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RESEARCH ARTICLE

Car-to-Car Communication Using RF Cognitive Radio With VLC Common Control Channel

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ABSTRACT This paper combines the advantages of both cognitive radio (CR) and visible light communication (VLC) for car-to-car applications to achieve a high data rate with minimum (delay, outage probability, bit error rate (BER), and cost). CR technology hops among the existing radio frequency (RF) available channels to increase the RF spectrum usage efficiency and dodge the scarcity limitation. Moreover, using CR as a license-free application will reduce car-to-car communication running costs. However, CRs require a common control channel (CCC) to communicate the spectrum availability map within the CR network and to inform the receiver end about the change in the transmitter-end channel. Therefore, the CCC is the bottleneck in the car-to-car CR network. Then, we explore the types of CCCs and discuss using each of them to solve this bottleneck issue. In the proposed scheme, we adopt using VLC as CCC. A MATLAB simulation for a car-to-car framework is built to demonstrate the capabilities of VLC through the chosen metrics (i.e., data rate, delay, outage probability, cost, and bit error rate). Our results show that VLC achieves up to 90% of the licensed data rate with a small outage probability of 21.2% and moderate BER and delay. In addition, VLC presents the minimum cost, placing second after the licensed type with a score of 84.2% in the combined metric. In conclusion, with the VLC's bright future of expansion and growth in the car-to-car application, we have proven that VLC is worthy of implementation practically in modern cars.

INDEX TERMS Car to car, CCC, CR, fog effect, rain effect, VLC.

I. INTRODUCTION

Due to the increased usage of social media platforms, people nowadays get distracted more often even while driving. Moreover, the excessive dopamine dose received while watching social media platforms makes people quickly feel bored while driving. Consequently, car accidents have increased dramatically in the last decade [1]. Therefore, many researchers proposed adding the car-to-car communication function to all newly manufactured cars to increase road safety [2], [3]. That communication means providing vital data about the road, ahead cars, and the following cars. The car-to-car communication transfers data between cars to give each one a global view of the road. It aims to achieve accident-free traffic and smooth road flow with a small congestion probability.

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A. BACKGROUND

There are many communication methods to transmit data between cars. One of the V2V communication system methods is radio frequency (RF) communication [4]. However, due to the popularity of RF, the RF channels are mostly booked and crowded. Using the standard channel assigning technique to cars is not the best solution for transmitting data between vehicles as there is no available backup spectrum for all cars on the road. Some researchers propose using the current infrastructure of wireless telecommunication networks [5]. At the same time, the others propose the establishment of a stand-alone network that is designed spatially for car-to-car communication [6]. These two assumptions are too costly to be implemented in real situations. Moreover, the RF spectrum is too crowded to accept the new car-to-car communication bandwidth either within the mobile communication network or using the establishment of a stand-alone network [7].

To avoid this overcrowded RF problem, Academia has recently introduced the idea of communication systems in the millimeter-wave (mmWave) bands to overcome the problem of over-occupied low-frequency bands (i.e., systems that operate in the RF band from 3 kHz to 300 GHz) [8]. In the meantime, mmWave communication systems provide higher data rates. In contrast, the challenges of using the mmWave band in radio frequency (RF) systems are not limited to the maximum produced transmission power from the electronic devices in that band and the complexity of channel modeling due to the rain attenuation and atmospheric varieties. Moreover, the mmWave communication band faces practical issues such as antenna alignments and beamforming because of its challenging multiple propagation characteristics [9]. On the other hand, communication systems in mmWave bands are predicted to be the strongest candidate for 6G and beyond and these systems might introduce some new IEEE standards (e.g., at the 60 GHz band, the IEEE standard 802.11ad is introduced) [10].

In contrast, many researchers proposed using cognitive radio (CR) technology to hop among the existing RF available channels [11]. This assumption will increase the RF spectrum usage efficiency and will dodge the aforementioned limitation. Moreover, using cognitive radio is a license-free application that reduces the car-to-car communication cost compared to the other RF-licensed techniques. In addition, using cognitive radio improves the quality of service (QoS) by sensing environmental and inadvertent man-made radio interference [12]. Therefore, cognitive radios can select frequency channels with higher signal-to-noise ratios (SNR) to improve the utilization efficiency of the radio wave spectrum and postpone the spectrum scarcity problem [13]. In CR, the primary users (PUs) are the ones who have the license to use that frequency band, meanwhile, the secondary users (SUs) are the ones who do not have the license to use that frequency band [14]. However, SUs are allowed access to the PUs licensed spectrum bands opportunistically on the condition of not causing interference to PUs [15]. To minimize the interference, the network of cognitive radio SUs access the spectrum through overlay, underlay, or interweave based on the sensed PUs network information and the type of regulatory available constraints [16].

The main two factors that decide good CR design are the probability of miss-detection (PMD) for the primary user signal and the probability of false alarm (PFA) for free channels. The effect of PMD is more severe as it harms PUs and the system might not be approved to work if this factor is above a certain threshold. The PFA affects degradation in the CR system's overall throughput and delay. These two factors are heavily affected by the fading effect [17].

In fading the signals from multipath aggregate to form constructive or distractive interferences. The distractive interference causes degradation in the PUs signal which increases the PMD. While the constructive interference amplifies the background noise sparks which increases the PFA [18]. The academia proposed using cooperation between nodes to overcome these fading effects by taking advantage of the fading uniqueness effect at each node [19]. Therefore, if 10% of nodes are in destructive interference, the remaining nodes correct their decision through cooperation. Such cooperation requires a separate communication channel between SUs to transmit control messages other than the data channels.

Consequently, cognitive radios require a common control channel to communicate the spectrum availability map within the network and to tell the receiver end about the change in the transmitting channel. Hence, the common control channel is the bottleneck for this method [17]. There are many types of common control channels and each of them tries to solve this bottleneck issue from a philosophical point of view. Generally, the common control channel types fall into two categories (i.e., in-band and out-of-band) [18], [19]. The in-band common control channel is either an underlay channel using an ultra-wideband spread spectrum (e.g., CDMA) or uses one of the channels with the least existence of primary users (PUs) [20]. The underlay approach suffers from a complex transmitter and receiver design and a very small data rate while using one of the CR channels does not guarantee the channel availability for important applications such as car-to-car communications. On the other hand, the out-of-band category contains 1) buying a license for the common control channel from mobile network service providers, 2) using the industrial, scientific, and medical (ISM) radio bands such as the free 2.4 GHz band which coexists with wi-fi and other interferences, and 3) using a non-RF approach such as wired communication or visible light communication (VLC) [21]. In contrast, buying a license for a common control channel adds a subscription cost for each car, which increases the overall system cost. Meanwhile, the ISM band is overcrowded and suffers from a very high noise level [22].

B. RESEARCH GAP, MOTIVATION, AND PROBLEM STATEMENT

Therefore, aiming to achieve more spectral efficiency, optical wireless networks can be used in incorporation with CR [23]. Consequently, the network throughput of the hybrid cooperative CR RF/VLC is way more enhanced. To further increase the throughput, the hybrid system may adopt using the multiple-input multiple-output (MIMO) in the network [24]. Wireless communication in the band of visible light (400 THz to 800 THz) has been proposed to compensate for the spectrum scarcity problem in RF band communication systems that operate at (3 kHz to 300 GHz) [25]. In 1880, Bell and Tainter proposed the photo phone (i.e., the idea of transmitting a signal using light) [26]. However, the proposed photo phone idea used a fluorescent lamp as a light source in the system implementation to transmit data [27]. After that, the fluorescent lamp was replaced by light-emitting diodes (LEDs) for fast switching and to produce a higher data rate [28]. Keio University's researchers were able to use the same LEDs for both communication and illumination. However, this experiment was in an indoor visible light communication (VLC) environment using multiple light sources and detectors to form small-cell access points (APs) within the wireless network. VLC is easier to prove operable in an indoor environment as there are fewer interference sources (e.g., sun, moon, traffic lights, etc.) and fewer weather conditions (e.g., rain, fog, etc.) [29].

Furthermore, the 2011 IEEE 802.15 working group for Wireless Personal Area Networks published the first IEEE standard about VLC (802.15.7-2011). That IEEE standard discussed the framework of VLC communication regarding the dimming mechanisms, modulation schemes, and data rates [30]. After that, the IEEE 802.15 working group proposed STD 802.15.7-2018 to broaden the previous STD 802.15.7-2011. The 2018 version includes categorizing the PHY layers into six categories to enable many more technologies in Optical wireless communications (OWC) [31]. Moreover, the 2018 version describes Optical Camera Communication (OCC) as the IEEE's first standard to use OWC in personal area networks (PANs) as the suffix well-known as (OWPANs) [32]. Additionally, IoT applications tend to take advantage of OCC technology benefits based on the VLC approach beyond 5 G key technologies [33]. It also takes advantage of the available infrastructures (i.e., LED lights in traffic lights, car headlights and taillights, parking cameras, and road surveillance cameras) which are considered the best compatible with several applications /scenarios. Consequently, safety-related traffic information (e.g., direction and speed-related information, accident notifications, and braking performance) can be exchanged using vehicle communication through VLC [34]. The camera detector used in OCC has a low frame rate that needs special modulation schemes to avoid flickering illumination [35]. OCC technology is described within the IEEE 2018 standard of 802.15.7 [36]. The IEEE 2018 standard of 802.15.7 physical layer (PHY) for OCC contains three categories within it such as:

- Category 4: For applications in outdoor areas and support high mobility. Consequently, car-to-car and car-to-infrastructure communication applications can be used under this category.
- Category 5: Unlike Category 4, this category is used for indoor applications with small distances. Commercial rolling shutter cameras used in smartphones might use this category for Li-Fi and similar communication applications.
- Category 6: This category concerns communication through screens. It can be applied to smartphones, tablets, and TV screens.

