Developing hybrid car-to-car communication system based on MIMO visible light and radio frequency

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Abstract

This paper combines the advantages of both VLC communication and RF communication for car-to-car applications to achieve a higher data rate, more range coverage, smaller delay, and smaller BER. In the proposed scheme, the VLC maximum communication distance is chosen as 100 m per-hop approximately, which can be extended through multi-hop up to the timeout window of 5 hops. In contrast, the RF maximum communication distance is chosen as 200 m per-hop approximately, which is reasonable at the frequency band of 70 GHz to 90 GHz due to the high attenuation at this frequency band. A MATLAB simulation for a car-to-car framework is built to demonstrate and compare the BER, throughput, and delay outcomes at a hybrid VLC and RF communication. Our results show that VLC can achieve up to four times of the RF throughput while maintaining low BER of 10^{-6} and small delay of 10^{-4} with respect to RF communication only.

Keywords: Fog effect, Rain effect, Hybrid RF, Hybrid VLC, MIMO VLC, Car to car

1 Introduction

RF communication is not always the best communication solution, so many researchers are looking for alternatives. One of the most popular alternatives is visible light communication (VLC), because of the modern optical communication breakthrough. We will show the pros and cons of both RF and VLC car-to-car communication that motivates us to build a hybrid system to harvest the benefits from both of them and overcome the limitation of each of them.

The Popularity of RF communication leads to overbooking in all its bands. New applications are trying to coexist with the current ones. However, there are no reserved bands for these applications. Then, one of the possible solutions is to remove a working application from its band and replace it with a new application in the same band (e.g., replacing the 3G mobile network with 5G) [1]. That means all mobiles that support only 3G will stop working and their owners must buy new 5G phones to get the same service again [2]. Moreover, the same problem will affect all other wireless devices (i.e., TV, radio, Wi-Fi, etc.).

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On the other hand, the possible solution for RF spectrum scarcity is frequency reuse by both legacy and new applications through introducing possible separators (e.g., time, code, power, location, etc.) [3, 4]. However, it is only a temporary solution and limits new applications' horizons while introducing more complexity to the system. For example, to decrease the interference in the system we must decrease the power of each tower which leads to dead zones and calls drops increase [5]. In addition, to refill these zones more towers are added which increases the overall system cost and so on. This cycle appears in every aspect of the RF communication, enhancing any parameter affecting all other parameters with a global limitation to the achieved data rate [6].

The appearance of smart new applications (e.g., calls and video with hologram, auto-drive, etc.), which need a higher data rate than the RF can cover, opens the way to other communication techniques such as visible light communication [7]. The VLC communication is popular of its higher data rate which can cover modern applications' needs.

Also, the spread of industrial light sources technology and devices (e.g., LED, light detector) enables cost-effective VLC communications [8]. VLC has an easy and small constellation to set up a communication link (i.e., LED, camera) at home where we can use the house light sources to communicate with our mobile phones' cameras. At the street, we can use the street lights with our mobile cameras or the car headlight with another car parking camera. In a short distance, the VLC communications show a smaller bit error rate (BER) compared to RF at the same distance and power level because it has a smaller noise level. However, faraway links cannot be achieved through VLC and need another means of communication [9, 10].

Consequently, this paper combines the advantages of both VLC communication and RF communication for car-to-car applications. By merging VLC with RF, the hybrid communication system achieves higher range coverage and smaller BER.

The authors in [11] proposed selective relaying based on the transmitted data type. They categorized the data types into two major types. On the one hand, the important control short packets that need to reach the receiver even if the delay time is longer than expected. On the other hand, the large amount of downloading and streaming packets that require large bandwidth, small delay, and able to accept packet drop percentage. In their algorithm, the authors use coalitional game (CG) and analytic hierarchy process (AHP) to separate the packets' flow for each type based on the car-to-car communication path properties. However, that algorithm recomputes each path property when a car enters or exits the neighboring zone which drains the system resources (e.g., batteries, processing). Moreover, the proposed system uses only RF communication which has a limited bandwidth and suffers from a high level of interference.

The authors in [12] proposed an air channel for the VLC communication with variable levels of foggy weather. The fog level is expressed through the meteorological visibility which varies from 10 m up to 10 km. However, what affects the VLC communication is meteorological visibility between 10 and 500 m. The authors proposed that the transmitter is LED and the receiver is a camera. For a constant distance between two cars and variable fog meteorological visibility, the BER is small for meteorological visibility up to 20 m at different LED light modulations. However, for meteorological visibility of 10 m or less and at the same LED light modulations the BER shows a dramatic increase that leads to consider the communication link as down. In contrast, no solution is proposed

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such as using the RF communication under this condition. Moreover, no study is presented at the multi-hop VLC communication under the fog weather condition.

The authors in [13] proposed a practical VLC communication system where the proposed system uses 4G telecom infrastructure as a backup. The VLC communication uses a single laser source as a transmitter and a light detector as a receiver. However, the throughput of the presented system is only 50 kbit/s at 10^{-7} BER and within small communication distances less than 50 m. The authors did not present detailed results to the VLC or RF communication in a car to car. Moreover, no MIMO is proposed to increase the VLC data rate.

The authors in [14] built a full VLC channel model from the car headlight as the source to the camera as the receiver that includes the distance between cars, the difference in azimuth, and elevation angles due to different road lanes and road irregular surface, respectively. The suspension system of each car that moves on irregular roads tries to compensate for the generated vibrations. However, these vibrations cause differentiation in the elevation angles that degrade the received signal by at most 4 dB.

On the other hand, different road lanes cause a change in the azimuth angles that degrades the received signal by at most 3 dB within the light beam field of view (i.e., half-power beamwidth) and are considered as blocked otherwise. Consequently, the change in azimuth and elevation angles leads the VLC communication to degrade in longer distances which is the main required parameter. However, the authors did not propose a solution to lower VLC car-to-car communication distance such as multi-hop or using RF as a backup means of communication.

The authors in [15] made a comparison between the communication through VLC and the communication through infrared. The authors built a practical model using real cars and used the engine control unit (ECU) of the car as a processing resource, the headlights as the transmitter, and a photodetector as the receiver. However, the presented results are somehow below the expectation because of the use of a photodetector as the receiver and not a camera. They study the weather effect on both the VLC and infrared and find out that VLC is less effective than infrared at foggy conditions. In contrast, VLC is better than infrared in all other weather conditions because the background ambient temperature of the cars works as interference in infrared communication that lowers its SNR.

