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Handover Procedure and Algorithm in Vehicle to Infrastructure Visible Light Communication

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ABSTRACT In vehicle-to-infrastructure visible light communication (V2IVLC) systems, the vehicle receives data from LED street lights that are placed along both sides of a street. At a certain time, a vehicle communicates with only one group of LEDs. As the vehicle moves, it needs to switch the communication from the current LED group to the next group. Because of the fast movement of the vehicle and the small coverage of each LED group, the handover between the LED groups is a difficult problem. This paper proposes an entire handover procedure for a V2IVLC system. The main point of this procedure is a distance-based probabilistic algorithm for the determining of the handover switching time. The switching time is chosen to maximize the signal quality subject to a constraint, so that the missing handover rate is lower than a predetermined threshold. The proposed algorithm is verified through simulations. The results show that the proposed handover algorithm can provide a high signal quality of the communication within a reasonable missing handover rate.

INDEX TERMS Visible light communication, vehicle, infrastructure, handover.

I. INTRODUCTION

In recent years, the intelligent transport system (ITS) has become a very active area of research [1], [2]. With the development of modern communication technologies, vehicles need to support not only speed and power, but also safety and comfort. The ITS is a means to fulfill such needs. A key part of an ITS is the vehicular communication, which includes the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication types. While V2V communication provides direct communications between vehicles [3]–[5], V2I communication provides indirect communications with all of the other vehicles in a street, as well as access to the Internet [6]–[8]. Therefore, V2I communication is the essential component of an ITS. There are several techniques that can be used for V2I communication including radio frequency (RF) and visible light communication (VLC).

Compared to the RF-based approach wich includes cellular network and WiFi, the several advantages of VLC include an immunity to electromagnetic interference, a free usability, an inherent safety and security, a high reuse factor due to the high spatial confinement, and a cost-effectiveness. VLC also suffers less from channel congestion in cases of high traffic [9]. In VLC, the communication is maintained through a directional and line of sight (LOS) channel, which greatly reduces the possibility of collisions, thereby increasing the systemic scalability. However, the requirement of the directional and LOS channel regarding VLC also underpins one of the most challenging problems regarding VLC; that is, handover. Especially in a vehicle-to-infrastructure visible-light communication (V2IVLC) system, the fast movement of the vehicles in a street intensifies the handover problem even more. In recent years, several V2IVLC systems have been proposed. The basic communications between the vehicle and the street lights in these systems have been experimentally proved as practical in the scenario where both the vehicle and the street lights are static. A work on the management of the communication maintenance in a V2IVLC system in the moving-vehicle scenario does not exist in the literature. The current cellular-network handover algorithms cannot be used in a V2IVLC system for three reasons.

First and most importantly, the switching time of the handover that needs to be chosen in a V2IVLC system must be of a very high precision. In the Global System for Mobile communication (GSM), the switching-time selection process is much more tolerant compared with that in V2IVLC. This is because, in the GSM, the cell coverage is very large, so a small error in the choosing of the switching time would result in merely a small degradation of the signal quality. In V2IVLC, the small size of the cell coverage combined with the fast movement of the vehicle leads to a small error in the switching-time result and a great degradation of the systemic performance. More specifically, a slightly late switching point might result in a missed handover, which causes communication disruptions. Alternatively, a switching point that is slightly too soon would result in a high signal bit-error rate. Therefore, the switching time must be chosen so that the missing handover rate is low while the signal quality is as high as possible. This is a difficult task that the handover algorithm in V2IVLC must be able to perform. Another factor that makes the handover more difficult in V2IVLC is the major traffic changes in streets from time to time. When the traffic is high, the network is unstable, the handover delay is long, and thus, the switching time must be sooner than that in the case of low traffic, as this guarantees that the handover will not be missed. Therefore, the V2IVLC handover algorithm must consider these dynamic network changes to determine the most suitable handover switching time.

Second, the GSM switching time is determined based on the strength of the radio signal, while that in V2IVLC is determined based on the coordinates of the street lights on a captured image. Therefore, the handover algorithm in V2IVLC must be based on image processing. Third, the entire handover procedure in GSM including the handover decision, selection of the target cell, and handover execution must be modified for its use in V2IVLC because of the differences between the two systems.

To solve the previously mentioned V2IVLC handover problem, this paper provides three contributions. First, the entire handover procedure for the visible light in V2IVLC is presented. Second, an image-processing technique that estimates the distance between a vehicle and a street light is proposed. Third, based on the estimated distance and other parameters, a probabilistic handover algorithm is proposed to determine a switching time that maximizes the signal quality within a guaranteed missing handover rate. The proposed handover algorithm also takes into account dynamic systemic changes to find the correct switching time for different situations. Matlab simulations are conducted to verify the performance of the proposed algorithm.

II. FUNDAMENTALS OF THE SYSTEM

A. LED STREET-LIGHT CELL AND THE HIERARCHICAL STRUCTURE OF THE SYSTEM

The hierarchical structure of the system is described in Fig. 1. A number of LED street lights are grouped into one cell. All of the LEDs in a cell transmit the exact same signal. A number of consecutive LED cells are under the control of an LED service center (LEDSC), and then a vehicle service center (VSC) controls several consecutive LEDSCs.