Smart devices especially mobile phones have dramatically increased the usage of advanced cameras. OCC is one system that uses smart device cameras rather than photodetectors to receive data [37]. The usage of OCC is open to making several challenges in different applications (e.g., digital signage, mobile robot (MR) communications, vehicle-to-everything (V2X), smartphone positioning, augmented reality (AR), and localized advertising). The OCC has a limited data rate because the available commercial cameras have a low sampling rate. Particularly, using cameras of 30 frames per second (FPS) achieves data rate in the range from several bits per second (bps) to several kilobits per second (kbps) [38]. This problem might be overcome by using high-speed sampling rate cameras of more than 1000 FPS [32], [39]. On the other hand, OCC has more advantages such as high SNR, low interference, high stability, and high security concerning non-fixed communication link distances, these characteristics make it one of the popular solutions for long-distance LOS communication links.

Our previous research used the VLC as the main car-to-car communication technique either, in urban areas using mobile networks (e.g., 4G or 5G) as a backup communication method or on highway roads using low earth orbit satellite constellations (e.g., Starlink, or OneWeb) as a backup while there is no mobile coverage [26], [40]. In both scenarios, VLC communications have great theoretical results which promise a great future for VLC communications.

However, we have conducted a practical experiment to implement these laboratory simulations. By comparing the results from both the lab experiment and implementation using practical car parts (i.e. camera and LED), our practical experiment shows a huge gap between what we expect to have and what we have achieved [40]. The maximum achievable data rate in the practical experiment was 200 kbit/s. While in the lab the data rate could reach 355 Mbit/s in the pure VLC channel communication which is about three times the pure RF channel communication (i.e., 108 Mbit/s). The difference is that the lab uses some state-of-the-art cameras and LED sources. Consequently, we propose a plan for the VLC development map that starts with the practical setup at hand. Then after a decade of research and development, the car manufacturer shall be convinced to implement these lab-advanced parts in new cars for high-speed VLC communication.

Therefore, this paper proposes using the VLC as a common control channel for the cognitive radio network in car-to-car applications, because choosing the common control channel in the RF makes the problem worse. Although VLC has great potential to be the main method for transmitting data between vehicles with huge bandwidth and higher data rates, the development of VLC as a means of transferring data between cars is still in the early stages. The VLC communication transmission data rate depends on the properties of the installed transmitting LED and the receiving camera. With the currently installed equipment, cameras and LED lights could reach up to approximately 200 Kbit/sec. On the other hand, road safety cannot wait until the VLC technology reaches its full capability.

Consequently, motivated to achieve the highest data transfer rate between cars, we will use an RF cognitive radio with a backup common control channel using VLC. Our metrics include data rate, delay, outage probability, cost, scalability, adaptability, and bit error rate. The comparison analyses shall compare VLC versus the other common control channel types. We focus on comparing practical systems, not theoretical or laboratory-achievable systems.

C. KEY CONTRIBUTIONS

- We propose building a car-to-car communication system that utilizes CR transmission with VLC as the CR's common control channel. In this proposal, we take advantage of their license-free nature to reduce the car-to-car communication system running cost.
- We target using the current car LED lights and sensor's camera as the VLC communication hardware to reduce the communication system cost. However, as our previous practical experiment mentioned, the practically achievable data rate is below expectations and still needs improvement to reach the theoretical levels. Mainly, due to a lack of hardware specs. Therefore, we aim to use the car-to-car VLC communication technology to encourage the industry to invest in upgrading VLC hardware components.
- Choosing the VLC communication as the CR's common control channel solves the CR bottleneck dilemma of choosing a licensed CCC or unreliable CCC for cognitive radio common control channel communications.
- We proposed dividing each of the car LED lights into segments. Each segment transmits its data using OOK modulation separately and independently to form multi-inputs. On the other hand, camera pixels form multi photodetector (i.e., multi-outputs). Therefore, the proposed system forms a MIMO to increase the data rate, improve the bit error rate, and decrease the outage probability.
- To validate the proposed car-to-car communication system's robustness, we present the study of the proposed system under different weather conditions. The simulation checks the resultant bit error rate and outage probability under each weather condition. The detailed results are in the results section.

D. KEY LIMITATIONS

- Concerning cost, the system might face increased costs if implemented with high lab specs. Such as the cost of the complex pieces of equipment to be added to vehicles for example high FPS cameras and MIMO LED lamps.
- Concerning communication distance, VLC has a limited distance (point-to-point communication) of approximately 100m which makes it limited in most applications. However, the distance can be improved through multiple hops relaying. In contrast, by increasing the number of hops, the noise accumulation might lead to data loss.
- Concerning delay, increasing the communication distance through multiple hops leads to a total huge delay due to the needed processing time by each repeater in the chain. Therefore, the number of hops must be limited to decrease delay and prevent loss of data.to minimize the processing time in each node, we proposed using an amplifier forward to decrease the delay in a tradeoff with the received accumulated noise.

II. RELATED WORK

Many surveys and published studies discussed the VLC systems' limitations, advantages, and applications. The authors of [41] have introduced VLC as a 5G candidate communication system and demonstrated the VLC advantages and limitations. The main advantage they found is the VLC can achieve a high data rate and avoid the spectrum sacristy problem of RF bands. However, the main limitations are the needed complex pieces of equipment to be added to mobile phones and vehicles such as high frame per second cameras and MIMO LED lamps or screens. The authors of [42] have been introduced using the automotive industry LED headlamps in VLC and the effect of that on the VLC data rate achieved in V2V applications and the utilization limitations. They found that the possible ways to increase the data rate using the automotive industry LED headlamps fall into two categories 1) increasing the number of independent ON/OFF LEDs in each headlamp and 2) changing the illumination level of each independent LED to form ASK levels. Therefore, if 2 headlamps where each headlamp containing 16 independent ON/OFF LEDs with 8 illumination levels, then each frame can receive 96 bits. For 100 FPS cameras, they prove that the system can communicate at the data rate of 9600 bit/s.

In [2], the authors present a comprehensive survey of hybrid RF/VLC communication systems. The author proposed a comparison between RF and VLC health safety, spectrum availability, energy consumption, coverage and mobility, and interference. They find that Visible light offers higher health safety than RF. Moreover, the spectrum availability of visible light is wider than RF. In addition, from a security point of view, visible light has more immunity to interception and jamming compared to RF. Additionally, the energy consumption of RF is much greater than visible light. While RF has higher EMI interference than visible light. On the other hand, the main advantage of RF is that RF has more coverage and offers greater mobility than visible light.

In [4], the authors propose using a CR-based ad-hoc vehicle network (VANET) or CR-VANET. The CR-VANET is a highly technologically sophisticated network that aims to compensate for the deficiency in VANET spectra. CR-VANET has some problems in sensing relative to other CR-based networks, including the effects of high-speed mobility and vehicle routes, the heterogeneous quality of service (QoS) specifications, security issues, shadowing, and multi-path fading problems. The authors proposed using machine learning, CSS, new PU activity modeling, the construction of faster convergent algorithms, and beamforming antennas as solutions to these problems. However, there is still a great deal of potential for research and study into spectrum sensing challenges in CR-VANET. In [11], the authors introduced simultaneous light wave information and power transfer (SLIPT). The authors proposed using both the VLC and the CR simultaneously to mitigate the outage probability

TABLE 1. MATLAB model simulation parameters.

Parameter	Value	Parameter	Value
Road Distance	10 km	**RF freq. band**	70 ~ 90 GHz
Simulation Lanes	8 lanes	**RF bandwidth**	2 GHz
Number of cars	60 cars	**Max. Distance of VLC**	~ 100 m
Car Speed	40 ~ 80 km/h	**MIMO**	9 LED / Headlight
Length of Data	64 kbit	**Camera FPS**	30 ~ 2000
Mount Carlo	100 simulations	**LED Tx Power**	10,000 lm
Max. Distance of RF	~ 200 m	**VLC multi-hop**	5 hop

in both systems. Therefore, if the VLC channel is blocked due to weather conditions or non-line-of-sight scenario constraints then the CR channel prevents the outage. On the other hand, if all RF channels are occupied with PUs, then the VLC channel prevents the outage. Moreover, a power transfer is proposed through the VLC channel. Then, whenever the device passes through a VLC access point such as street lights or commercials, it charges its battery and receives data simultaneously. However, the paper only assumes communication to stationary devices with no mobility probability is added. Therefore, their assumptions are not valid for car-to-car communication applications.

