance and enhance the resistance of environmental change, our proposed autonomous terahertz level relay (ATLR) becomes a suitable solution for vehicles. Since there is no universal standard for such short range communications, Tx can use the whole band to enhance the spatial reuse, which keeps a large volume of throughput in

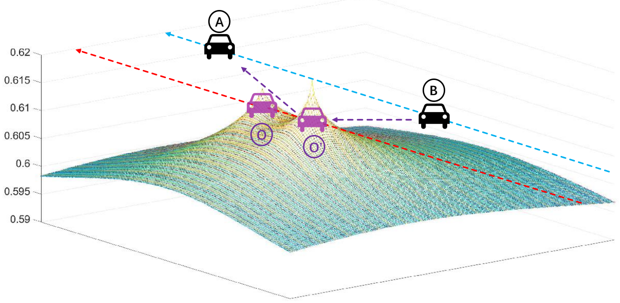

Fig. 5. An example of autonomous terahertz level relay algorithm (ATLR). Car A and B is the sender and receiver. Pink car tends to find an optimized position using ATLR for relaying A and B.

each interval. Besides, through relaying, it changes the lower penetration of NLOS communications into more stable LOS links. Moreover, it provides moderate length links which have the same distance with Wi-Fi but the bit rate is higher by 5-6 orders.

A. ATLR algorithm

However, terahertz transmitters and receivers have to suffer the constantly changing of propagation and noise when traveling on the road, which makes the relay point hard to select. Therefore, we propose an autonomous terahertz level relay (ATLR) algorithm to find the best relay position. The main idea of the optimization strategy is to detect the channel quality of each position in 2D representation and find the optimized point. In this scenario, we divide the whole space into very small blocks and detect the channel quality in each of them. However, under complicated traffic conditions and a l^2 plane area for detection (l is the defined side length of the plane for an independent relaying scenario), it is impossible for the relays to collect all the information from every space block. Our algorithm calculates the optimized relay point with relatively less movement when considering the advice of possible automatic driving routes.

Fig. 5 is an example of our proposed ATLR algorithm. Car A and B are autonomous vehicles with the mentioned support of 3D image detection system. Their autonomous systems advise them to advance following the blue line. A candidate relay Car R is by the side and has the similar self-driving route (noted as the red line). The car B sends a request to relay R, then R uses the mentioned carrierless IR pulses to detect nearby cars. Notice that the conventional RSS method or the state of the art LiDAR (Light Detection and Ranging) sensors can also be embedded on an autonomous car for positioning. With the awareness of surroundings' relative distances, relay R moves to the temporal optimal position O_1 as Round 1, which calculated by ATLR (the position noted as O in the figure). When moving to the suggested position, R detects the quality of the channel in each space block and stores in a channel quality matrix Q. After holding at the temporal optimal position, ATLR recalculates the optimal position as O_2 (noted as O' in the figure) based on the relay quality value $Q_{n,m}$ we defined. This value is stored in the channel quality matrix Q, where we have

$$Q_{n,m} = (Tx_{n,m} - Rx_{a_1,a_2}) * (Tx_{n,m} - Rx_{b_1,b_2}) * L_{n,m} \tag{3}$$

where $Tx_{n,m}$ is the signal quality of the transmitting antenna and $Rx_{i,j}$ presents the receiving antenna. We use $L_{n,m}$ to indicate recommendation rate of the route calculated by autonomous driving system. It depends on the traffic condition dynamically updated by the road understanding system, which the risk areas are eliminated. This setting can also avoid other nearby vehicular communication systems reasonably. When moving to O_2, ATLR recovers $Q_{n,m}$ and calculates O_3 at the end of Round 2. After k rounds, the relay vehicle fine-tunes itself to the stable position O_k. Since the relay can only monitor channel quality blocks passed by, the moving distance of each round is monotonically decreasing, which finally stops in a specific block. Through the process above, car A and B keep the stable and ideal terahertz channel through relay R.