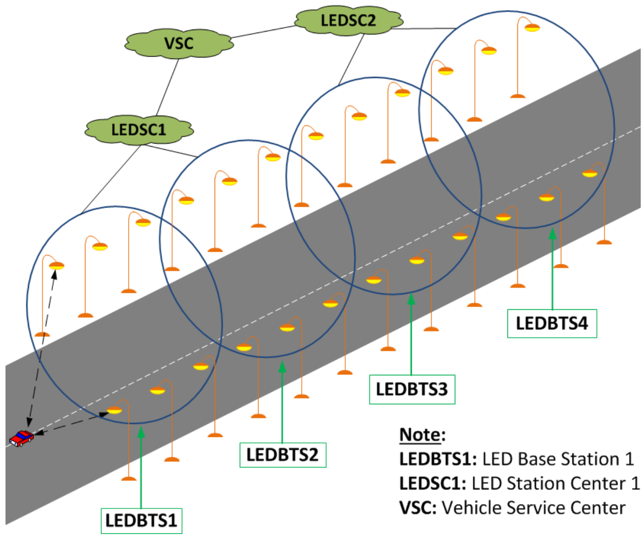

FIGURE 1. Overall system architecture.

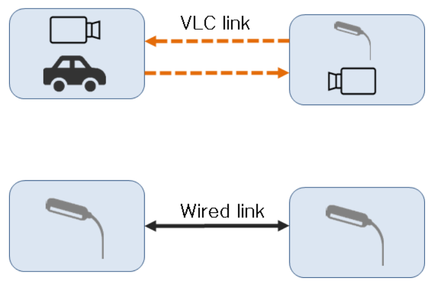

FIGURE 2. Links in the system.

B. LINKS IN THE SYSTEM

Different types of systemic communication are described in Fig. 2. The vehicle and the LED street lights communicate with each other using the camera-based VLC links. Both the street light and the vehicle are equipped with a camera for the receipt of the light signals that are emitted by each. The LED street lights are connected with wired connections.

C. COMMUNICATION BETWEEN THE VEHICLE AND THE LED STREET LIGHTS, AND TWO TYPES OF HANDOVER

Basically, the reason for the LED grouping is the enlargement of the communication coverage between the vehicle and the LED street lights. A vehicle communicates with only one LED in one cell at a time. During the time that the vehicle is moving in the street, the vehicle will keep switching the communication from the current LED to the next LED, and from the current LED cell to the next LED cell. Therefore, two types of handover are required for the vehicle to maintain its communicative functionality while it is moving.

Since all of the LEDs in a cell transmit the same signal, the vehicle can choose to receive the signal from any LED among these LEDs when moving inside a cell. However, because the signal from the closest LED should be the strongest, the vehicle will always receive signals from only the closest LED. When this closest LED moves beyond the view of the vehicle, the vehicle will immediately receive the signal from the next LED, which then becomes the closest LED to the vehicle. This type of handover is called intra-cell handover and it helps the vehicle to maintain the communication when it is moving inside an LED cell. Since all of the LEDs in a cell transmit the same signal and they are simultaneously present in the image, intra-cell handover can always be performed without any disruption, so it will not be addressed in this paper.

The second type of handover is intra-cell handover, and this occurs when the vehicle is moving out of the coverage of the current cell. This handover type is addressed in the present paper

III. HANDOVER PROCEDURE

A. TWO PHASES OF THE V2IVLC HANDOVER PROCEDURE

In a cellular network, the handover procedure includes the following three phases: handover decision, target-cell selection, and handover execution. Handover decision is the phase wherein the mobile device decides to switch the communication from the current cell to another cell. This decision is made based on the strength of the received signal of the mobile device. When the received signal becomes weak, the mobile device decides upon the switching time to switch to another cell. Since several cell candidates are available, the mobile device needs to choose one of them as the target cell to which the mobile device will switch. Once the target cell is determined, the handover-execution process takes place. Messages will be exchanged between the mobile device and the cells, as well as the mobile switching center, to transfer the communication from the current cell to the target cell.

In V2IVLC, the handover procedure includes only two of the phases, as follows: handover decision and handover execution. The purpose of these two phases in V2IVLC is similar to that in the cellular network. There is no stage for the choosing of the target cell because this task is very simple and straightforward in V2IVLC. In the cellular network, the mobile device is surrounded by numerous cells, so the determination of the cell that is the best to switch to is influenced by many factors. In V2IVLC, only one target cell needs to be chosen, which is the cell that is adjacent to the current cell, as described in Fig. 3.

B. HANDOVER DECISION

The primary goal of this phase is the determination of the time to switch to the next cell. There are many existing algorithms in the cellular network for this task. However, the selections of the switching time in V2IVLC and the cellular network are very different. First, as mentioned earlier, the switching time in V2IVLC is determined based on the images of the street lights, not the radio-signal strength that is used in the cellular network.

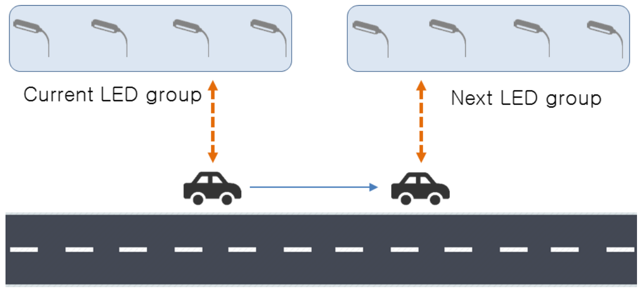

FIGURE 3. Choosing the target cell in V2IVLC.