In [16–18], a MIMO VLC performance analysis is introduced for indoor applications. In these applications, the MIMO idea means dividing the light lamp into sectors; each of them transmits independently toward the same camera. The resolution of the camera and the distance from the light lamp are the main factors that affect the BER, while the data rate is affected by the camera's number of frames per second. Therefore, the trade-off in indoor applications is the maximum number of sectors in the light lamp, the camera's resolution, and the number of frames. Increasing the MIMO VLC system dimensions will increase the system cost. Consequently, the authors' target is to optimize the VLC system requirement for the different scenarios in indoor applications.

In [19–21], the authors proposed using variable intensity LED lights so that the modulation is not as simple as OOK. Despite higher-order QAMs increasing the data rate, it decreases the system BER and required high-resolution cameras to successfully detect the transmitted message. On the other hand, LED lights suffer from decreased intensity

during their lifetime. Moreover, weather conditions affect the light intensity which requires a variable threshold between QAM levels. Therefore, the authors' target is to optimize the variable threshold with respect to the desired QAM level while maintaining the BER within the acceptable level.

In [22, 23], the authors proposed using complex methods to overcome the VLC channel challenges. The proposed channel estimation is based on compressive sensing, and the block coding using bit-shuffle helps decrease the BER in the VLC system, especially in outdoor applications. Such techniques are required and adopted in much VLC research within academia.

In [24–27], the authors proposed using VLC in the vehicular car-to-car network. Adopting the VLC in car-to-car communication is driven by the increasing demand in car-to-car communication and the availability of LEDs, cameras, and processing units within the car structure. The authors investigate the BER performance in car-to-car communications and the most suitable methods to optimize the VLC communication for outdoor applications. Moreover, the author proposed not only using the VLC for car-to-car communication but also IoT sensors installed on each car.

In [28], the authors proposed using multi-hop to extend the VLC communication limited distance by using neighboring cars as relays. In the meantime, the authors proposed using terrestrial communication such as 5G or 6G as a backup. Such technique can extend the maximum VLC distance to multiple cars far away from the sender car while using the backup 6G if the chain of relays is broken.

In this paper, we aim to benefit from the modern technology of automotive manufacturing. Firstly, we use the car's LED light and parking cameras to form VLC communication links between cars to transmit road data. Moreover, we benefit from VLC's high data rate and small error rate for short coverage. Then, we extend the VLC communication coverage in the distance out of VLC single-hop range using the multi-hop technique by making other cars within the road work as repeaters between the source and destination while maintaining the high data rate and small error rate. Finally, when VLC reaches its time out of hopes, more coverage is realized by using RF communication which is known for its larger coverage even if its data rate is smaller. Therefore, by merging VLC with RF, the hybrid communication system assumes high range coverage and small BER. Our study is devoted to determining the performance parameter of the hybrid system including bit error rate BER, throughput and delay under clear weather, heavy fog, and heavy rain conditions. Our novelty is not only studying the addition of the multi-hop VLC relaying with the high data rate MIMO VLC and keeping the RF as backup, but also extending to study the effect on that system under different environmental conditions.

The rest of this paper is organized as follows: Sect. 2 describes the methods/experiments of the study. Section 3 describes the system model. Section 4 presents the proposed VLC multi-hop communication system. Section 5 depicts the simulation results and their analysis, and then, Sect. 6 concludes the paper.

2 Methods/experimental

2.1 The design of the study

The research design is a MATLAB framework of 80 cars within six lanes road with three lanes in one direction and the other three lanes in the opposite direction. The

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communications among the cars will be modeled, simulated, and analyzed through some metrics. The type of research is semi-experimental, while its sub-type is a research problem whether the hybrid VLC/RF communication has improved metrics compared to RF only or not.

2.2 The setting

After importing the recorded movement of the cars on the selected road into the MAT-LAB simulation file, we select one of the cars at random as the transmitter and another car as the receiver. The transmitter car generate the data and starts forming a connection with the receiver either through VLC or RF as will be illustrated. Once the connection is established, the MATLAB program measures the needed metrics. Finally, we analyze the output charts to determine the effectiveness of the study.

2.3 The type of participants or materials involved

We have recorded the movement of 80 cars in a section of the ring road in Cairo, Egypt, at dawn. The recorded data contain locations at different time stamps. From that data, we can compute each car's speed.

2.4 A clear description of all interventions and comparisons

In results Sect. 5.

2.5 The type of analysis used

We have chosen the inferential analysis, as it uses samples from the world to test the authors' theory.

3 System model

As shown in Fig. 1, our car-to-car communication system comprises a framework of 80 cars within six lanes road with three lanes in one direction and the other three lanes in the opposite direction. Those communications will be modeled and simulated using MATLAB. In Fig. 1, green arrows represent single-hop VLC, red arrows represent multi-hop VLC, and yellow arrows represent multi-hop VLC to overcome the field of view problem, while yellow lightning represents single-hop RF.

The selected road distance is 25 km. Each car has a variable speed from 60 to 100 km. To reduce the randomness in the results, a Mount Carlo of 120 simulations is performed. Also, these different simulations, i.e., different senders to different destinations, add robustness to the results. In each simulation, a transmission data set of 100 kbit/ packet is established from a sender to a destination through the available communication type as single-hop—multi-hops—and RF to test the algorithm operation. The VLC maximum communication distance is chosen as 100 m approximately which can be extended through multi-hop up to the timeout window of 5 hops.

In contrast, the RF maximum communication distance is chosen as 200 m approximately which is reasonable at the frequency band of 70–90 GHz due to the high attenuation at this frequency band. The number of LEDs in each car headlight is 9 in a 3 by 3 grid; each of them sends transmission data independently, while the receiver
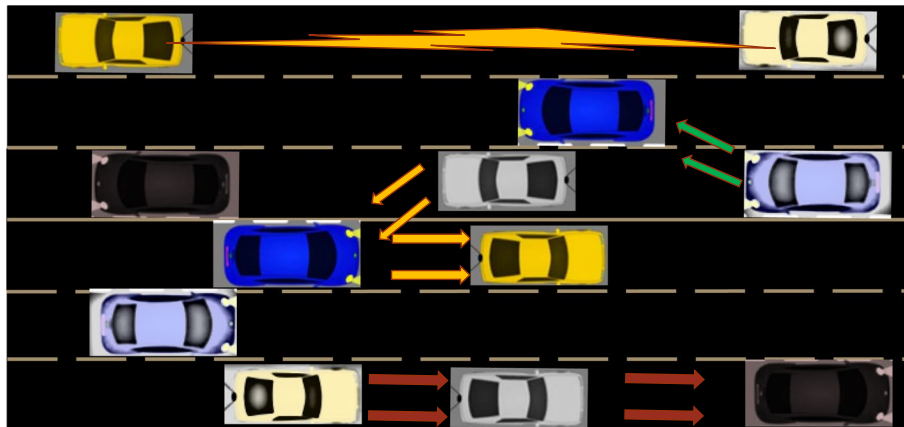
Fig. 1 The proposed framework of 80 cars connects through VLC/RF within 6 lanes road. The car-to-car communication system comprises a framework of 80 cars within six lanes road with three lanes in one direction and the other three lanes in the opposite direction. Green arrows represent single-hop VLC, red arrows represent multi-hop VLC, and yellow arrows represent multi-hop VLC to overcome the field of view problem, while yellow lightening represents single-hop RF. The selected road distance is 25 km. Each car has a variable speed from 60 to 100 km