B. Autonomous Multiple Relaying

Under the condition of certain dense traffic, there may be more than one candidate relay available in this scenario. The multiple relays are introduced here to further extend the limited range between car A and B. Firstly, through position sensors, the ATLR system estimates the needed number of relays to establish multiple hopping. Similar to our previous study [11], we propose a multi-deviation transmission protocol to improve the channel quality aggressively. The basic idea is that by setting common id as a priority (such as MAC address, user id, etc.), the ATLR produces a map with suggested position $O_{0,i}$ for the first priority Relay R_i. The relay R_i firstly moves to its optimal position $O_{0,i}$ then a single relay $\{R_j | id(R_j) < id(R_i)\}$ starts to collect the channel information when moving to its $O_{1,j}$. Then relay R_i moves to its optimal position $O_{1,i}$ and finishes the first round. Notice that this process can be applied to more than one relay, which can avoid priority or collision problems. A thoughtful setting of the priority in a specific scenario can even improve the efficiency of the whole system.

V. ENHANCED AUTONOMOUS DRIVING

Some pioneers consider the autonomous driving system should perform better than human driving in an all-round way, which requires more remarkable perceptibility and reaction in emergency situation. However, even if the autonomous system can nearly understand the visual information as well as human beings, it can never surpass human being's perception. One of the advantages of vehicle network is the information sharing ability. Conventional vehicles share information and traffic condition through DTN or RSUs [12], which only provide size limited message transmission. The application of vehicle terahertz band communication will bring new opportunities to the autonomous system, to see what human drivers can never see and to learn what human can never learn.

Next, we conduct the simulations in a scenario of autonomous vehicle networks. The scenario contains a 6 six lane expressway, where 3 lanes in each side. The width of each road is 3.5 m and the total length for observation is 200 m, where 12 RSUs (Road-Side Unit) are established at the road side. These RSUs contain the equipment of various vehicle communication systems and imaging sensors, providing 3D imaging and HD videos for autonomous vehicles nearby. The antennas of mmWave system and THz system are both considered as omni-directional antennas. If one transmitter sends information to the receiver of another autonomous vehicle, the receiver cannot collect others' information using the same frequency channel. If the channel collision happens, vehicles with higher priorities can establish the links. The problem of priority can be solved by many ways, such as importance of data, vehicle types, etc.

In Fig. 6, it shows the simulation results of average number of links using different wireless communication systems. One link represents two or more connected autonomous vehicles. All the vehicles obey the rules of the road and minimize the dangers of driving. Three basic transmission modes are tested here, gigabit communication, mmWave communication, DSRC intelligent transportation systems (ITS). The Gigabit communication (noted as THz in the figure) can approach 2.5 Gbit/s in real deployment [13] within 10 meters while mmWave can keep 0.1-1 Git/s using different approaches [14]. IEEE 802.11p based DSRC has the rate of 3-27 Mb/s with the communication range of 30 meters. RSUs are used in both mmWave and THz to provide additional road information in case of no vehicle's part, noted as $RSU\&mmWave$ and $RSU+$ respectively. Since conventional communication technologies such as DSRC can remain stable links only for images, we consider the captured HD video data can only be used by mmWaves and THz technologies. $ATLR+$ represents the links established by three vehicles, where one is the relay that builds bridge using different channels.

With the increase of autonomous vehicles, the average number of links is growing. However, the slops of all the communication systems decrease due to the interference of other links. The DSRC keeps stable standard due to the relatively long communication range, where the collision problem is obvious. The number in THz system is larger than than the number in mmWave due to the purer communication environment in short range. It is more flexible to establish reliable links in high density. Never than less, by the supporting of RSUs, there are more information shared in the air to improve the driving decision system. The $ATLR+$ is used to establish multihop links, and more links are established due to the higher density. It collects more information from different vehicles to improve the accuracy of road condition recognition system.

Currently, higher frequency transmission systems such as Thz bandwidth may be not fully developed to deal with complicated traffic conditions [15]. However, the advantages of higher transmission rate and attenuation help create more efficient transmission environment in short distance. Therefore, one of the future tend is the hybrid transmission systems which use various communication formats to handle different situations. It minimizes the interference from different channels. The hybrid approach may adapt more single or multihop links to heterogenous networks, which provides more flexible options for vehicle communications.

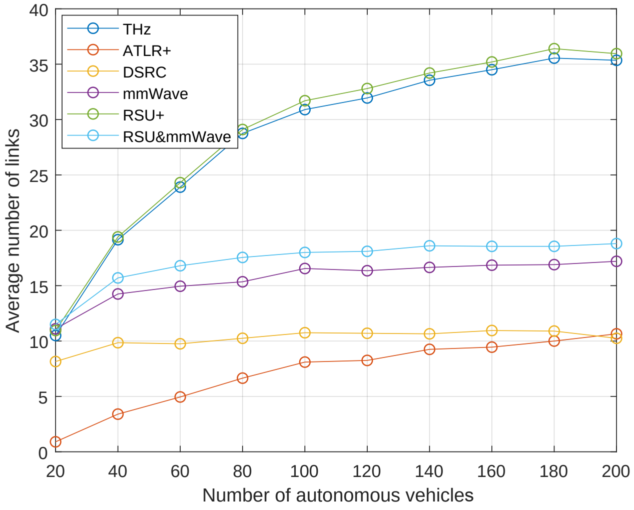

Fig. 6. Precision comparison in autonomous driving through different technologies.