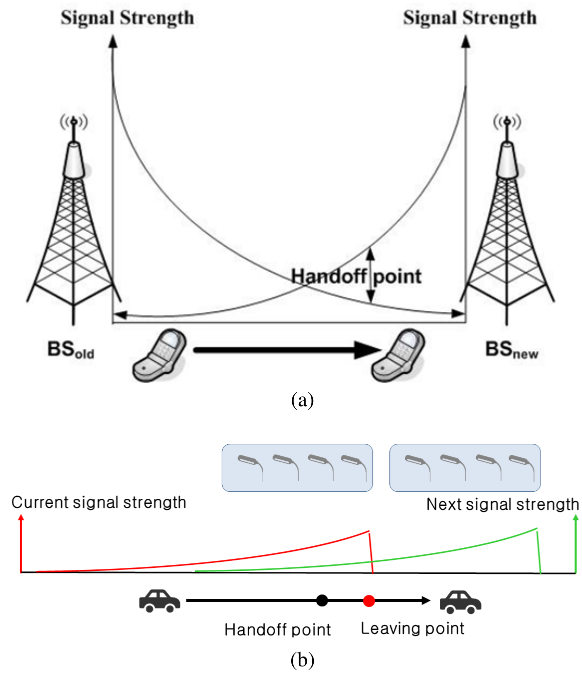

FIGURE 4. Changing pattern of the signal strength in the cellular network and V2IVLC. (a) Changing pattern of the signal strength in the cellular network. (b) Changing pattern of the signal strength in V2IVLC.

The second difference, which makes it much more difficult to determine the switching time in V2IVLC compared to the cellular network, is the pattern of the changes of the signal strength of the two systems. As shown in Fig. 4 (a), in the cellular network, the radio-signal strength from the current cell would gradually decrease to zero, while that from the target cell would gradually increase as the mobile device moves toward the target cell. The contrasting signal changes from the two cells make it easy to determine the switching time, as the mobile device can perform the switch immediately after the transition point, which is the point in time when the current cell is weaker than the target cell.

In V2IVLC, both the image signals from the current cell and the target cell would increase as the vehicle moves toward the target cell, as shown in Fig. 4 (b). Therefore, a clear indication for the selection of the switching time is not evident. More importantly, in V2IVLC, the image signal from the current cell would suddenly drop as the final street light in the current cell disappears from the view of the vehicle. The sudden drop of the signal from the current cell requires

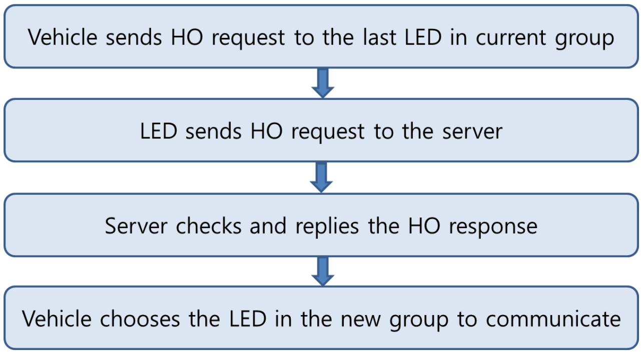

FIGURE 5. **Handover execution in V2IVLC.**

the switching time to be determined more precisely, because if the handover procedure is not finished on time, the handover will be missed and the communication will be interrupted. In the cellular network, since the signal from the current cell only gradually decreases, a late handover only results in a degradation of the signal quality, not an interruption of the communication.

Another difference between the cellular network and V2IVLC is the cell size, which is mentioned previously. Typically, cellular networks have cell sizes ranging from 1 to 20 km and the mobile device has plenty of time before it needs to move out of the current cell. In V2IVLC, each cell only includes a few consecutive street lights where the interdistance is a few tens of meters, and thus the maximum cell size is only several hundreds of meters. Due to the fast movement speed, the vehicle only has a small amount of time before it needs to move out of the current cell, so the possibility of a missed handover would be much higher compared to the cellular network.

Because of those reasons, an algorithm that can precisely determine the switching time for the handover in V2IVLC is an important tool, and one will be proposed in the subsequent sections of this paper.

C. HANDOVER EXECUTION

The handover-execution phase is described in Fig. 5. Exactly at the switching time, which is determined in the previous phase, the vehicle sends a handover (HO) request to the last street light in the current group. Then, the street light will send the HO request to the LEDSC. The LEDSC checks the request and then sends the HO response to the street light. Then, the street light sends the confirmation to the vehicle that the next cell is ready for the vehicle to communicate with it. From that point onward, the vehicle can communicate with the new cell.

IV. DISTANCE BASED PROBABILISTIC HANDOVER DECISION ALGORITHM

A. TWO STEPS OF THE DETERMINATION OF THE SWITCHING TIME

There can be many means to determine the switching time in V2IVLC. The signal strength can be defined as the size of the street lights in the captured image. The closer the light is, the larger the image of the light is, and the stronger that the signal is. As the vehicle moves in the street, the size of the light image also changes, and thus it can be used as an indication to determine the switching time. However, the size of the light is dependent on numerous parameters including the focal length of the lens, the size of the sensor, and the physical size of the street light. Furthermore, as the vehicle moves toward the target cell, the size of the light in the current cell will become larger and suddenly disappear. Therefore, the signal strength in terms of the light size is not a proper parameter for the determination of the switching time.