The authors of [43] have introduced a survey on systems that use wireless optical communication, their applications, and network architectures. Wireless optical communication is either used in an outdoor environment or an indoor environment. The indoor applications are much easier to implement and operate and have a simpler network architecture. For the downlink, the lighting system of an indoor home or mall is used to transmit the needed data while the selfie cameras of the mobile phones receive and decode the transmitted messages. The uplink uses LED illuminance levels of mobile phone screens to transmit the needed data to the surveillance cameras which decode the reply messages. On the other hand, outdoor applications use commercial screens and traffic lights for the downlink which are received by vehicles parking cameras and mobile phone selfie cameras. The uplink uses LED illuminance levels of mobile phone screens or the vehicle's headlamps and taillamps to transmit the needed data to the road surveillance cameras which decode the reply messages. The authors of [44] have introduced the communication system details based on VLC. They propose using LED lamps or LASER sources as VLC communication transmitters and photodetectors or cameras as VLC communication receivers. Moreover, they introduced possible applications such as indoor localization, vehicle-to-vehicle (V2V) communication, and VLC sensing. In each application, they provide the advantages, possible challenges, future research trends, and optimization techniques used to maximize the data rate. They concluded that most of the current research concerns the theoretical approach for VLC and that the practical experiment results are still in the early stages of achieving the required data rate and outage probability.

III. SYSTEM MODEL

We propose a framework of a two-way road with 60 cars within six lanes (i.e., three lanes in each direction) As shown in Figure 1. A blue arrow represents a single-hop or multi-hop VLC, while purple lightning represents overlay, green arrows represent underlay, and yellow arrows represent licensed RF that communicates with the NSP access point mounted on traffic lights. When the VLC distance is greater than 100m the communication is considered blocked as shown with a red cross in Figure 1. Meanwhile, if there is a car in between it communicates through multi-hop VLC with the middle car considered as a repeater as shown with the two consecutive blue arrows. In addition, overlay cognitive radio mostly happened away from the access point as shown with the purple lighting. The green arrow that represents the underlay is not restricted to certain conditions. A MATLAB simulation of the car-to-car communication system under this framework will be used and modeled according to the following parameters. The road simulated distance is chosen as 10 km. Variations in the speed of each car are assumed to be from 40 to 80 km. Mount Carlo simulations are used to minimize the randomness in the results and to increase the result's robustness. Each car is assumed to transmit a data set of 64 kbit to its surrounding cars through the proposed communication system to measure the algorithm's metrics. Our MATLAB simulation parameters are summarized in Table 1.

In our simulation, the road has access points along its way either mounted on lights, road signs, or commercial boards. The access points communicate with the on-road cars to deliver vital road instructions (e.g., speed limits, closed lanes ahead, congestion, etc.). However, these instructions only reach a portion of cars that are nearest to the access point with minimum transmitted power to be able to reuse the frequency spectrum and save energy. All other cars (i.e., out of the limited coverage range of the access points) on the road depend on hopping this information among them through the car-to-car communication means. In addition, each car transmits additional information to the following cars regarding its intentions and directions on the road to avoid crashes.

As aforementioned, we assume the main car-to-car communication uses RF cognitive radio communications. The RF frequency band of 70 GHz to 90 GHz is proposed because of its currently limited applications and huge bandwidth.

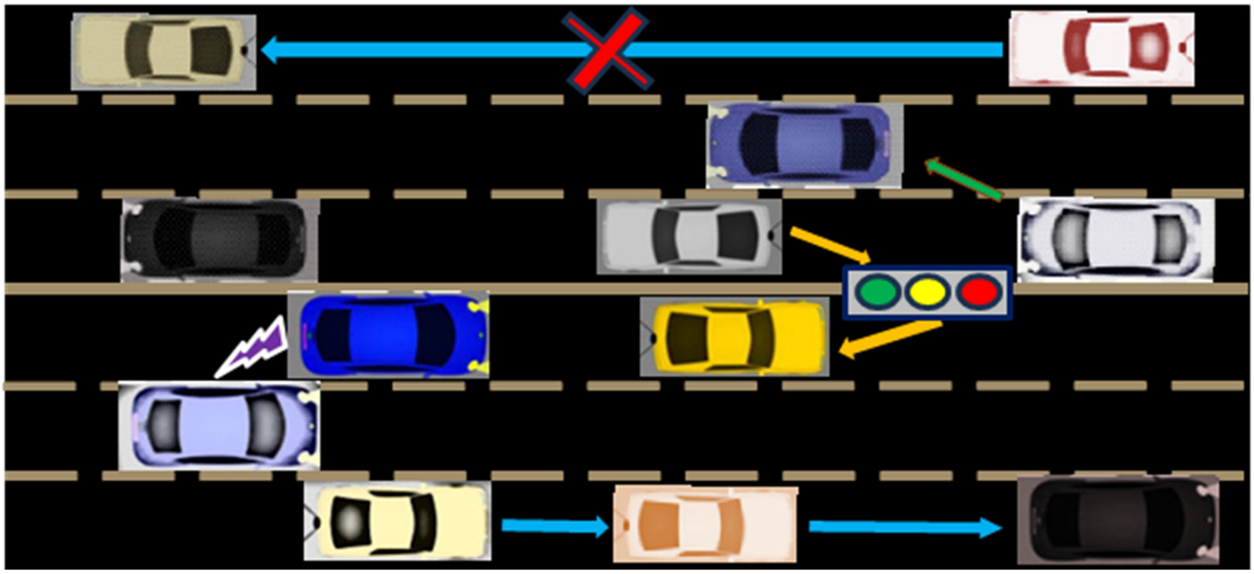

FIGURE 1. The proposed framework of 60 cars communicates through VLC/RF within 6 lanes road (3 lanes in each direction).

However, this frequency band suffers from high attenuation that limits its communication distance to a few tens of meters. This is not a problem in car-to-car communication because the required communication distance between cars is within that range. While the CR common control channel is compared between the VLC, overlay-paid, overlay-ISM, and underlay. The traffic types on the common control channel contain the following instructions 1) spectrum sensing results, 2) cooperation packets among secondary users (i.e., cars), 3) request to transfer from the sender to the destination, 4) broadcast to allow the pool of secondary users to know that this channel is reserved, 5) the acknowledgment packet from the destination to the sender, and 6) create and update the routing map among the secondary users. These traffic types can be summarized into broadcast and unicast (i.e., point-to-point full duplex). For comparison purposes, we assume alternative common control channels such as 1) licensed overlay, 2) unlicensed overlay in the ISM band, 3) underlay, and 4) using VLC. In what follows, we will discuss each CCC alternative for exploring their advantages and drawbacks theoretically.

A. USING LICENSED OVERLAY AS CCC OF CR CAR-TO-CAR COMMUNICATION

In RF communication in the licensed bands, each car buys a license to use that band in car-to-car communication. That license might be a subscription (i.e., the amount paid every period even if not used by that band) or data-centric (i.e., the amount paid per packet sent through that band). In this paper and for comparison purposes, we adopt the data-centric license approach from the service providers. Therefore, the overall system cost is the initial telecommunication system cost and the data transmission cost compared to other approaches with no running costs at all. On the other hand, the use of licensed bands guarantees a better performance in terms of outage probability, SNR, and BER as the service provider's role is to ensure these performance metrics. However, the licensed bands cannot be used by all cars due to the spectrum scarcity problem and a portion of cars must use other communication techniques. That portion is going to increase as more and more cars adopt car-to-car communication.

B. USING UNLICENSED OVERLAY AS CCC OF CR CAR-TO-CAR COMMUNICATION

In RF communication in the ISM band, an omnidirectional antenna is used to transmit an electromagnetic wave in the frequency band from 70 to 90 GHz with a bandwidth of 2 GHz. Consequently, that huge bandwidth might have sufficient channels for car-to-car communication in the near and medium future. However, this band has higher attenuation compared to other bands because the attenuation in free space is proportional to the carrier frequency and that frequency is more likely to suffer from gas attenuation peaks such as oxygen O_2 and water vapor H_2O. This high level of attenuation in such a band decreases the communication distance and limits the number of applications (car-to-car communication is one of them). The channel in RF communication is less affected by the air's attenuation due to weather conditions in comparison to the VLC channel. In contrast, attenuation in the RF channel is affected by concretes or metals. On the other hand, The RF omnidirectional antenna receives electromagnetic communication waves in both non-line-of-sight and line-of-sight. This paper proposes a modulation of 1024 QAM because if the modulation increases beyond that limit the SNR will decrease dramatically which leads to decreased communication distance. The proposed transmission range of RF is less than 200 m to avoid high attenuation levels because transmission through RF from all cars with the chosen communication distance is considered interference concerning other cars. That's why we need to minimize the number of cars using RF communication within a given area and make them more dependent on other communication techniques.