Table 1 MATLAB model simulation parameters

Parameter	Value
Number of cars	80 cars
Simulation lanes	6 lanes
Road distance	25 km
Car speed	60–00 km/h
Length of data	100,000 bits
MIMO	9 input/camera output
Camera	2000 FPS
LED Tx power	15,000 luminance
Timeout window	5 hops
Mount Carlo	120 simulations
VLC distance	~100 m
RF distance	~200 m
RF frequency	70–90 GHz

camera receives all of them at once through the captured frame processing. The camera captures up to 2000 frames in each second. Table 1 summarizes our simulation parameters.

3.1 Communication through visible light

In the communication through visible light, the transmitter is a photonic source (i.e., laser or LED), the propagation media is air with all its weather conditions (e.g., sunny, foggy, rainy, or night), and the receiver is a photonic absorber generally a photodetector or especially a camera. In car-to-car communication, modern cars have built-in LED lights and sensor cameras. Then, this paper proposes using the LED light as a VLC transmitter and the camera as the receiver.

3.1.1 *LED characteristics and applications*

The light-emitting diode (LED) is a light source consisting of two-lead semiconductors. The LED is a special type of PN junction diode, and it has similar electrical characteristics within 1 mm^2 area or less. Different types of doping materials in both the LED's N-type and P-type regions change the LED's characteristics as follows: For LED operating in infrared, gallium arsenide (GaAs) doping is used. For LED operating in orange, red, and infrared, gallium arsenide phosphide (GaAsP) doping is used. For LED operating in high-brightness red, orange-red, orange, and yellow aluminum gallium arsenide phosphide (AlGaAsP) doping is used.

To generate white light, the blue, green, and red LED chips are merged within the same area and lead with the same intensity. When changing these different colors' intensity quantities, different color sensations are produced. The other approach to produce a single white LED mainly depends on using a phosphor coating that generates white light once struck through ultraviolet photons. The LEDs' luminous efficacy is defined as for unity electrical power in watts [W], how much luminous flux is produced in [lm]. The blue color efficacy is 75 lm/W, while the red color efficacy is 155 lm/W.

The advantages of light-emitting diode include the following: (1) The cost of LED's is less and they are tiny, and (2) controlled electricity and microcontrollers can change the LED intensity. In addition, LED advantages include (3) long lifetime, (4) energy efficiency, (5) no warm-up period, (6) rugged, while the disadvantages of light-emitting diode include the following: (1) price, (2) temperature sensitivity and dependence, (3) light quality and electrical polarity. Moreover, (4) voltage sensitivity, (5) efficiency droop over time. Then, the applications of light-emitting diode are not limited to the following: (1) LED bulbs are used in homes and industries, (2) in cars and motorcycles, (3) in smartphones, and (4) as traffic light signals.

3.1.2 *LED specification*

The specification of the car-to-car VLC system LED source is as follows. The LED white light occupies all the visible light emission bandwidth from 430 to 740 THz. Each car headlight is divided into 9 independent LED lights in a 3 by 3 grid to form multiple input algorithms; each of them transmits independently using ON–OFF key (OOK) modulation.

The communication channel of VLC is normally modeled as additive white Gaussian noise (AWGN) with a specific attenuation coefficient depending on the communication distance. The channel is affected by different weather conditions such as fog, sand storms, or rain. In addition, external interference such as street lights, commercial boards, and sunlight affect the VLC communication.

The receiver camera captures shoots from 30 frames per second (FPS) up to 2000 FPS. Higher FPS increases the data rate. Each shot captures all the transmitter car headlight LEDs. Then, the receiver camera receives all of the 9 LEDs at once through each captured frame. The captured camera shot is processed to identify the LED grid and an illumination threshold per LED is set to distinguish the received data either ones or zeros. The multiple inputs LED grid and the camera output shots form a MIMO system to increase the VLC data rate.

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3.2 Channel characteristics

Beer's law is used to determine the fog channel coefficient H_{FOG} [12]. Beer's law describes the absorption and scattering of light in the air as a medium at different visibility levels. As this paper is concerned about the short-range car-to-car communication, and then, Beer's law can be simplified for meteorological visibility (V) less than 0.5 km as:

$$H_{\mathrm{Fog}} = e^{-\left(\frac{3.91}{V}\right)} \tag{1}$$

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

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

where A is the amplitude of light in illuminance, θ and ϕ are the transmitter and receiver angles from the communication line-of-sight centerline, and D is the distance from the transmitter to the receiver. Moreover, to compute the rain channel coefficient H_{Rain} that depends on temperature, rain size, and frequency, we adopt the Marshal and Palmer distribution of raindrop size [5]. In Marshal and Palmer's formula, the wireless optical attenuation is related to the rain rate (RR) in millimeter per hour, and the parameters of power law $A = 0.365$ and $B = 0.63$. Then, γ in dB/km is equal to:

$$A \times RR^B \tag{3}$$

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

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

Finally, the received light signal captured by the camera is equal to the transmitted OOK modulated light multiplied by all the aforementioned channel coefficients and adding the additive white Gaussian noise as shown in Fig. 2, then:

$$Y_{\mathrm{Rx}} = H_{\mathrm{LOS}} H_{\mathrm{Rain}} H_{\mathrm{Fog}} X_{\mathrm{Tx}} + N_{\mathrm{AWGN}}. \tag{5}$$
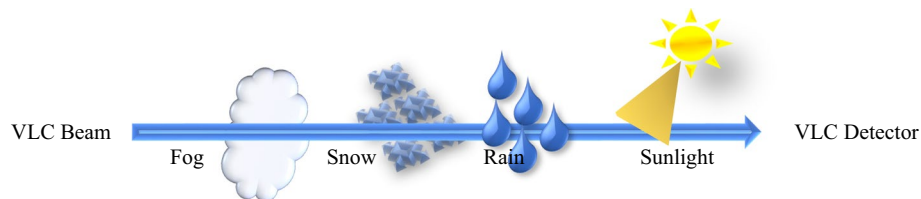