To answer the question regarding the identification of the parameters that are the decisive parameters for the determination of the switching time, one needs to look at the primary handover target. Of course, the primary target is the achievement of a seamless connection as the vehicle is moving between the cells. The two requirements that enable the handover algorithm to achieve this target are as follows: First, the missing handover rate must be as low as possible, and there are usually noticeable degradations in the signal quality after the vehicle switches to the next cell; therefore, the second requirement for the handover algorithm is the easing of the signal-quality degradation after the completion of the handover.

Regarding the first requirement, the handover tends to be missed when the remaining distance, which is the distance between the vehicle and the last LED in the current cell at the switching time, is short, whereas the handover delay, which is the time for the entire handover-execution process, is long. This is because, when the remaining distance is short, the dwell time, which is the time that is left for the vehicle to communicate with the current cell, would be brief, so the time to complete the handover-execution process might be insufficient. Regarding the second requirement, the signal quality immediately after the handover occurrence would be low if the vehicle switches to the next cell too quickly, which also means an excessive handover distance. Therefore, the two decisive parameters for the deciding of the switching time are the remaining distance and the handover delay. Consequently, the first step in the determining of the switching time is the attainment of these two parameters.

While the handover delay can be easily obtained as historical statistical information, the remaining distance can be estimated using the proposed algorithm that is presented in this section. Once the handover delay and the remaining distance have been obtained, the second step in the determining of the switching time is the application of an algorithm that takes into account these two parameters to determine the most suitable switching time. Such an algorithm will also be presented in this section.

B. PROPOSED ALGORITHM FOR THE ESTIMATION OF THE REMAINING DISTANCE

1) PRINCIPLE AND HARDWARE REQUIREMENTS OF THE ALGORITHM

The principle of the proposed distance-estimation algorithm is described in Fig. 6. The camera is attached inside the

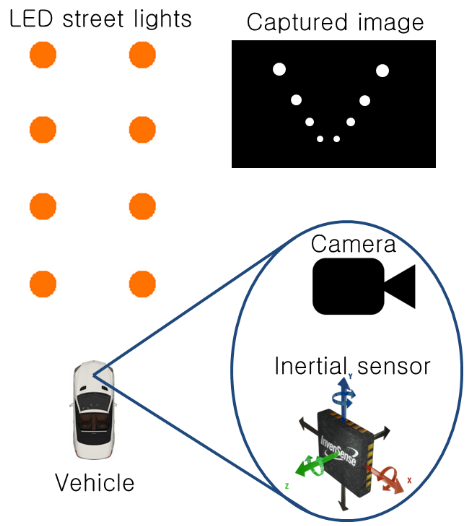

FIGURE 6. Architecture of the proposed distance estimation algorithm.

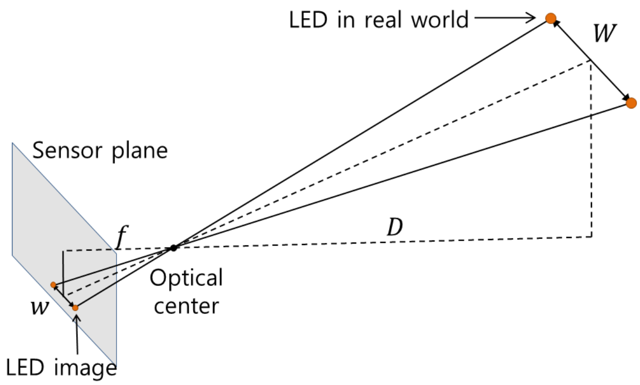

FIGURE 7. Proposed distance estimation algorithm.

vehicle to capture pictures of the LED street lights. An inertial sensor is attached to the camera to obtain the information that is relevant to the camera orientation. After the street-light image is taken, the image is processed to determine the distance between the vehicle and the street light.

2) DISTANCE ESTIMATION IN THE STANDARD POSE OF CAMERA

Basically, the distance from the vehicle to the street light is determined based on the geometric relationship between the position of the street light in the real world and that of the street light in the image. This geometric relationship is derived from the pinhole-camera model, as illustrated in Fig. 7. Assume that the camera sensor plane is perpendicular to the axis of the street and the wide edge of the sensor is parallel to the surface of the street. Two street lights of the same height need to be in the view of the camera. Let W denote the distance between the two lights in the real world and w denote the distance between them in the image. Let f denote the focal length of the lens, and the distance from the vehicle to the two street lights, denoted as D, can be determined as follows:

$$D = \frac{f}{w} W. \tag{1}$$

3) DISTANCE ESTIMATION IN CASE OF ARBITRARY POSE OF CAMERA

In Eq. (1), for the attainment of W, it is given that the real-world coordinates of the two street lights can be obtained through the signals that are transmitted from these lights. The focal length, f, is also known. The distance between the two lights in the image, w, is obtained through image processing. Therefore, the distance, D, can be determined by using Eq. (1), as long as the camera has the pose that is described in Fig. 7.