VI. Conclusion

In this paper, we study the impact of terahertz band towards vehicle networks. THz band communication relieves the spectrum scarcity and capacity restriction of the existing communication systems. In short range, the THz link can be considered as a transmission window with almost 1 THz, which supports the growing real-time data transmission. Moreover, we develop an autonomous terahertz relay algorithm called ATLR which gives the advice of ideal relaying position to bypass obstacles and avoids stronger NLOS fading. Finally, we apply this algorithm in autonomous vehicle network. It helps create more flexible communication environment and provide more traffic information to nearby autonomous vehicles.

Actually, not limited to autonomous vehicles on the road, terahertz band can be widely applied to all mobile nanocell networks, such as delivery drones or UAVs (Unmanned Aerial Vehicle). Different kind of 'vehicles' has very different ability to adapt communication environments. These 'vehicles' support the exploration of missing details, which helps human beings and human made machines understand the known world more smartly.

ACKNOWLEDGEMENT

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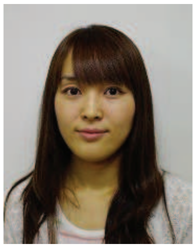

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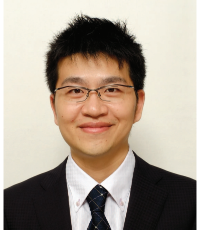

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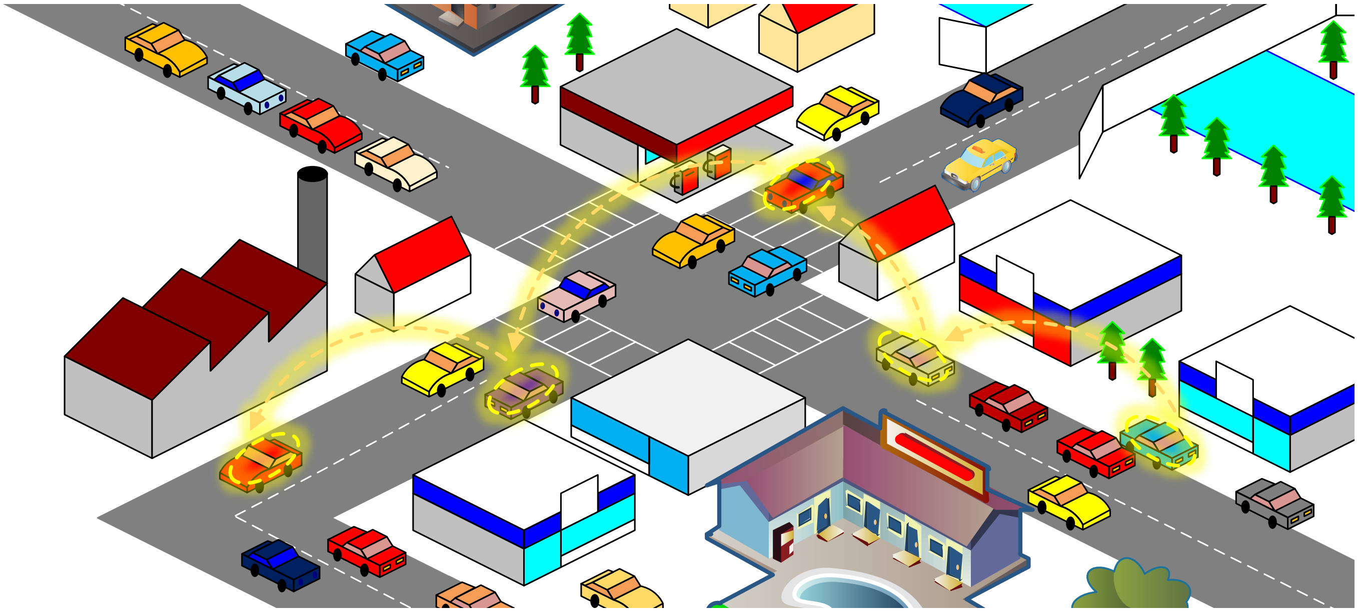