Fig. 2 The VLC channel characteristics at different weather conditions. The received signal is affected by the channel attenuation coefficients such as fog, rain, dust, and snow. Moreover, the additive white Gaussian noise from light sources such as the sun, commercial boards, and Lampposts

3.3 RF communication

In RF communication, the transmitter is an electromagnetic emitter with carrier frequency from 70 to 90 GHz and an omnidirectional antenna. In the 70–90 GHz frequency band, the assigned bandwidth is 2 GHz approximately (i.e., the highest compared to lower bands). However, the attenuation in this band is also higher than other bands which decreases the communication distance that limits the applications in such band. Then, this band has limited applications and one of them is car-to-car communication. The RF receiver is an electromagnetic detector with an omnidirectional antenna in both line-of-sight and non-line-of-sight communication. The RF communication channel is less affected by the VLC channel attenuation conditions in the air (e.g., fog, walls, or sandstorm). However, both VLC and RF channels are affected by attenuation in metals or concretes. In this paper, we assume 1024 QAM modulation and the RF critical transmission range is 200 m because of the high attenuation level. In addition, increasing the QAM beyond 1024 dramatically decreases the SNR and leads to decreased distance. All cars' transmission through RF is considered interference to each other. Then, we need to minimize the number of cars using RF communication and make them more dependent on VLC communication.

4 The proposed hybrid VLC and RF scheme

As shown in the flowchart in Fig. 3, the proposed scheme tries to communicate through VLC single hop and then increases the number of hops if it fails to close the connection. The proposed scheme aims to achieve high car-to-car throughput and overcome the
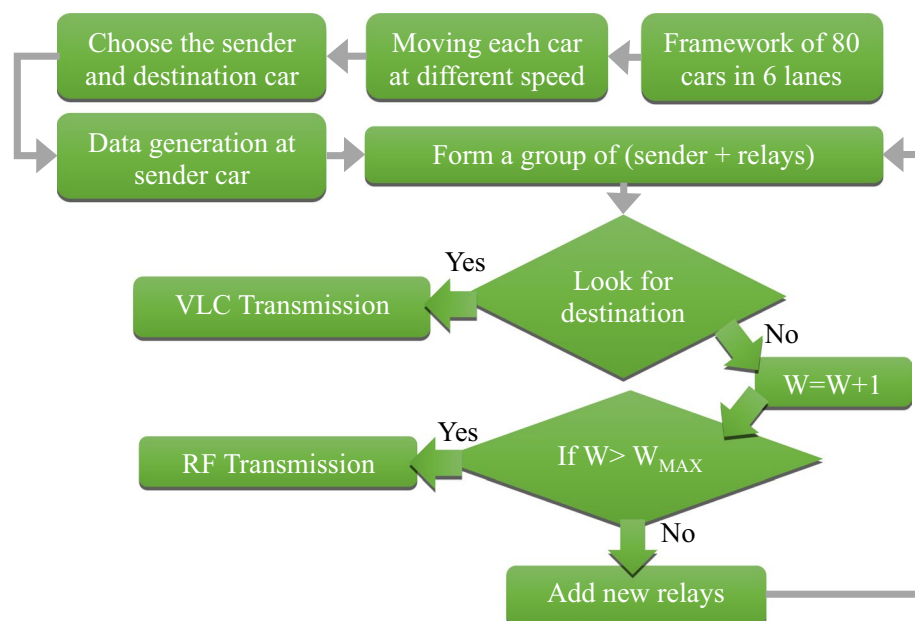

Fig. 3 The proposed scheme flowchart. The proposed flowchart builds a framework of the road and randomly allocates 80 cars within the road. Then, set a random speed for each car and choose one car and sender and another as the receiver. The generated data in the sender car try to communicate with the receiver through VLC single hop. Then, the car increases the number of hops if it fails to close the connection. However, in some weather conditions, the VLC communication cannot succeed. Then, if the maximum number of hops is reached, the scheme switches the communication type to RF

coverage limitations. However, in some weather conditions, the VLC communication cannot succeed. Then, if the maximum number of hops is reached, the scheme switches the communication type to RF.

4.1 Transmission through VLC

If the receiver is within the VLC line-of-sight of the transmission source, academia calls it a single-hop transmission. The VLC line of sight has two limitations, distance and the angle of view. Then, if the receiver is out of the VLC communication distance even if it is within the angle of view or out of the angle of view even if it is within the communication distance, the receiver fails to perform single-hop transmission. In addition, any obstacle that blocks the line of sight between the transmitter and the receiver will fail the single-hop transmission. The proposed scheme always tries to communicate through single-hop VLC first as shown in the flowchart.

In contrast, if the transmitter did not find the receiver within its single-hop range, the transmitter records all the reachable cars as relays. The relays search for the receiver within their VLC line-of-sight range. If the receiver is found, then the nearest relay reports back to the transmitter to start the communication session. Otherwise, if all relays did not find the receiver, then the scheme starts another round of relays to find the receiver. Figure 4 shows the multi-hop concept. In Fig. 4, the transmitter source (i.e., white car) communicates through the repeater (i.e., blue car) to reach the receiver (i.e., yellow car). Therefore, multi-hop communication forms a chain of repeaters between the source and destination. An important remark is that if the scheme is left to increase the relays pool for infinity, the receiver may not be found at all and the system fails. Consequently, the proposed scheme introduces the hop counting feature with a maximum number of hops as W_{max}. When the maximum number of hops is reached, the scheme switches to the RF communication. Moreover, if a repeater receives the same message more than once, it discards all the replicas to prevent loops within the repeaters chain.

4.2 Transmission through RF

After reaching the maximum number of hops in VLC communication, the scheme shifts to RF communication at distances greater than 100 m (i.e., after the VLC hop maximum communication distance) up to 200 m. In RF, the omnidirectional and non-line-of-sight features make it easier to reach the destination. However, we consider no

Fig. 4 Multi-hop car-to-car communication. Cars VLC communication is either through headlights or tail lights. Then, no communication is possible between neighboring cars. Consequently, the transmitter source (i.e., white car) communicates through the repeater (i.e., blue car) to reach the receiver (i.e., yellow car). Therefore, multi-hop communication forms a chain of repeaters between the source and destination

communication at distances greater than 200 m to ensure the minimized interference in RF and to maximize the frequency reuse in car-to-car RF communication.

In other words, the RF communications from other cars act as interference to each other. Consequently, a higher interference level decreases the RF data rate and may drop the communication link entirely. Therefore, having a limited communication distance and minimizing the dependence on the RF channel keeps the interference level below the assigned threshold for those cars in real need for RF communication type within the scenario and also preserves an acceptable data rate.