In the case where the camera pose is different, the inertial sensor that is attached to the camera is used to obtain the camera-pose information. From this information, the captured image is transformed into an image as if it had been captured by the camera at the standard pose. The ability to perform this transformation is owing to the pinhole-camera model.

In the pinhole-camera model, two types of coordinate systems are used, as follows: 3D world-coordinate system and 2D image-coordinate system [10]. Suppose that a point on the scene has the 3D world coordinates $\mathbf{X} = (X, Y, Z)^T$, its 2D image coordinates $\mathbf{x} = (x, y)^T$ are then defined as

$$\mathbf{x} = C \times R \times T \times \mathbf{X}, \tag{2}$$

where C is the camera intrinsic matrix, R is the 3×3 rotation matrix, and T is the 3×3 translation matrix.

The camera intrinsic matrix C can be obtained if it is given that the intrinsic parameters of the camera such as the focal length and the sensor size are known. The camera rotation matrix R can be calculated due to the camera-pose information from the inertial sensor. Then, the image can be transformed into the standard captured image through the application of the following transformation to every point in the image:

$$\mathbf{x}' = C \times R^{-1} \times C^{-1} \times \mathbf{x}, \tag{3}$$

where $\mathbf{x}'$ is the image coordinate corresponding to $\mathbf{x}$ in the standard captured image.

Once the transformed image is obtained, the distance from the vehicle to the street light can be determined using Eq. (1) according to the same process.

C. PROPOSED ALGORITHM TO DETERMINE THE SWITCHING TIME FROM THE HANDOVER DELAY AND THE DISTANCE

After the attainment of the handover delay and the remaining distance, an algorithm is required to determine the switching time based on these two parameters. The two approaches for this algorithm are deterministic and probabilistic.

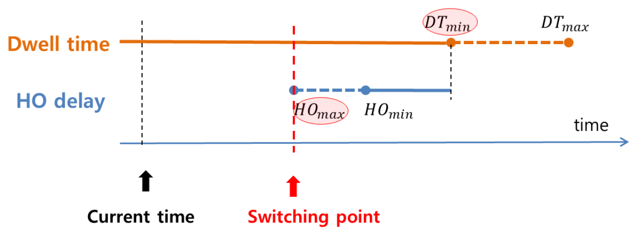

FIGURE 8. **Deterministic approach for determining switching time.**

1) DETERMINISTIC APPROACH TO DETERMINE THE SWITCHING TIME

In terms of the handover, the most concerning problem is the missed handover. Accordingly, the deterministic approach tries to choose the switching time that minimizes the missing handover rate. To do this, the switching time is chosen so that the dwell time of the vehicle must be longer than the handover delay. The dwell time, which is derived from the remaining distance and the vehicular speed, might be determined with some errors. The handover delay also randomly changes with some variances. Therefore, to ensure that the handover will not be missed, the switching time can be determined as follows:

$$Switchingtime = Min(Dwelltime) - Max(HOdelay). \tag{4}$$

The reason underpinning Eq. (4) can be explained using Fig. 8. While this approach is very simple, it has many drawbacks. To ensure the maximum handover-delay value, a considerable number of historical handover-delay values must be compared. The problem here is that the variation of the handover delay might change over time, and an unusually large handover delay, the cause of which is some kind of rare severe accident, would be meaningless to the possible handover delay in the current time period. By taking into account these unusual handover delays, the maximum handover delay would be very large. Similarly, the dwell time is determined by the distance-estimation algorithm. By considering the maximum distance-estimation error, the minimum dwell time might be much smaller than the actual dwell time. Therefore, with the deterministic approach, the switching time is typically determined much sooner than necessary; while this would guarantee that the handover would not be missed, the sacrificed signal quality might be unnecessarily excessive.

The second problem of the deterministic approach is that it does not provide an alternative choice for the switching time. As the signal quality must be sacrificed for the lower possibility of the missed handover, the designer of the system might wish to choose the extent of the sacrificed signal quality that needs to be traded for the desired missing handover ratio. However, the deterministic approach always results in a switching time that effectively minimizes the missing handover probability while the signal quality is not considered.