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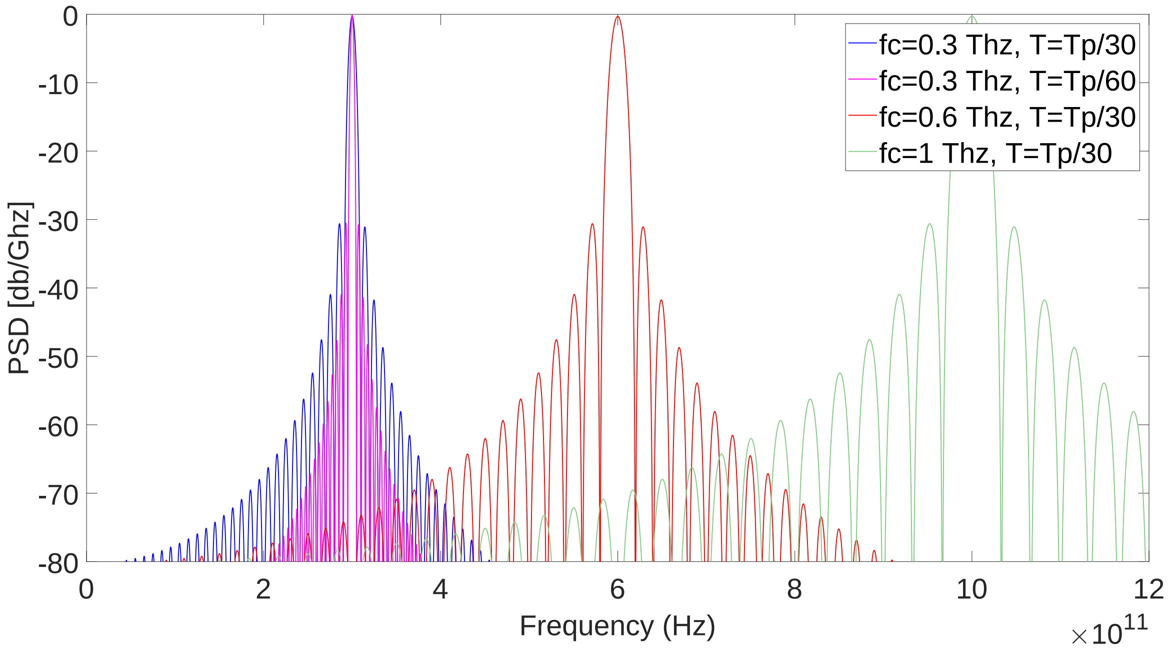