4.3 Real-time experiment

We have conducted a real-time experiment that consists of two vehicles communicating with each other through the VLC channel as shown in Fig. 5. Through the back camera, the destination vehicle detects the headlight status of the transmitting vehicle either ON or OFF. Meanwhile, the destination vehicle's front camera detects the transmitting vehicle's taillight status. The system parameters are: (1) Each camera can capture up to 120 FPS, (2) the number of independent LED lights are 9 on the right and left lamp, and (3) each LED operates in OOK modulation. Each LED generates a Tx power of 15,000 luminance which is equal to SNR of 10.6 dB compared to the background noise of 1300 luminance in the daytime or 13.9 dB compared to the background noise of 600 luminance at night. In this experiment, no forward error correction (FEC) algorithm is addressed. Each camera's frame is recorded as a grid of pixels. Each pixel intensity is represented in the range from zero (black) to 255 (white). In order to detect a LED light source within the recorded frame, we need a cluster of pixels that have a near-constant intensity, while the neighboring pixels have a much lower intensity (e.g., 9 pixels with 170 intensities within the surrounding pixels of 112 intensity) which is detected as a LED light. As a distance increased between the LED source and the receiver camera, the
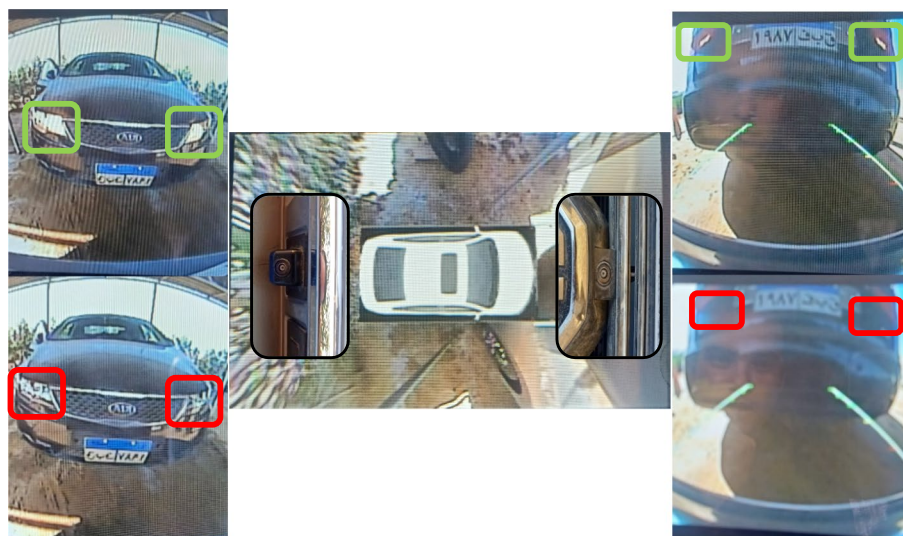

Fig. 5 The real-time experiment. This figure illustrates the real-time experiment where the destination vehicle's back camera detects the transmitted signal from the following vehicle's headlight either ON or OFF. In the meantime, the destination vehicle's front camera detects the transmitted signal from the leading vehicle's taillight either ON or OFF

pixel intensity decreased, while the surrounding intensity remains the constant which decreases the SNR. Then, the VLC communication maximum recorded data rate is $120 \times 18 \approx 2.1$ kbit/s. However, increasing the camera' FPSs and the number of independent LEDs will increase the data rate dramatically.

5 Results and discussion

A MATLAB simulation for the aforementioned car-to-car framework is built to demonstrate and compare the outcomes at VLC and RF communication. In each simulation of the 120 Mount Carlo simulations, a transmitter car and a receiver car enter the 25 km road and start trying to communicate with each other through VLC or RF and use the other cars in the road as repeaters. With the varying speed, the distance between the transmitter and receiver cars may get smaller or larger.

Consequently, the communication type changes through the simulation period. Each packet of 100 kbit is received with some errors because of the noise and weather conditions as in Eq. (5). The received packet is compared to its original transmitted packet to determine the errors and then calculate the BER. The number of received packets during a simulation determines the system throughput in this simulation. On the other hand, the delay is computed as the needed time for the communication beam to travel the distance between the cars plus the needed processing time in each repeater to receive the data and retransmit it.

Each LED generates a Tx power from 10,000 to 25,000 luminance. Meanwhile, the background luminance is on average in the order of 1300 luminance in the daytime or 600 luminance at night. In this simulation, the camera records each frame as a grid of pixels in three colors (i.e., blue, green, and red). Each pixel intensity is represented by a number of bits (e.g., 8 bits or more). In case of 8-bit luminance scenario, each pixel intensity is represented in the range from zero (dark) to 255 (bright). The image processing algorithm detects a LED light source in the captured frame if a cluster of bright pixels is detected compared to the neighboring darker pixels. However, as a distance between the LED source and the receiver camera increases, the recorded LED pixel intensity decreased while the surrounding intensity remain constant. Therefore, the BER increases as the distance increases between the LED source and the receiver camera. Adding a FEC correction algorithm [e.g., the hamming code (7,4)] will decrease the BER as a trade-off decreasing the data rate.

5.1 The proposed system performance metrics

The BER versus distance is studied in Fig. 6. In VLC communication, increasing the distance leads to higher BER until approximately 100 m (i.e., the maximum allowed distance for VLC communication) in each hop. In VLC first hop, a small BER with a max of 6.3×10^{-6} is noticed. In the second hop, the error increased due to the repeater amplify and forward scheme errors with a max of 8.1×10^{-6}. At higher hops max errors of 1.3×10^{-5}, 1.85×10^{-5}, and 2.55×10^{-5} are measured for third, fourth, and fifth hop, respectively.