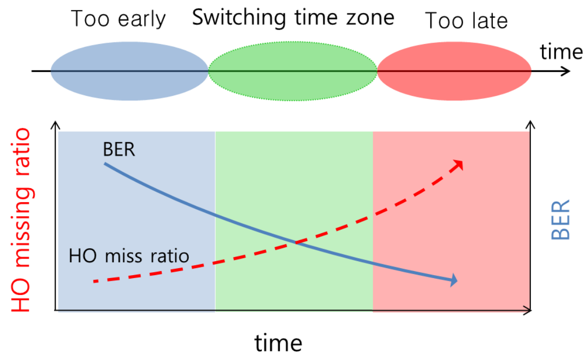

FIGURE 9. **Trade-off between too-soon and too-late switching time.**

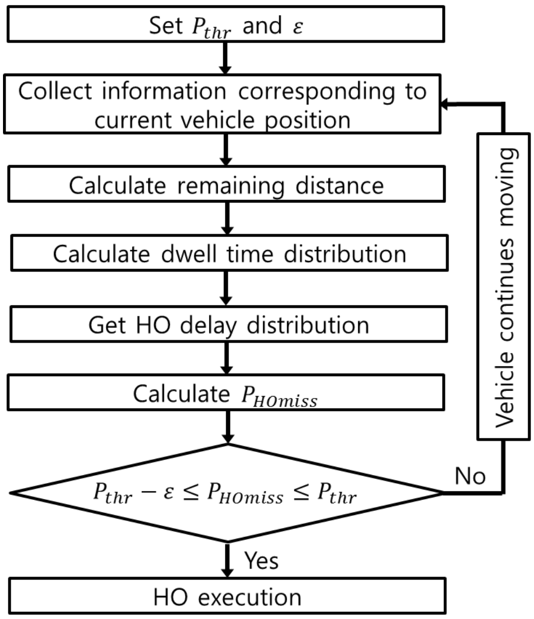

FIGURE 10. **Algorithm to determine switching time.**

2) PROBABILISTIC APPROACH TO DETERMINE THE SWITCHING TIME

a: IDEA OF THE PROBABILISTIC APPROACH

Since the deterministic approach does not consider the signal quality in the selection of the switching time, another algorithm that takes into account both the missing handover rate and the signal quality needs to be proposed. However, because of the tradeoff between the missing handover rate and the signal quality, it is difficult to determine a proper switching time. To be more specific, while a switching time that is too late would increase the probability of a missed handover, a switching time that is too soon would degrade the signal quality, as described in Fig. 9.

The idea of the proposed probabilistic approach in the solving of this dilemma is presented in Fig. 10. First, a threshold P_{thr} for the missing handover rate is set beforehand. This threshold is solely determined based on the desire of the system designer. Then, as the vehicle is moving in the street, it will constantly collect the information about the remaining distance and the handover delay to estimate the probability of a missed handover P_{HOmiss}. At the time that is too soon, this probability would be nearly zero and the vehicle would know that the switching time has not occurred yet. When the probability is close to the predetermined threshold within some predetermined margins ε, the vehicle will choose that as the time to switch to the next cell. If the switching time is chosen in this way, it would ensure that the switching point is as close to the next cell as possible, thereby making the signal quality as high as possible; meanwhile, it is guaranteed that the missing handover rate will be lower than the desired level.

Since the proposed probabilistic approach for the determination of the switching time relies on the missing handover probability, the main point of this approach is the method for the estimation of the missing handover probability.

b: PROPOSED METHOD FOR THE CALCULATION OF THE MISSING HANDOVER PROBABILITY

The missing handover probability of the vehicle at a specific position can be determined given three kinds of information. First, the information regarding the distribution of the estimated remaining distance that corresponds to a specific position of the vehicle is used. The second set of information is the distribution of the measured-speed errors of the vehicle. From these two sets of information, the distribution of the dwell times of the vehicle can be obtained. The third information set is the distribution of the historical handover-delay data. From the distributions of the dwell times and the handover delays, the missing handover probability can be obtained and the switching time can be determined, as described in Fig. 11.

In Fig. 11, let Y and Z denote the probability density functions of the dwell time and the handover delay, respectively. Let X denote the distance from the vehicle to the last light in the current cell. The missing handover probability is calculated as the probability that the dwell time of the vehicle at a given position is smaller than the handover delay. That is, the missing handover probability P_{HOmiss} is calculated as follows [APPENDIX]:

$$P_{HOmiss} = \int_{y=0}^{\infty}\int_{z=y}^{\infty} Y_{X=x}(y) \times Z_{X=x}(z)\partial z\partial y \tag{5}$$

In Eq. (5), $Y_{X=x}(y)$ is the probability that the dwell time equals y when the distance between the vehicle and the street light is x, and $Z_{X=x}(z)$ is the probability that the handover delay equals z when the distance between the vehicle and the street light is z. While $Z_{X=x}(z)$ is determined by the network performance of the recent history, $Y_{X=x}(y)$ is largely dependent on the distance between the vehicle and the street light x since the error of the distance estimation algorithm is largely dependent on this parameter.

As the vehicle is moving toward the next cell, the missing handover probability is constantly estimated. Assuming that P_{thr} is the threshold for the missing handover probability and ε is a small margin that is set by the system designer, the switching time is determined as the first point in time when

$$P_{thr} - \epsilon \leq P_{HOmiss} \leq P_{thr}. \tag{6}$$

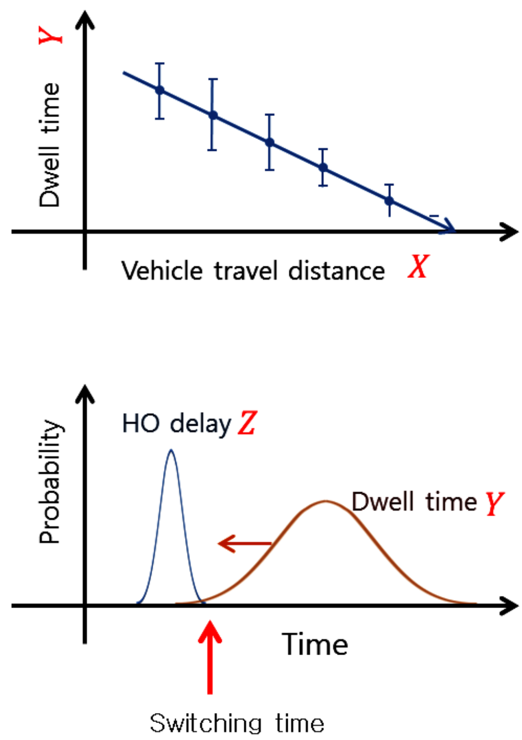

FIGURE 11. Probabilistic approach for the determination of the switching time.