C. USING UNDERLAY AS CCC OF CR CAR-TO-CAR COMMUNICATION

In RF communication in the underlay, the CR SUs spread the transmitted data using the spread spectrum (SS) key techniques. In such techniques, the transmitted data occupies more bandwidth but with low power (i.e., lower than noise level) to not cause any harm to PUs. The SU receiver reconstructs that data message perfectly from the surrounding noise by knowing the transmitted SS key and multiplying the received message with that key. However, there is a finite number of SS keys that can be used orthogonally without interfering with each other. Beyond that limit more and more interference levels are present and all communications might be dropped. Therefore, CR using underlay in CCC communications limits the maximum number of CR networks operating in the same area. However, underlay in CCC ensures no damage to PUs and its outage probability is not an opportunistic manner but rather is a function of the number of current cars using the CR network.

D. GENERAL BER EQUATION IN OVERLAY AND UNDERLAY COGNITIVE RADIO

The bit error rate general equation for both overlay and underlay cognitive radio systems is discussed in this section This equation calculates the effective SNR that is affected by both noise and interference. Combining the effective SNR with the modulation-specific BER, we get the general BER for a cognitive radio system with M-QAM, for instance, is:

$$\boldsymbol{BER_{CR} \approx 2\left(1-\frac{1}{\sqrt{M}}\right)Q\left(\sqrt{3\cdot\frac{SNR_{eff}}{M-1}}\right)} \tag{1}$$

and:

$$\boldsymbol{SNR_{OVL\_eff} = \frac{P_s}{N_0B+I}} \tag{2}$$

$$\boldsymbol{SNR_{UL\_eff} = \frac{P_s}{N_0B+I+I_P}} \tag{3}$$

where:

SNR_{ovl_eff}	is the overlay signal to noise ratio.
SNR_{ul_eff}	is the underlay signal to noise ratio.
B	is the bandwidth.
P_s	is the transmission power of the secondary user.
N_0	is the noise power spectral density.
I_p	is the interference power from primary users.
I	is the interference from other secondary users.

1) INTERFERENCE AND POWER CONSTRAINTS IN OVERLAY AND UNDERLAY COGNITIVE RADIO

In underlay cognitive radio, the secondary users must operate under strict power constraints to avoid causing interference to primary users. This can affect the transmission rate R and thus the transmission delay T_{trans}. The effective transmission rate $\boldsymbol{R_{eff}}$ considering the power constraint can be expressed as:

$$\boldsymbol{R_{eff} = B\,log_2\left(1+\frac{Ps}{N_0B+I_p}\right)} \tag{4}$$

where

B	is the bandwidth.
P_s	is the transmission power of the secondary user.
N_0	is the noise power spectral density.
I_p	is the interference power from primary users.

E. GENERAL DELAY EQUATION IN OVERLAY AND UNDERLAY COGNITIVE RADIO

The delay general equation for both overlay and underlay cognitive radio systems is discussed in this section several parameters affect the delay influenced on secondary users. These parameters include the dynamic nature of spectrum availability, transmission power constraints, and interference from primary users. Therefore, we calculate the following parameters.

1) TRANSMISSION DELAY

The time needed to send a packet from the transmitter to the receiver is called the transmission delay. It can be expressed as:

$$\boldsymbol{T_{trans} = \frac{L}{R}} \tag{5}$$

where:

L	is the packet length in bits.
R	is the transmission rate in bits per second (bps).

2) QUEUEING DELAY

The time a packet spends waiting in the queue before it is transmitted is called Queueing delay. It is affected by the service rate and the traffic loads of the system. For a Poisson arrival process system with service times exponentially distributed (M/M/1 queue), the average queueing delay T_{queue} is calculated by:

$$\boldsymbol{T_{queue} = \frac{\rho}{\mu\,(1-\rho)}} \tag{6}$$

where:

ρ	is the traffic intensity, defined as $\boldsymbol{\rho = \frac{\lambda}{\mu}}$.
λ	is the average packet arrival rate.
μ	is the service rate, which is the reciprocal of the average service time.

3) PROPAGATION DELAY

The time it takes for a signal to propagate from the transmitter to the receiver is called Propagation delay and It is calculated by:

$$T_{prop} = \frac{d}{v} \tag{7}$$

where:

- d is the distance between the transmitter and receiver.
- v is the propagation speed of the signal (approximately the speed of light for wireless communication).

4) PROCESSING DELAY

The time it takes for a node to make routing decisions and process a packet header is called Processing delay. It is usually constant as T_{proc}.

5) TOTAL DELAY

The total delay T_{total} occurred by a secondary user in an overlay and underlay cognitive radio network can be calculated by summing all the individual delay components:

$$T_{total} = T_{trans} + T_{queue} + T_{prop} + T_{proc} \tag{8}$$

Substituting T_{trans} with the effective transmission rate:

$$T_{trans} = \frac{L}{R_{eff}} = \frac{L}{B\log_2\left(1+\frac{P_s}{N_0B+I_p}\right)} \tag{9}$$

Thus, the total delay equation becomes:

$$T_{total} = \frac{L}{B\log_2\left(1+P_sN_0B+I_p\right)} + \frac{\rho}{\mu\left(1-\rho\right)} + \frac{d}{v} + T_{proc} \tag{10}$$

F. GENERAL THROUGHPUT EQUATION IN OVERLAY AND UNDERLAY COGNITIVE RADIO

The throughput is essentially the rate at which data is successfully transmitted from the sender to the receiver. It depends on some factors as power constraints, the available spectrum, and interference from primary users.

The general equation for throughput in an overlay and underlay cognitive radio network is calculated as follows.

1) EFFECTIVE TRANSMISSION RATE (CAPACITY)

The effective transmission rate for a secondary user in the existence of interference from primary users can be calculated using the Shannon-Hartley theorem:

$$R_{eff} = B\log_2(1+\frac{P_s}{N_0B+I_p}) \tag{11}$$

where:

- B is the bandwidth available for the secondary user.
- P_s is the transmission power of the secondary user.
- N_0 is the noise power spectral density.
- I_p is the interference power from the primary users.

2) THROUGHPUT CALCULATION

As the data is successfully transmitted and received it is called Throughput T. It can be expressed as the product of the effective transmission rate and the packet success probability:

$$T = R_{eff} \times P_{success} \tag{12}$$

Substituting the effective transmission rate and packet success probability:

$$T = B\log_2(1+\frac{P_s}{N_0B+I_p}) \times (1-BER)^L \tag{13}$$

3) GENERAL THROUGHPUT EQUATION

The general throughput equation for an overlay and underlay cognitive radio network can be written by multiplying the above two components

$$T = B\log_2(1+\frac{P_s}{N_0B+I_p}) \times \left(1-Q\left(\sqrt{2\cdot\frac{P_s}{N_0B+I_p}}\right)\right)^L \tag{14}$$

IV. USING VLC AS CCC OF CR CAR-TO-CAR COMMUNICATION

In VLC communication applications such as car-to-car, we use existing equipment to minimize the needed cost. Therefore, this paper proposes taking advantage of modern cars' built-in LED lights as VLC transmitters and the parking sensor cameras as the receiver. In VLC communication, the transmission is carried by laser or LED (i.e., visible light photon source). In each car, the headlight LEDs are divided into a grid of independent transmitters in a 3 by 3 with a total number of 9 LEDs. Each independent LED sends its data separately from the others' transmission. The propagation channel carrying the information data is the air either indoors or outdoors. The weather conditions (e.g., fog, sunlight, night stars, sandstorms, or rain) affect only outdoor communication such as in this car-to-car application. On the other hand, the reception is carried by a camera or generally a photodetector (i.e., visible light photon absorber). The receiver camera captures all of the LEDs' illumination in each frame at once and then processes the received data. The LED ON/OFF sampling time must be equal to the camera FPS and synchronous with it. Commercial cameras capture from 30 FPS up to 2000 FPS. Therefore, VLC is optimum compared to all other aforementioned RF approaches to cost, effect on PUs, outage probability, and BER. However, the VLC CCC must include all VLC car-to-car links in the routing map generation that require alteration periodically due to the nature of the car-to-car application.

A. LED APPLICATIONS AND CHARACTERISTICS

Two-lead semiconductors of a special type of PN junction diode are used to form the light source which is commonly named the light-emitting diode (LED) within an area of less than 1 mm2. Choosing the doping materials in the semiconductors in both regions the P-type and the N-type changes the characteristics of the LED's illuminations as shown in Table 2.

On the other hand, white light is generated by merging LEDs of red, green, and blue in a small area while maintaining the same intensity. However, to produce different sensations of color, intensity quantities of the red, green, and blue LEDs are changed. Each LED produces luminous flux [lm] for a measured electrical power [W], and then The LEDs' luminous efficacy [lm/W] is the ratio between both of them. The efficacy of the blue color is the lowest at 75 lm/W while the efficacy of the red color is the highest at 155 lm/W.

The LED's main advantages are listed as the following: 1) The LEDs have low cost and small area, and 2) the LED intensity is controlled by microcontrollers and the electricity level. Moreover, LEDs are 3) Energy efficient, 4) Long Lifetimes, 5) Rugged, and 6) do not require a period to warm up. While the LED's main disadvantages are listed as 1) Temperature dependence and sensitivity, and 2) Electrical polarity and Light quality. In addition, 3) Efficiency drops over time, and 4) Voltage sensitivity. Then the LED main applications are listed as the following: 1) in smartphones, 2) using LED bulbs in industries and at homes, 3) as signals for the traffic light, and 4) in motorcycles and cars' headlights and taillights.