On the other hand, in RF communication, we measure the BER at distances from 100 m (i.e., after the VLC hop maximum communication distance) up to 200 m. We consider no communication at distances greater than 200 m to ensure the minimized
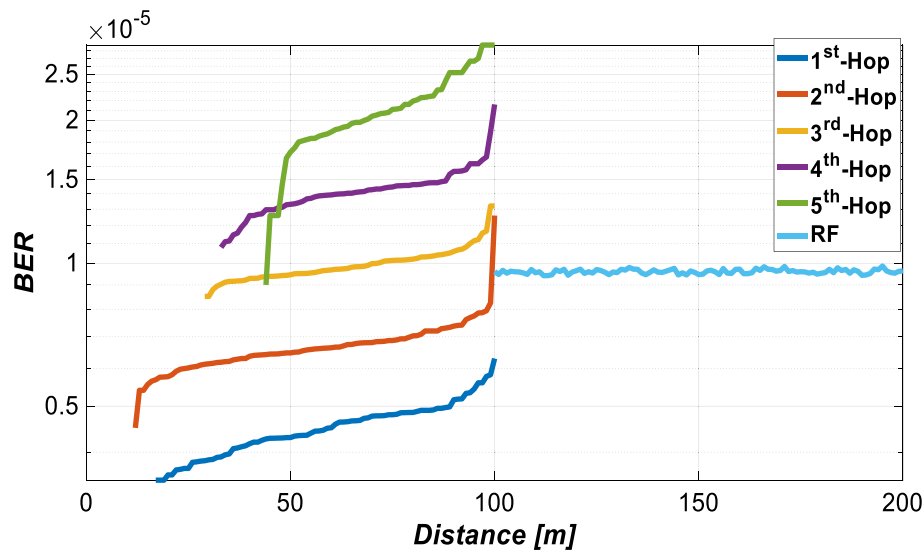
Fig. 6 The BER versus distance. In VLC communication, increasing the distance leads to higher BER until approximately 100 m (i.e., the maximum allowed distance for VLC communication) in each hop. In VLC first hop, a small BER is noticed, in the second hop, the error increased due to the repeater amplify and forward scheme errors, while at higher hops have higher max errors. In contrast, RF communication has near-constant BER at distances from 100 m (i.e., after the VLC hop maximum communication distance) up to 200 m. We consider no communication at distances greater than 200 m to ensure the minimized interference in RF (omnidirectional radiation pattern) and to maximize the frequency reuse in car-to-car RF communication

interference in RF (omnidirectional radiation pattern) and to maximize the frequency reuse in car-to-car RF communication. Distance variation has a small effect on RF communication BER with an average of 9.7×10^{-6}, while as distance reaches 200 m, a very small increase in BER is noticed. Normally in RF communication, the communication distance is much larger than the allowed for car-to-car communication and then the BER shows small variations under that range of distances.

The BER at different weather conditions (i.e., clear weather, heavy fog, and heavy rain) in all communication scenarios is studied, and the results are depicted in Fig. 7. In general, the VLC and RF communication at clear weather conditions has the lowest BER compared to other weather conditions, while the VLC and RF communication at foggy weather has the highest BER at VLC with low noticeable effect on RF because the fog even if it minimizes the visibility in the visible light band does not block the other electromagnetic radiations such as RF communication.

In contrast, the rainy weather has a moderate effect on VLC communication and an increased BER effect on RF communication because the water drops scatter the visible light band beam and absorb (attenuate) the RF electromagnetic beam. On the other hand, the BER for a smaller number of VLC hops (i.e., first hop of 4.6×10^{-6}, 5.2×10^{-6}, and 4.9×10^{-6} and second hop of 6.9×10^{-6}, 8.1×10^{-6}, and 7.5×10^{-6}) is lower compared to RF communication BER of 9.6×10^{-6}, 9.6×10^{6}, and 1.23×10^{5} at all weather conditions, respectively. At the third VLC hop, the BER of 1.03×10^{5}, 1.41×10^{5}, and 1.17×10^{5} is competitive to RF communication BER at all weather conditions except for the fog, while at higher VLC hops, the BER gets higher than RF.

Figure 8 illustrates the system's overall throughput due to the VLC percentage in each simulation versus the RF percentage at different weather conditions. As in
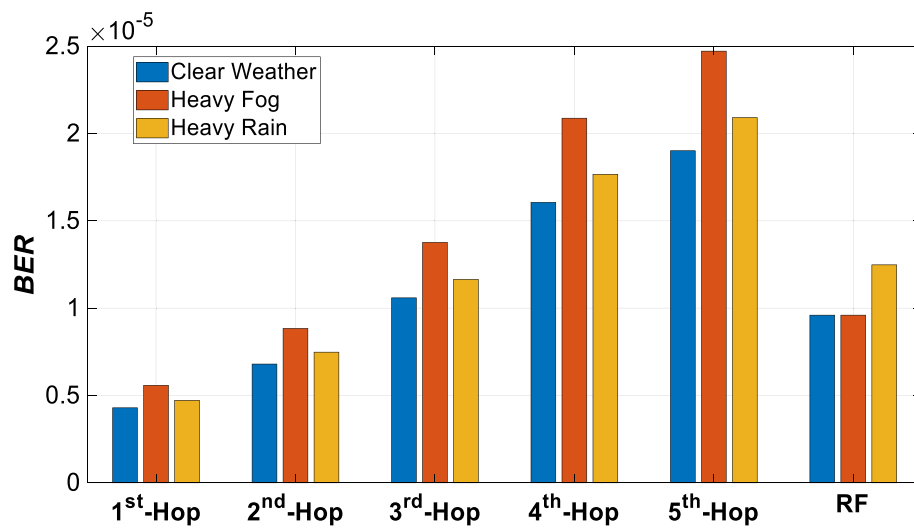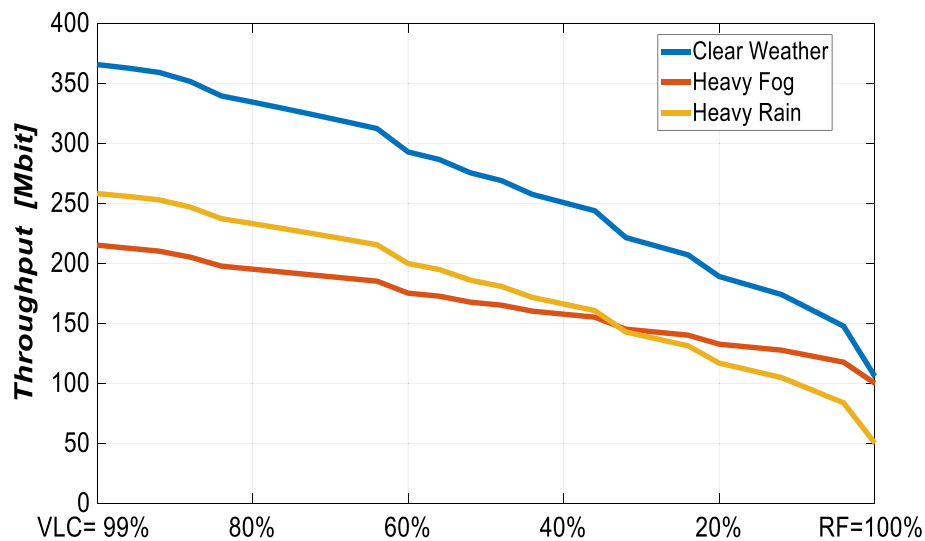
Fig. 7 The BER at different weather conditions. The BER at different weather conditions (i.e., clear weather, heavy fog, and heavy rain) in all communication scenarios. In general, the VLC and RF communication at clear weather conditions has the lowest BER compared to other weather conditions, while the VLC communication at foggy weather has the highest BER at VLC with low noticeable effect on RF because the fog even if it minimizes the visibility in the visible light band does not block the other electromagnetic radiations such as RF communication

Fig. 8 The throughput at the VLC percentage. The system overall throughput due to the VLC percentage in each simulation versus the RF percentage at different weather conditions. As in Eq. (5), we add or remove the transfer function of each weather condition to study its effect. In clear weather (i.e., only the line-of-sight transfer function is considered), the pure VLC channel communication data rate is about three times that of the pure RF channel communication data rate

Eq. (5), we add or remove the transfer function H of each weather condition to study its effect. In clear weather (i.e., only the line-of-sight transfer function is considered), the pure VLC channel communication data rate of 355 Mbit/s is about three times that of pure RF channel communication of 108 Mbit/s.