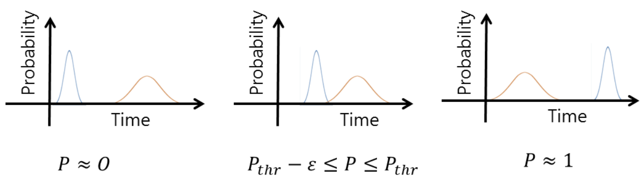

FIGURE 12. Intuition of the value of missing handover probability.

The three switching-time cases of too soon, too late, and right are illustrated in Fig. 12. Note that the margin of the missing handover threshold, ε, must be large enough so that, as the vehicle moves toward the next cell, at least one value of the estimated missing handover probability will fall within this margin.

The advantage of the proposed probability-based switching-time algorithm is that the system designers can choose the threshold for the missing handover probability. Then, it would be guaranteed that the achieved missing handover rate would be lower than that threshold, and the level of the achieved signal quality would be the highest possible with respect to the constraint regarding the missing handover rate. Furthermore, the dynamic changes in the system, which include the changes in the variance of the speed-measurement error, the variance of the distance-estimation error, and the variance of the handover delay, are always taken into account

TABLE 1. Simulation environment.

Parameter	Value
Sensor physical size	$36 \times 24\,(mm^2)$
Sensor resolution	3600×2400 (pixels)
Lens focal length	20 to 100 (mm)
Frame per second	1000(fps)
LED panel street light area	$50 \times 50\,(cm^2)$
Number of LED chips in each street light	6×6 (LEDs)
Inter-distance between LED chips	10 (cm)
Height of LEDs	7 (m)
Interdistance between LEDs	25 (m)
Street length	10(km)
Lane width	10 (m)
Number of light in one group	4
Number of vehicles	200 to2000
Channel access method	$TDMA$
Vehicle speed	20 to 100 (km/h)
Speedometer error	0 to 10 (%)

by the proposed probabilistic algorithm in the determining of the most precise switching time for the achievement of the optimal system handover.

V. SIMULATION

A. SIMULATION ENVIRONMENT

Matlab simulations were conducted to examine the performance of the proposed algorithm. The settings of the systemic parameters for the simulations are listed in Table 1. It is assumed that the system can observe a segment of the street that is 10-km long. At first, it is assumed that an initial number of vehicles are present in the street, with each vehicle moving at a random speed. The speeds of the vehicles will randomly change over time, and each vehicle has a random travel distance. After the vehicle travels this distance, it is assumed that it will disappear from the street. New vehicles can randomly appear at random times in the street. It is assumed that the vehicle accesses the channel through the Time Division Multiple Access (TDMA). The street light transmits data to each vehicle within a number of time slots, of which there is a total of 1024. Each vehicle is allocated a number of time slots depending on the request. Transmission failures also randomly occur depending on the bit-error rate. When the vehicle is moving in the street, it will constantly estimate the distance from it to the street light, and then it determines the switching time. When the switching time arrives, the vehicle executes the handover process as per the previous description. Then, the missing handover ratio and the signal quality will be measured to evaluate the performance of the proposed algorithm. To measure the handover ratio, the number of missing handover was counted and divided to the total number of handovers occurred during the simulation process.

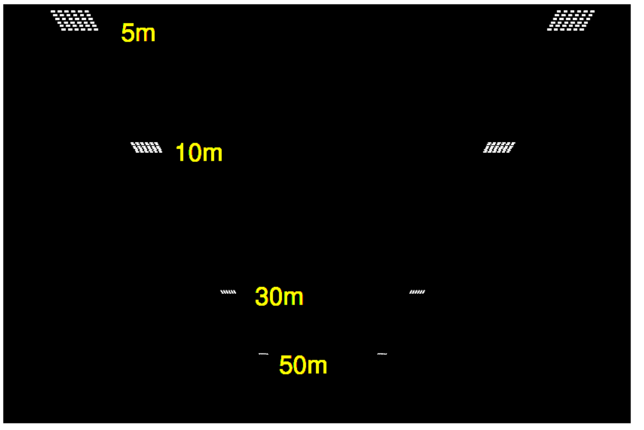

FIGURE 13. LED street lights captured at different distance.

To measure the signal quality, the images of LED street lights captured at different distances were simulated. Each LED street light is indeed a panel consisting of 6×6 LED chips. The simulated LED street light images were then processed to detect every single LED chips in LED street lights. The bit error rate (BER) of the LED detection was considered to be the measurement for the signal quality.

B. SIMULATION RESULTS

As mentioned in the previous section, the error of the distance-estimation algorithm is dependent on the real distance from the vehicle to the street light. This is because, similar to all vision-based algorithms, the accuracy of the proposed distance-estimation algorithm is determined by the distance between the street lights in the image. When the distance between the vehicle and the street light is small, the two street lights that are used to determine the distance would be far away in the image as shown in Fig. 13, and the achieved accuracy of the algorithm would be high.

The signal quality is also dependent on the distance. When the distance is long, the LED street light would be small in the image and thus causes more errors in detection and increases the BER. As shown in Fig. 13, the LED street light captured at the distance of 5m is noticeably larger than that captured at 10m.