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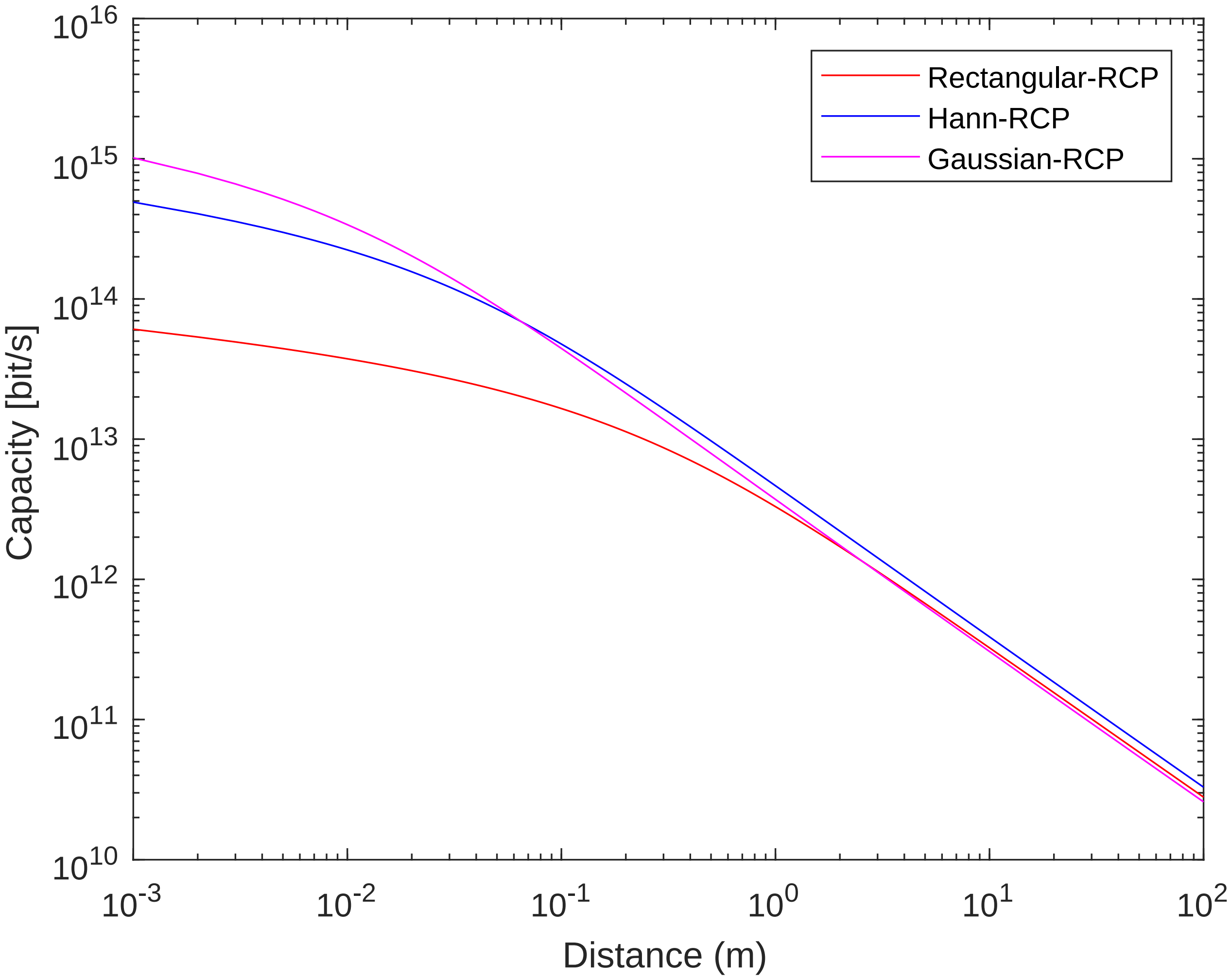
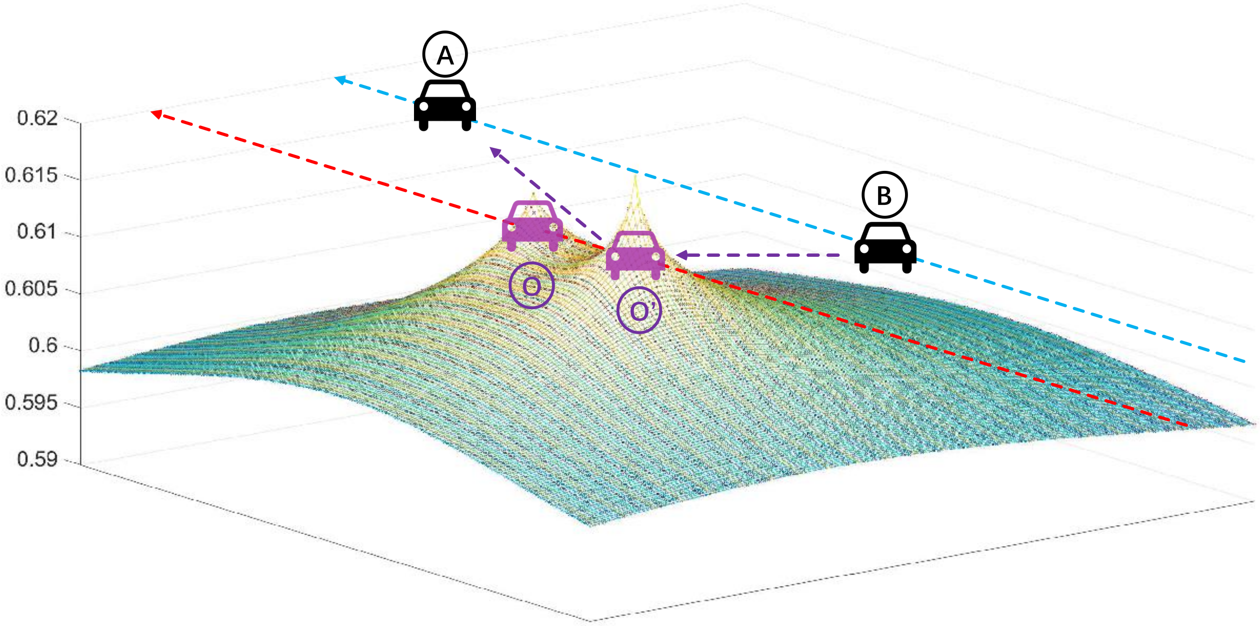