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In heavy fog (i.e., both the line-of-sight transfer function and fog effect transfer function are considered), the pure VLC channel communication data rate of 206 Mbit/s amounts to about twice that of pure RF communication 98 Mbit/s. In heavy rain (i.e., both the line-of-sight transfer function and rain effect transfer function are considered), the pure VLC channel communication data rate of 257 Mbit/s is five times that of the pure RF channel communication with 48 Mbit/s. Consequently, increasing the percentage of time the system is working in the RF communication, and it suffers from decreased overall throughput at most weather conditions.

Figure 9 illustrates the delay of VLC and RF communication. In both RF and single-hop VLC, a small delay of 4.9×10^{-4} s and 4.3×10^{-4} s, respectively, is noticed. In contrast, the multi-hops delay increases as the number of hops increases because it resamples a multiple of one hope delay. Some critical information needs to be transferred with a very small delay. Then, a higher number of hops is not a practical approach for such critical information and it should be covered through RF communication.

5.2 Comparison analysis

The proposed system uses 18 independent LEDs each using the OOK modulation, while in the 32 QAM constellation system, only two LEDs are used with 16 QAM each [21]. Assuming the same camera resolution and FPS to detect both systems for only a single hop, we can fairly compare the two systems as shown in Fig. 10. Despite the 32-QAM system providing a data rate increase by 42%, it suffers from more than double the BER compared to the proposed system. Therefore, using the 32-QAM system in multi-hop will accumulate a very high error probability beyond the acceptable levels for VLC communications in car-to-car applications.

The proposed system uses 5 multi-hops VLC, in each hop we select the best route only with MIMO of 18 independent LEDs each using the OOK modulation, while diversity
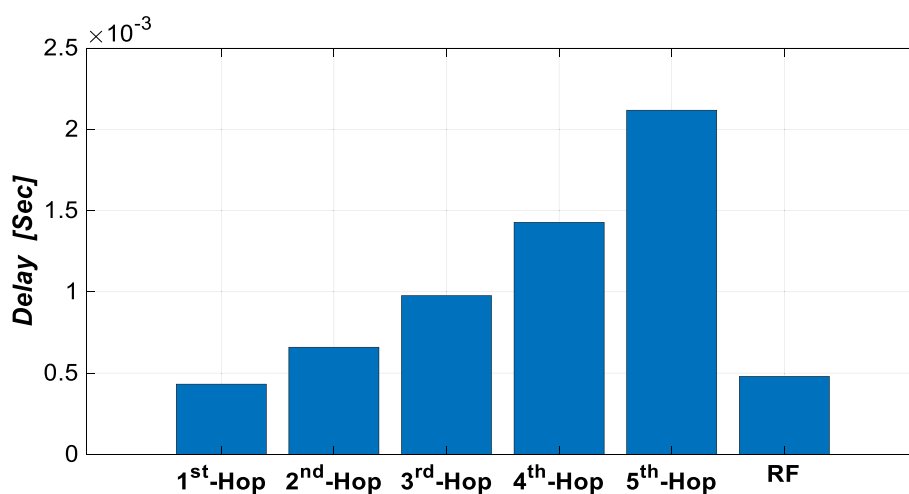

Fig. 9 The delay at VLC and RF communication. This figure illustrates the delay of VLC and RF communication. In both RF and single-hop VLC, a small delay is noticed. In contrast, the multi-hops delay increases as the number of hops increases because it resamples a multiple of one hope delay. Some critical information needs to be transferred with a very small delay. Then, a higher number of hops is not a practical approach for such critical information and it should be covered through RF communication
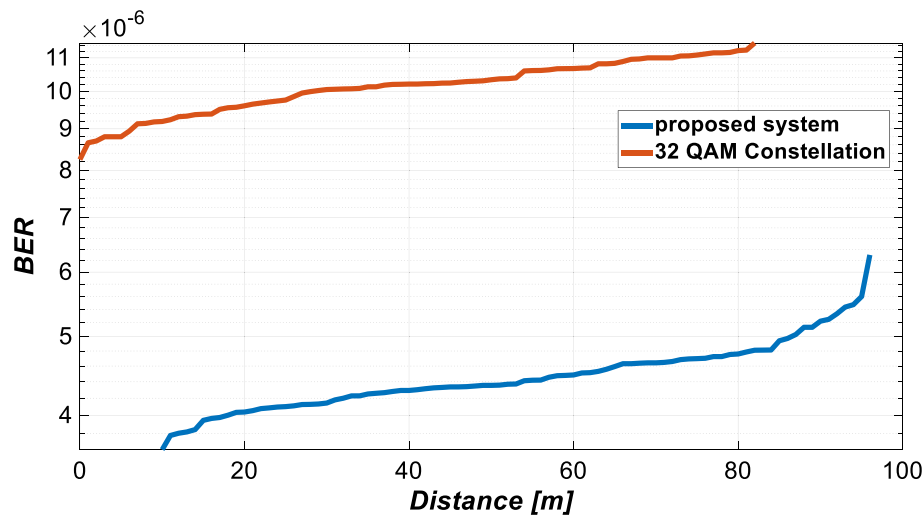
Fig. 10 Comparing BER for single hop. This figure illustrates the comparison between the proposed system BER versus the 32 QAM system for single hop only at distance from 0 to 100 m. The 32-QAM system suffers from more than double the BER compared to the proposed system. Consequently, using multi-hop 32-QAM system will accumulate a beyond acceptable levels error probability
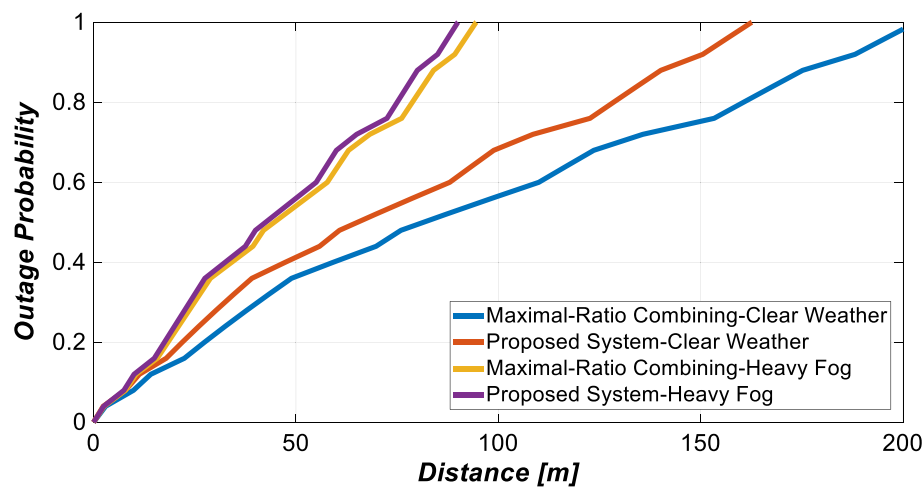