B. SPECIFICATION OF THE LED IN CARS' HEADLIGHTS

The VLC system LED source in the car-to-car is a white light with the following specifications. The bandwidth emission of the visible light is from 400 to 700 THz then the white LED covers all that band. The headlight of each car is composed of independent LEDs in a grid of 3 by 3 with a total of 9 lights to form multiple transmission sources each of them independently uses ON OFF key (OOK) modulation to transmit its share of data.

On the other hand, each shot of the receiver camera records the reading of all LED illumination levels from the transmitted car headlight. Cameras' shooting speed varies from as high as 2000 FPS for advanced cameras to as low as 30 FPS for commercial ones. Consequently, we increase the data rate by choosing a camera with a higher FPS but suffers from higher system costs. In addition, each captured frame detects the illumination of the 9 LEDs at once. To distinguish zeros from ones the received frame is compared to an illumination threshold.

C. VLC CHANNEL CHARACTERISTICS

VLC's noise in the communication channel is usually modeled as additive white Gaussian (AWGN) with a certain attenuation coefficient that depends on the distance between the transmitter and the receiver. The attenuation coefficient varies by different channel weather situations such as rain, sand storms, or fog. Moreover, VLC communication is affected by interferences from sunlight, commercial boards, and street lights.

To determine the channel coefficient in foggy weather, this paper uses Beer's law [12]. Beer's law describes the light scattering and absorption in the channel medium (i.e., air) at various levels of visibility H_FOG. Since this paper focuses on vehicle-to-vehicle communication in short-range, when the fog visibility (V) is less than 0.5 km, Beer's law can be as simple as

TABLE 2. LED operation band versus the used doping material.

LED operation band	Doping in P- & N- types
infra-red	Gallium Arsenide (GaAs)
infra-red, red, and orange	Gallium Arsenide Phosphide (GaAsP)
yellow, orange, orange-red, and high-brightness red	Aluminum Gallium Arsenide Phosphide (AlGaAsP)

$$H_{Fog} = e^{-\left(\frac{3.91}{V}\right)} \tag{15}$$

where V in kilometers is the visibility meteorologically. In addition, the coefficient of the free space channel H_{LOS} at line-of-sight communication follows the general formula of loss in free space:

$$H_{LOS} = \frac{A\cos(\theta)\cos(\varphi)}{2\pi D^2} \tag{16}$$

where A in illuminance is the amplitude of light, φ and θ are the receiver and transmitter angles from the centerline of the line-of-sight communication, and D is the receiver towards the transmitter distance.

On the other hand, this paper adopts the Palmer and Marshal channel coefficient for rain attenuation H_{Rain}. Rain attenuation depends on rain size, transmission frequency, and temperature [5]. In the formula of Palmer and Marshal, the rain rates (RR) cause the attenuation in wireless optical communication. Where rain rate is measured by meter/hour and γ in dB/km while the power-law parameters are $B = 0.63$ and $A = 0.365$.

$$\gamma = A \times RR^B \tag{17}$$

$$H_{Rain} = \frac{4\lambda}{\pi \times hc} \times 10^{-\frac{\gamma L}{10}} \tag{18}$$

where the wavelength is λ, the constant of Planck is h, and the speed of light is c in free space. Note that we assume a spherical shape raindrop to make the Marshal and Palmer assumption independent of polarization.

$$Y_{Rx} = H_{LOS}H_{Rain}H_{Fog}X_{Tx} + N_{AWGN} \tag{19}$$

The camera captures the received light signal after passing by all the channel coefficients aforementioned (i.e., multiply the transmitted modulated light by them) and then adding the additive white Gaussian noise to the OOK signal as shown in FIGURE 2, then:

D. SCALABILITY AND ADAPTABILITY

Cars communicate with infrastructures such as road signs and commercials as data sources. Then, distribute the received information through car-to-car communications through the

FIGURE 2. The Characteristics of the VLC Channel under various conditions of weather such as fog, direct sunlight, rain, or snow.

road for cars non-neighboring to infrastructures. Higher scalability for car-to-car communication leads to the need for less infrastructure on the road which reduces the overall system cost. Therefore, this paper adopts high scalability by prolonging the VLC communication distance through multi-hop. The ability of the VLC system to withstand noise and delay threshold is the main limit to prolong the multi-hop communication. Consequently, this paper proposal aims to provide higher hop counts within the same noise and delay level to increase our system scalability.

The proposed system aims to adapt to the currently manufactured car parts such as parking cameras and headlight LEDs. Therefore, no need to install expensive parts to use the car-to-car communication feature. Adding higher complex parts is backward compatible with the current parts. However, these complex parts achieve higher data rates when communicating with each other.

V. RESULTS AND DISCUSSION

A. THE CCC DATA RATE VERSUS THE NUMBER OF CARS

As shown in FIGURE 3,, the common control channel average data rate versus the number of nodes (cars) within the road is discussed. For the VLC CCC, the line-of-sight communication coverage on the road is dependent on the availability of cars to hop among them from the source to the destination. Therefore, having a small number of nodes does not give the best data rate results (i.e., 1.2 kbps). This is because the average VLC communication distance is around 70 m at a low number of nodes. However, the VLC system operates with a high data rate (i.e., 1.8 kbps) and no visible problem at a higher number of nodes. This is because the average VLC communication distance is around 40 m at a high number of nodes. In contrast, the RF CCC is affected by the noise created by the adjacent nodes. Then, the data rate of the RF at a lower number of nodes is higher (i.e., 2.5 kbps) than the data rate as the node number increases (i.e., 1.5 kbps). This is because, at a low number of nodes, the average overlay RF communication noise level is around −110 dB, and at a high number of nodes, the average overlay RF communication noise level is around −70 dB due to the high ISI level. Moreover, the overlay RF shows a higher data rate compared to the underlay data rate by 25%. The licensed type is not included in the figure as their data rate is controlled by the service provider to be constant at a high level.

B. THE CCC OUTAGE PROBABILITY VERSUS THE NUMBER OF CARS

As shown in FIGURE 4, the common control channel average outage probability versus the number of nodes (cars) within

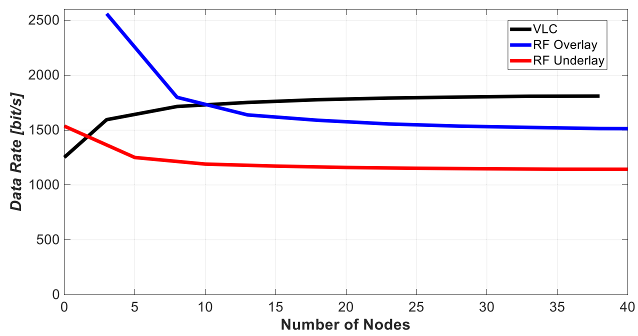

FIGURE 3. The CCC data rate versus the number of cars in the CR network for VLC, overlay, and underlay.

the road is discussed. For the VLC CCC, the line-of-sight communication coverage on the road is dependent on the availability of cars to hop among them from the source to the destination. Therefore, having a small number of nodes gives higher outage probability results (i.e., near 1 for less than 10 cars). However, the VLC system operates with a small outage probability (i.e., 0.1) and no visible problem at a higher number of nodes. In contrast, the RF CCC is affected by the noise created by the adjacent nodes. Then, the outage probability of the RF at a lower number of nodes (i.e., 0.1 for less than 5 cars) is lower than the outage probability as the node number increases (i.e., 0.9 for more than 40 cars). Moreover, the overlay RF shows a higher outage probability than the underlay outage probability as the competition for the availability of secondary users' slots increases with no available slots (e.g., 4 slots available for 15 cars). The licensed type is not included in the figure as their outage probability is controlled by the service provider to be constant at a low level.

C. THE CCC BER VERSUS FADING EFFECT

As the fading effect increases the destructive interference leads to increased attenuation in dBs in the received signals. This paper monitors the fading effect in the received signals. In FIGURE 5, the common control channel average BER versus fading effect is discussed. For the VLC CCC, the BER shows no visible effect as the fading effect increases because there is little to no multipath in VLC. Therefore, VLC shows a near-constant value as the fading increase (i.e., in the order of 10^{-6}). In contrast, the RF CCCs are affected by fading effect. As the fading increases, the BER increases for the overlay and the underlay channels (i.e., from $5{*}10^{-6}$ to 10^{-4}).

D. THE CCC DATA RATE VERSUS FADING EFFECT

As aforementioned in the previous result, the BER increases with the fading effect increases. Therefore, the received data suffers from data loss due to the dropping of the faulty packets which decreases the effective data rate received. For the VLC CCC, the data rate is not affected by the fading effect, therefore, it seems approximately constant (i.e., 2 kbps) as shown in Figure 6. Because there is little to no multipath in VLC. In contrast, the RF CCCs are affected by fading effect.