Fig. 4. Capacity as a function of the distance for three different power spectral densities



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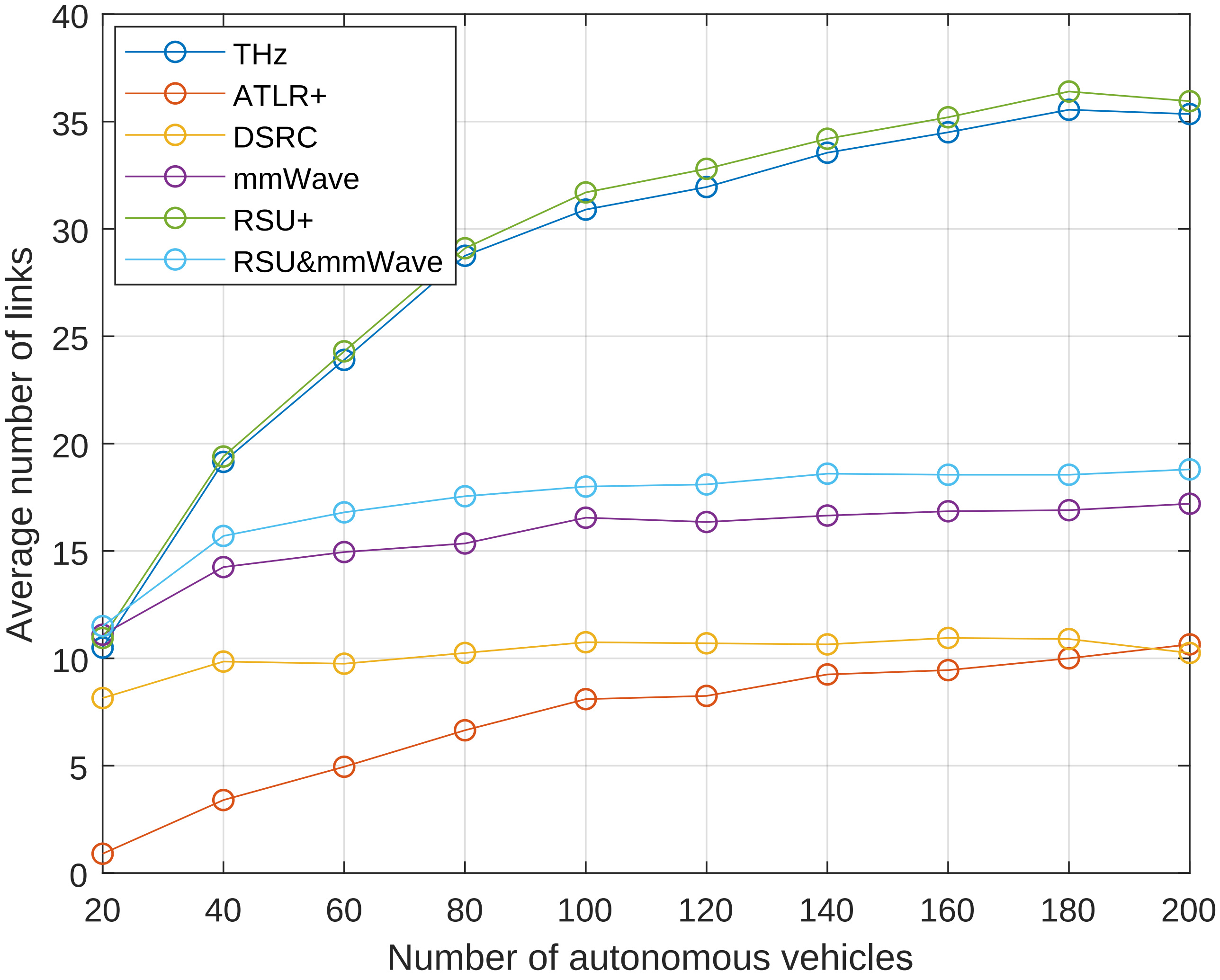

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