Fig. 11 Comparing the outage probability. This figure illustrates the comparison between the proposed system outage probability versus the maximal ratio combining system at distance from 0 to 200 m. In each hop, the proposed system selects the best route only, while diversity schemes multi-hop system uses the maximal ratio combining which select all routes in order to decrease the outage probability. The outage probability in clear weather is around 60% at 100 m for both systems with a noticeable advantage for diversity schemes multi-hop system (i.e., 57% for diversity system versus 68% for the proposed system). In contrast, for different weather conditions such as heavy fog, the outage for the two systems is nearly the same (i.e., both have 52% outage for 50 m distance)

schemes multi-hop system uses the maximal ratio combining which decreases the outage probability but sacrifices the data rate, especially with no proposed MIMO LEDs used for VLC [28]. As the two systems propose using the terrestrial telecom infrastructure as backup, we believe that there is no need to present such data rate sacrifices, then for enhancing the outage probability from 0.5 to 0.4 while accepting a data rate loss of 60% ~ 90% in diversity routing and not using the MIMO VLC. Figure 11 shows that

the outage probability in clear weather is around 60% at 100 m for both systems with a noticeable advantage for diversity schemes multi-hop system (i.e., 57% for diversity system versus 68% for the proposed system). In contrast, for different weather conditions such as heavy fog, the outage for the two systems is nearly the same (i.e., both have 52% outage for 50 m distance). As a fact, this paper assumes an outage probability of more than 50% as blockage and tries to find an alternative route that meets the best route selection criterion while maintaining the VLC main advantage of the high data rate.

6 Conclusion

In this paper, we have introduced the problem facing car-to-car communication and why the RF communication alone could not fulfill the needed requirements within the next decade. Then, we have demonstrated the VLC communication advantages such as higher data rate which can cover modern applications need and the easy setup requirements (i.e., camera and LED). After that, the proposed scheme in this paper combines the advantages of both the VLC communication and the RF communication for car-to-car applications to have a higher data rate, higher range coverage, and smaller BER. Our results showed that VLC can achieve up to four times the RF throughput.

Consequently, increasing the percentage of time the system working in the RF communication condition not only suffers from higher BER but also suffers from decreased overall throughput. However, due to the car-to-car critical communication situations, it is necessary to have an RF communication backup. The proposed system BER in VLC first hop has a max of 6.3×10^{-6}, and the second hop has a max of 8.1×10^{-6} increased compared to the first hop due to the repeater accumulated error. For the third, fourth, and fifth hop, max errors of 1.3×10^{-5}, 1.85×10^{-5}, and 2.55×10^{-5} are measured, respectively.

Our comparison analysis discusses the possible alternatives for increasing the data rate. The presented system adopts the MIMO approach with simple modulation OOK, while other literature proposed using QAM modulation. We have demonstrated that the complex modulation had increased the BER and prevented the system multi-hop ability. The comparison shows that the BER at distance 20 m is 9.5×10^{-6} for high QAM system, while BER is 4×10^{-6} for the proposed system. At distance 40 m, the BER is 10×10^{-6} for high QAM system and 4.5×10^{-6} for the proposed system. At distances 60 m and 80 m, the high QAM system BER is 10.7×10^{-6} and 11.6×10^{-6}, while the proposed system has only 4.2×10^{-6} and 4.5×10^{-6} BER at these distances, respectively.

In addition, the comparison analysis discusses the possible alternatives for multi-hop. The presented system adopts the best route approach, while other literature proposed using diversity in routing and then the received replicas perform maximal ratio combining to decrease the system outage. We have demonstrated that even if the routing diversity did enhance the system outage a little, it also severely degraded the data rate. In clear weather, the outage probability at 100 m is 57% for diversity system versus 68% for the proposed system. In heavy fog, the outage at 50 m is 51% for diversity system versus 53% for the proposed system. Meanwhile, diversity routing system accepts a data rate loss of 60–90% compared to the proposed system.

In future work, we would like to enhance the real-time experiment by using a higher FPS camera and LED lamp with more sectors. Then, we aim to add the detection of

different colors as independent LEDs. Moreover, we aim to add a FEC correction algorithm to decrease the BER. The future road map for car-to-car applications is to provide drive assist, auto-drive, and enhanced signaling between cars.

Abbreviations

3G	Third-generation mobile network
4G	Fourth-generation mobile network
5G	Fifth-generation mobile network
AHP	Analytic hierarchy process
AWGN	Additive white Gaussian noise
BER	Bit error rate
CG	Coalitional game
dB	Decibel
ECU	Engine control unit
FPS	Frame per second
LED	Light emitting diode
MIMO	Multi-input multi-output
OOK	ON–OFF key modulation
QAM	Quadrature amplitude modulation
RF	Radio frequency
RR	Rain rate
SNR	Signal-to-noise ratio
VLC	Visible light communication

Author contributions
NMO presented the paper idea, wrote the paper sections, built the MATLAB model, and discussed the findings. AHAZ reviewed the paper idea and sections, supervised the model, and proofread the manuscript. FAN reviewed the manuscript. All authors read and approved the final manuscript.

Availability of data and materials
A MATLAB simulation video shows the simulation environment at different scenarios (i.e., different sender and destination vehicles). In the video, a single hop is represented by a blue line, two hops are represented by green lines, three hops are represented by red lines, and RF is represented by black dashes. The video link is (last checked 21 MAR 2022): https://drive.google.com/file/d/1iF6pgSM4upA8j_cHIdR3AYVfzC07azxo/view?usp=sharing.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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