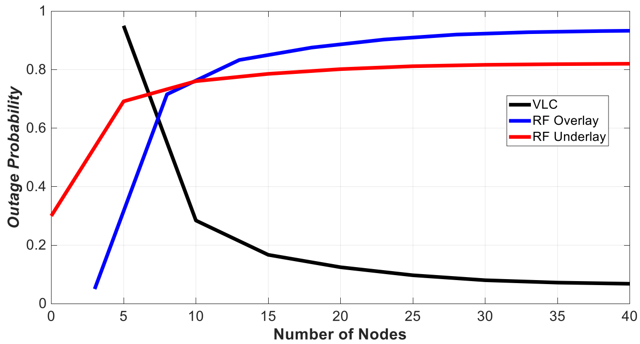

FIGURE 4. The CCC outage probability versus the number of cars in the CR network for VLC, overlay, and underlay.

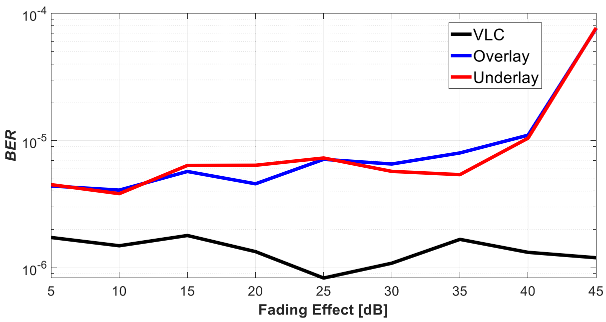

FIGURE 5. The CCC BER versus fading effect in the CR network for VLC, overlay, and underlay.

As the fading increases, the data rate decreases for the overlay and the underlay channels (i.e., it decays from 2.5 kbps for overlay and from 1.5 kbps for underlay CR).

E. THE VLC CCC ADAPTABILITY

The relation between data rate and the number of LEDs for VLC adaptability is discussed in Figure 7. For low resolution, the data rate is small and seems constant with an increasing number of LEDs. This is because the low-resolution camera can see a limited number of LEDs and any additional LED will not contribute to the VLC communication. In medium-resolution cameras, as the number of LEDs increases the data rate has increased to 2 kbps then seems to be constant with an increasing number of LEDs beyond the camera resolution limits. While for high resolution, the data rate continues to increase with increasing number of LEDs.

F. THE AVERAGE BER VERSUS THE COMMUNICATION DISTANCE

As shown in FIGURE 8, the average BER versus the communication distance between cars is discussed. The BER increases as the distance increases in all cases except for the licensed CCC type as it doesn't depend on the distance between cars and is controlled by the service provider. For the VLC CCC, as the distance increases between the transmitter car's LED light source and the receiver car's camera, the received illumination decreases in both the power and the number of covered pixels. Therefore, any interference source

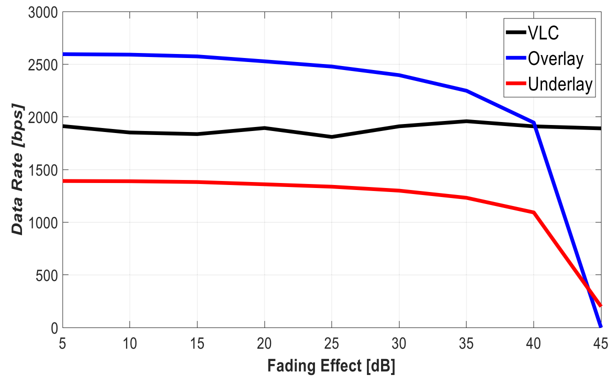

FIGURE 6. The CCC data rate versus fading effect in the CR network for VLC, overlay, and underlay.

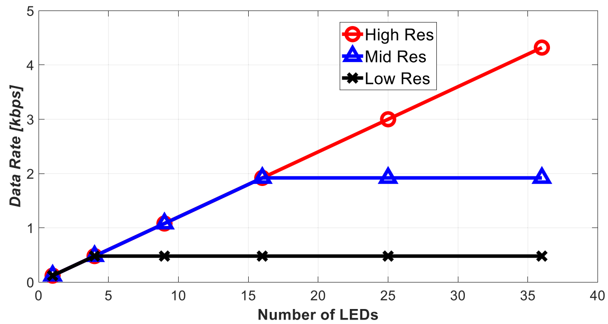

FIGURE 7. VLC CCC adaptability (Data rate versus number of LEDs for different camera resolutions.

and the background noise greatly affect the recorded illumination in each pixel. Consequently, BER ranges from 6×10^{-6} at a distance of 10 m and increases by 50% to 9×10^{-6} at a distance of 70 m. For CR underlying CCC as the distance increases multiple cars transmitting at the same underlay code interfere with each other. such interference leads to increasing BER from 3×10^{-6} to 5×10^{-6} for the same distance range. In contrast, the overlay CCC has BER 9×10^{-6} at a distance of 10 m and 12×10^{-6} at a distance of 70 m.

G. THE AVERAGE BER AT DIFFERENT WEATHER CONDITIONS

As shown in FIGURE 9, the average BER versus the CCC of different types over different weather conditions are discussed. For clear weather, no environmental harsh conditions exist therefore, the minimum that can be achieved at clear weather. consequently, BER is 4×10^{-6} for both underlying CCC and licensed one while it reaches 7×10^{-6} and 10×10^{-6} for VLC and overlay CR respectively. In the case of heavy fog, the humidity in the air leads to degradation in the received signal level for all RF communication techniques. While the VLC suffers the most because the fog affects the light coming from the LED. Therefore, the BER is 4×10^{-6} for licensed CCC and 5×10^{-6} for underlying one while it reaches 8.5×10^{-6} and 12.5×10^{-6} for VLC and overlay CR respectively. For heavy rain, all CCCs are affected by rain,

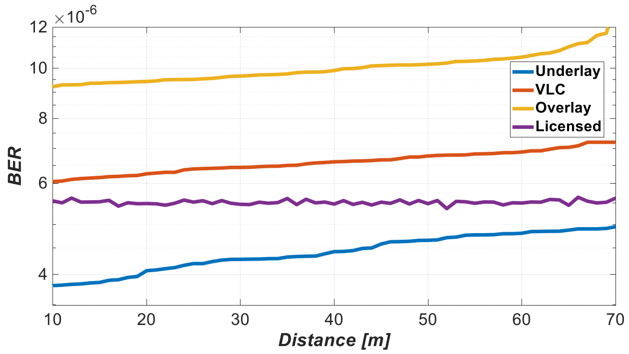

FIGURE 8. The average BER versus the communication distance between cars.

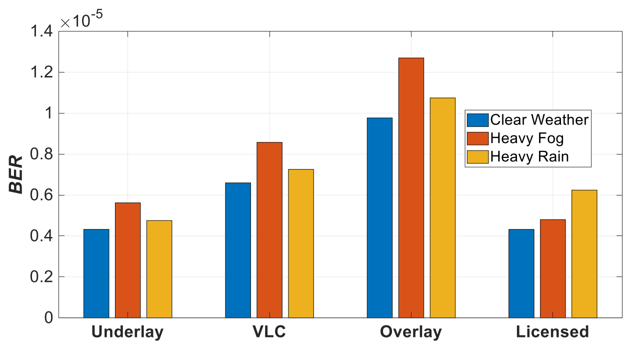

FIGURE 9. The average BER at different weather conditions for CCC types.

while the overlay and VLC suffer the highest effect when they reach 7.5×10^{-6} and 10.5×10^{-6} respectively. BER is 6×10^{-6} for licensed CCC and 4.5×10^{-6} for underlying.

H. THE AVERAGE DELAY FOR DIFFERENT CCC TYPES

As shown in FIGURE 10, the average packet delay versus the CCC of different types is discussed. The overlay CCC has the highest delay of 10×10^{-4} sec compared to other types because in overlay CR sensing cycle (i.e. sensing cooperation decision adapt) requires a delay time before communication. While VLC CCC has a delay of 7×10^{-4} sec, as it's the average delay between single-hop and multi-hop VLC. In each VLC repeater, the processing delay of receiving and then retransmitting data packets is added for each repeater in the multi-hop chain. While the underlay and license have a delay of 4×10^{-4} and 5×10^{-4} respectively. Because they require no sensing phase and do not suffer from retransmission delay.

I. COST AND OVERALL RATING

FIGURE 11 shows the cost of different CCC types including both the initial installation cost (i.e., fixed cost) and the average subscription fees (i.e., variable cost). The VLC cost includes the software only as the LEDs and cameras are considered included in cars. In both the overlay and underlay CRs, the cost includes the purchase of telecom nodes and attaching them to the cars. While in the licensed CCC, the cost includes all the software, hardware, and subscription fees. Therefore, VLC is considered the cheapest approach.

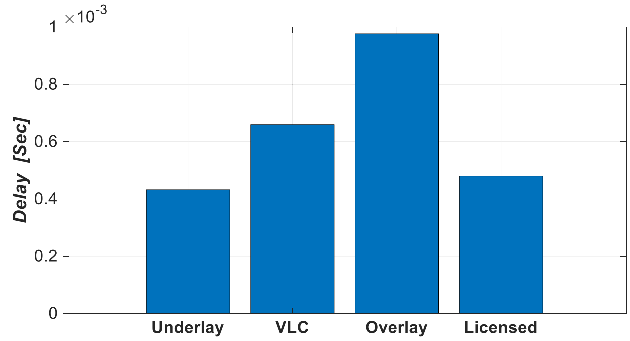

FIGURE 10. The average delay for different CCC types.

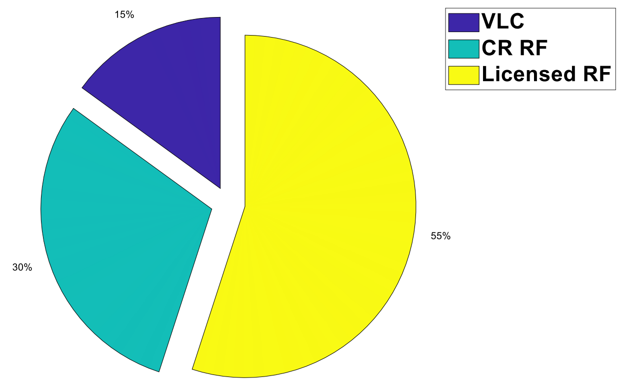

FIGURE 11. The cost of different CCC types including the initial installation cost and the subscription fees.

TABLE 3. Rating the different types of CCC in comparison with each other.

	Licensed	VLC	Overlay	Underlay
Data Rate	100.0%	90.0%	75.0%	60.0%
Outage Prob.	11.8%	21.2%	100.0%	94.1%
BER	55.0%	65.0%	100.0%	45.0%
Delay	51.1%	70.7%	100.0%	44.6%
Cost	100.0%	27.3%	54.5%	54.5%
Overall Rating	88.2%	84.2%	45.3%	64.1%

In Table 3, we present the highest average value for each metric (best or worst) as 100%. Then, we show the relativity of other CCC types with a comparison to it. For example, the licensed CCC type has the highest average data rate while the VLC CCC average data rate is 90% of the licensed CCC. Therefore, the licensed CCC has the highest data rate and cost while the overlay CR has the highest outage probability, BER, and delay. The overall rating shows that the licensed CCC is the best choice followed by the VLC CCC while the underlay is third place and the overlay is not suitable for this application. However, given the future potential of the VLC, the 4% gap is expected to shrink over time.

VI. CONCLUSION

We have demonstrated in this paper that the CCC is the bottleneck in the car-to-car CR network. Then, we explored the different types of CCCs used to solve this bottleneck issue such as licensed overlay, overlay CR, underlay CR, and VLC. A MATLAB simulation for a car-to-car framework has been built to demonstrate and compare these types of CCC through the chosen metrics. Our metrics included data rate, delay, outage probability, cost, and bit error rate. The comparison analyses included comparing VLC versus the other CCC types. Our results show that VLC can achieve up to 90% of the licensed data rate with a small outage probability of 21.2% while maintaining moderate BER and delay. In addition, VLC presents the minimum cost, and as the introduced combined metric it placed second after the licensed type with a score of 84.2%. With the VLC's bright future of expansion and growing car-to-car application, the 4% gap is expected to shrink over time. Therefore, we have proven that VLC is worthy of implementation practically in modern cars.

REFERENCES

[1] M. Ahmed, M. A. Mirza, S. Raza, H. Ahmad, F. Xu, W. U. Khan, Q. Lin, and Z. Han, "Vehicular communication network enabled CAV data offloading: A review," *IEEE Trans. Intell. Transp. Syst.*, pp. 1–29, Aug. 2023, doi: 10.1109/TITS.2023.3263643.

[2] H. Abuella, M. Elamassie, M. Uysal, Z. Xu, E. Serpedin, K. A. Qaraqe, and S. Ekin, "Hybrid RF/VLC systems: A comprehensive survey on network topologies, performance analyses, applications, and future directions," *IEEE Access*, vol. 9, pp. 160402–160436, 2021, doi: 10.1109/ACCESS.2021.3129154.

[3] M. M. Céspedes, B. G. Guzmán, V. P. Gil Jiménez, and A. G. Armada, "Aligning the light for vehicular visible light communications: High data rate and low-latency vehicular visible light communications implementing blind interference alignment," *IEEE Veh. Technol. Mag.*, vol. 18, no. 1, pp. 59–69, Mar. 2023, doi: 10.1109/MVT.2022.3228389.

[4] M. A. Hossain, R. Noor, S. R. Azzuhri, M. R. Z'aba, I. Ahmedy, K.-L. A. Yau, and C. Chembe, "Spectrum sensing challenges & their solutions in cognitive radio based vehicular networks," *Int. J. Commun. Syst.*, vol. 34, no. 7, p. e4748, Feb. 2021, doi: 10.1002/dac.4748.

[5] E. S. El-Mokadem, N. I. Tawfik, M. H. Aly, and W. S. El-Deeb, "Design and performance evaluation of vehicular visible light communication system under different weather conditions and system parameters," *Opto-Electron. Rev.*, vol. 31, no. 2, Nov. 2023, Art. no. 145580, doi: 10.24425/opelre.2023.145580.

[6] P. Gajewski, J. Łopatka, and P. Łubkowski, "Performance analysis of public safety cognitive radio MANET for diversified traffic," *Sensors*, vol. 22, no. 5, p. 1927, Mar. 2022, doi: 10.3390/s22051927.

[7] S. Yahia, Y. Meraihi, S. Refas, A. B. Gabis, A. Ramdane-Cherif, and H. B. Eldeeb, "Performance study and analysis of MIMO visible light communication-based V2V systems," *Opt. Quantum Electron.*, vol. 54, no. 9, p. 575, Sep. 2022.

[8] Y. Zhang, W. Wang, X. Zhao, and J. Hou, "Performance analysis for mixed RF/VLC-based cognitive electric vehicle networks with imperfect CSI," *Sensors*, vol. 22, no. 5, pp. 481–488, Sep. 2022.

[9] E. Zadobrischi, "The concept regarding vehicular communications based on visible light communication and the IoT," *Electronics*, vol. 12, no. 6, p. 1359, Mar. 2023, doi: 10.3390/electronics12061359.

[10] Y. Yang, F. Zhang, Z. Zeng, J. Cheng, and C. Guo, "Visible light communication for vehicular applications: A novel architecture with proof-of-concept prototype," *China Commun.*, Feb. 2023, doi: 10.23919/JCC.2023.00.021.

[11] Y. Xiao, P. D. Diamantoulakis, Z. Fang, L. Hao, Z. Ma, and G. K. Karagiannidis, "Cooperative hybrid VLC/RF systems with SLIPT," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2532–2545, Apr. 2021, doi: 10.1109/TCOMM.2021.3051908.

[12] M. Karbalayghareh, F. Miramirkhani, H. B. Eldeeb, R. C. Kizilirmak, S. M. Sait, and M. Uysal, "Channel modelling and performance limits of vehicular visible light communication systems," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 6891–6901, Jul. 2020, doi: 10.1109/TVT.2020.2993294.

[13] U. Divakarala, K. Chandrasekaran, and K. H. K. Reddy, "A hierarchical blockchain architecture for secure data sharing for vehicular networks," *Int. J. Inf. Technol.*, vol. 15, no. 3, pp. 1689–1697, Mar. 2023, doi: 10.1007/s41870-023-01175-0.

[14] F. Aghaei, H. B. Eldeeb, and M. Uysal, "A comparative evaluation of propagation characteristics of vehicular VLC and MMW channels," *IEEE Trans. Veh. Technol.*, vol. 73, no. 1, pp. 4–13, Jan. 2024, doi: 10.1109/TVT.2023.3302991.

[15] S. Begum and N. B. Patil, "An intelligent vehicle control system for enhancing road safety using optimal visible light communication network," *J. Opt. Commun.*, vol. 44, no. 1, pp. 81–94, Jan. 2023, doi: 10.1515/joc-2019-0049.

[16] R.-R. Yin, X.-Y. Shen, P.-C. Zhao, and X.-Y. Ma, "Optimization of 2×2 MIMO vehicular visible light communications model," *Acta Electonica Sinica*, Jan. 2023.

[17] G. Singamsetty and S. Nallagonda, "Throughput performance analysis of cooperative spectrum sensing network with improved energy detectors in Hoyt fading environment," in *Proc. 4th Int. Conf. Electron., Commun. Aerosp. Technol. (ICECA)*, Coimbatore, India, Nov. 2020, pp. 720–725, doi: 10.1109/ICECA49313.2020.9297530.

[18] S. Nallagonda, A. Bhowmick, and B. Prasad, "On selection of parameters for cooperative spectrum sensing schemes over $\kappa - -\mu$ fading channels," *IETE J. Res.*, vol. 69, no. 11, pp. 7684–7694, 2023, doi: 10.1080/03772063.2022.203870019.

[19] S. Nallagonda, "Data fusion-aided cognitive radio network over generalised fading channels," *Electron. Lett.*, vol. 55, no. 5, pp. 285–287, Mar. 2019, doi: 10.1049/el.2018.7727.

[20] G. Singh, A. Srivastava, V. A. Bohara, Z. Liu, N. A. Rahim, and G. Ghatak, "Heterogeneous visible light and radio communication for improving safety message dissemination at road intersection," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 10, pp. 17607–17619, Oct. 2022, doi: 10.1109/TITS.2022.3156119.

[21] P. Kumar and A. Chakravarty, "Optimized resource management over connected vehicles in RF-CRN environment," in *Proc. 2nd Int. Conf. Adv. Technol. Intell. Control, Environ., Comput. Commun. Eng. (ICATIECE)*, Bangalore, India, Dec. 2022, pp. 1–5, doi: 10.1109/ICATIECE56365.2022.10047516.

[22] M. A. Vieira, M. Vieira, P. Louro, and P. A. Vieira, "Cooperative vehicular visible light communication in smarter split intersections," *Proc. SPIE*, vol. 12139, pp. 28–29, May 2022, doi: 10.1117/12.2621069.

[23] E. M. H. Abouzohri and M. M. Abdallah, "Performance of hybrid cognitive RF/VLC systems in vehicle-to-vehicle communications," in *Proc. IEEE ICIoT*, Doha, Qatar, May 2020, pp. 429–434, doi: 10.1109/ICIoT48696.2020.9089610.

[24] M. M. A. Momen, H. A. Fayed, M. H. Aly, N. E. Ismail, and A. Mokhtar, "An efficient hybrid visible light communication/radio frequency system for vehicular applications," *Opt. Quantum Electron.*, vol. 51, p. 364, Oct. 2019, doi: 10.1007/s11082-019-2082-7.

[25] H. B. Eldeeb, S. Naser, L. Bariah, and S. Muhaidat, "Energy and spectral efficiency analysis for RIS-aided V2V-visible light communication," *IEEE Commun. Lett.*, vol. 27, no. 9, pp. 2373–2377, Jun. 2023, doi: 10.1109/LCOMM.2023.3290025.

[26] J. Parikh and A. Basu, "Technologies assisting the paradigm shift from 4G to 5G," *Wireless Pers. Commun.*, vol. 112, pp. 481–502, Jan. 2020, doi: 10.1109/gsmm.2017.7970330.

[27] H. Ouamna, Z. Madini, and Y. Zouine, "6G and V2X communications: Applications, features, and challenges," in *Proc. 8th Int. Conf. Optim. Appl. (ICOA)*, Genoa, Italy, Oct. 2022, pp. 1–6, doi: 10.1109/ICOA55659.2022.9934407.

[28] F. M. Alsalami, O. C. L. Haas, A. Al-Kinani, C.-X. Wang, Z. Ahmad, and S. Rajbhandari, "Impact of dynamic traffic on vehicle-to-vehicle visible light communication systems," *IEEE Syst. J.*, vol. 16, no. 3, pp. 3512–3521, Sep. 2022, doi: 10.1109/JSYST.2021.3100257.

[29] N. M. Okasha, A. H. A. Zekry, and F. A. Newagy, "Hybrid VLC vehicle to vehicle and LEO satellite communication system for highway road coverage," in *Proc. 6th Int. Tech. Conf. Adv. Comput., Control Ind. Eng. (CCIE 2021)*, Singapore, Jul. 2022, pp. 571–583, doi: 10.1109/TAES.2021.3113880.

[30] A. Chaabna, A. Babouri, H. Chouabia, T. Hafsi, Z. E. Meguetta, and X. Zhang, "Experimental demonstration of V2V communication system based on VLC technology for smart transportation," in *Artificial Intelligence and Heuristics for Smart Energy Efficiency in Smart Cities: Case Study* Tipasa, Algeria. Cham, Switzerland: Springer, Nov. 2022, pp. 653–661, doi: 10.1007/978-3-319-73192-6_5.

[31] S. Yahia, Y. Meraihi, A. Ramdane-Cherif, A. B. Gabis, and H. B. Eldeeb, "Performance evaluation of vehicular visible light communication based on angle-oriented receiver," *Comput. Commun.*, vol. 191, pp. 500–509, Jul. 2022, doi: 10.1016/j.comcom.2022.05.025.

[32] S. Mishra, R. Maheshwari, J. Grover, and V. Vaishnavi, "Investigating the performance of a vehicular communication system based on visible light communication (VLC)," *Int. J. Inf. Technol.*, vol. 14, pp. 877–885, Jan. 2022, doi: 10.1007/s41870-020-00447-3.

[33] M. Meucci, M. Seminara, T. Nawaz, S. Caputo, L. Mucchi, and J. Catani, "Bidirectional vehicle-to-vehicle communication system based on VLC: Outdoor tests and performance analysis," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 8, pp. 11465–11475, Aug. 2022, doi: 10.1109/TITS.2021.3104498.

[34] S. Bahramnejad and N. Movahhedinia, "A reliability estimation framework for cognitive radio V2V communications and an ANN-based model for automating estimations," *Computing*, vol. 104, no. 8, pp. 1923–1947, Apr. 2022, doi: 10.1007/s00607-022-01072-7.

[35] A.-M. Cailean, C. Beguni, S.-A. Avatamanitei, and M. Dimian, "Experimental demonstration of a 185 meters vehicular visible light communications link," in *Proc. IEEE Photon. Conf. (IPC)*, Vancouver, BC, Canada, Oct. 2021, pp. 1–2, doi: 10.1109/IPC48725.2021.9592878.

[36] H. B. Eldeeb, M. Elamassie, S. M. Sait, and M. Uysal, "Infrastructure-to-vehicle visible light communications: Channel modelling and performance analysis," *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 2240–2250, Mar. 2022, doi: 10.1109/TVT.2022.3142991.

[37] K. Jadav, V. Sorathiya, W. El-Shafai, T. Altameem, M. H. Aly, V. Vekariya, K. Ahmed, and F. M. Bui, "Shadow extraction and elimination of moving vehicles for tracking vehicles," *Comput., Mater. Continua*, vol. 77, no. 2, pp. 2009–2030, 2023, doi: 10.32604/cmc.2023.043168.

[38] C. Beguni, A.-M. Căilean, S.-A. Avătămăniţei, A.-D. Potorac, E. Zadobrischi, and M. Dimian, "Increasing vehicular visible light communications range based on LED current overdriving and variable pulse position modulation: Concept and experimental validation," *Sensors*, vol. 23, no. 7, p. 3656, Mar. 2023, doi: 10.3390/s23073656.

[39] E. Eso, A. Burton, N. B. Hassan, M. M. Abadi, Z. Ghassemlooy, and S. Zvanovec, "Experimental investigation of the effects of fog on optical camera-based VLC for a vehicular environment," in *Proc. 15th Int. Conf. Telecommun. (ConTEL)*, Graz, Austria, Jul. 2019, pp. 1–5, doi: 10.1109/ConTEL.2019.8848552.

[40] S. Ghosh and M.-S. Alouini, "On the performance optimization of two-way hybrid VLC/RF-based IoT system over cellular spectrum," *IEEE Internet Things J.*, vol. 9, no. 21, pp. 21204–21213, Nov. 2022, doi: 10.1109/JIOT.2022.3177581.

[41] G. Singh, A. Srivastava, and V. A. Bohara, "Visible light and reconfigurable intelligent surfaces for beyond 5G V2X communication networks at road intersections," *IEEE Trans. Veh. Technol.*, vol. 71, no. 8, pp. 8137–8151, Aug. 2022, doi: 10.1109/TVT.2022.3174131.

[42] M. Mukherjee and K. Noronha, "Experimental analysis of received power for OOK-NRZ visible light communication system using off-the-shelf components," *Int. J. Inf. Technol.*, vol. 14, no. 6, pp. 2839–2853, Aug. 2022, doi: 10.1109/COMST.2019.2913348.

[43] N. M. Okasha, A. H. A. Zekry, and F. A. Newagy, "Developing hybrid car-to-car communication system based on MIMO visible light and radio frequency," *EURASIP J. Wireless Commun. Netw.*, vol. 2022, no. 1, p. 114, 2022, doi: 10.1186/s13638-022-02192-6.

[44] J. Tiwari, A. Prakash, and R. Tripathi, "An adaptive and cooperative MAC protocol for safety applications in cognitive radio enabled vehicular ad-hoc networks," *Ad Hoc Netw.*, vol. 138, Jan. 2023, Art. no. 103019, doi: 10.1016/j.adhoc.2022.103019.

[45] J. Gallego-Madrid, R. Sanchez-Iborra, J. Ortiz, and J. Santa, "The role of vehicular applications in the design of future 6G infrastructures," *ICT Exp.*, vol. 9, no. 4, pp. 556–570, Aug. 2023, doi: 10.1016/j.icte.2023.03.011.

[46] S. Kumari and B. Singh, "5G standard : The next generation wireless communication system," *J. Interdiscipl. Math.*, vol. 23, no. 1, pp. 275–283, Jan. 2020, doi: 10.1080/09720502.2020.1721922.

[47] M. Vinodhini and S. Rajkumar, "Performance analysis of vehicle-to-everything communication using internet of LoRa computing for intelligent transportation system," *Intell. Decis. Technol.*, vol. 17, no. 12, pp. 577–594, May 2023, doi: 10.3233/IDT-220312.

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