Figure 14 shows the change of the accuracy of the algorithm as the vehicle moves toward the street light. The pattern of the error that repeats after every 50-m length is due to the fact that the inter-distance between the street lights is 50 m. Due to the repetitive pattern of the distance-estimation error, it would be easy to find the variance of the estimated-distance error that corresponds to a given position of the vehicle. Consequently, the variance of the dwell time can be calculated with a higher accuracy, and this is also the same for the missing handover probability.

The tradeoff between the missing handover rate and the signal quality is illustrated in Fig. 15. Note that the switching time in this simulation is not determined by the proposed algorithm. Instead, each vehicle chooses a random switching time that corresponds to a remaining distance from 5 to 50 m.

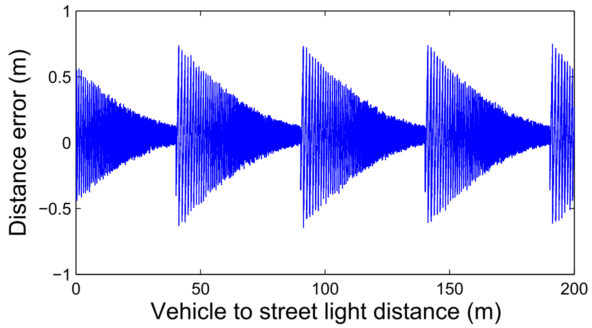

FIGURE 14. Dependency of distance estimation error versus the actual distance.

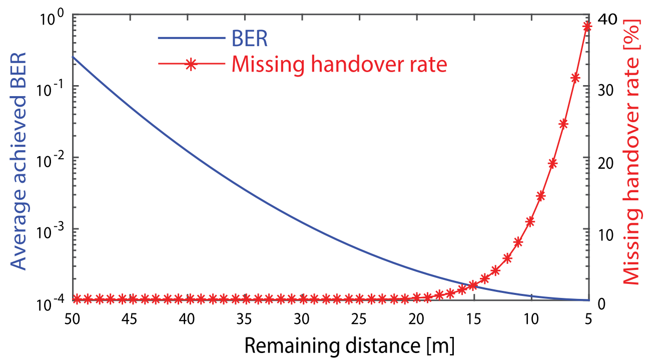

FIGURE 15. Achieved missing handover rate and BER at difference remaining distance.

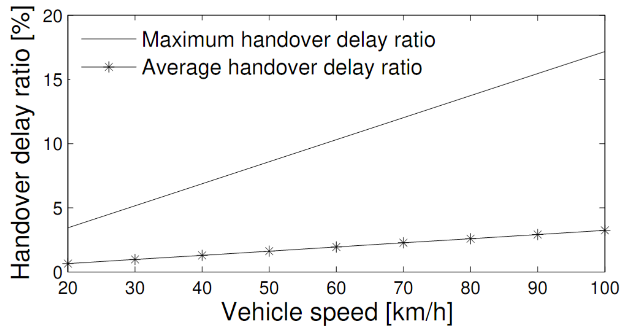

FIGURE 16. Handover delay ratio.

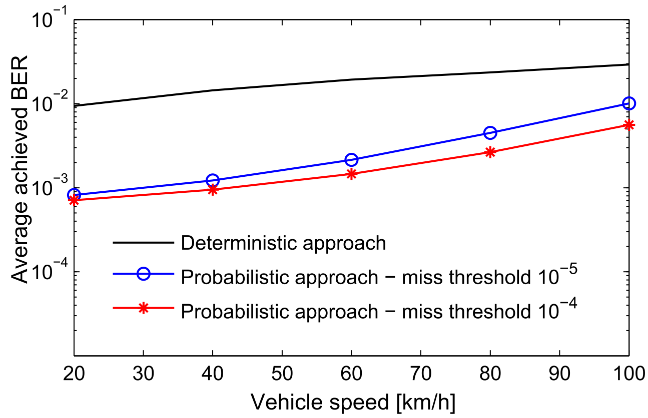

FIGURE 17. Effect of vehicle speed on BER.

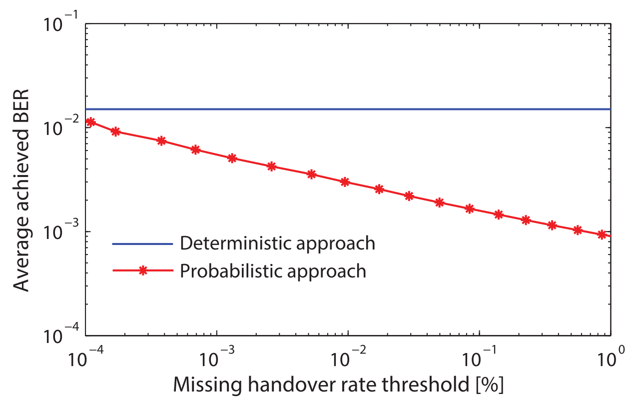

FIGURE 18. BER achieved by deterministic and probabilistic handover algorithm.

The missing handover ratio and the BER of the signal after the handover are measured to show the tradeoff between these two systemic-performance aspects. It is evident that the missing handover ratio increases as the remaining distance decreases; however, the signal quality increases as the remaining distance decreases.

The handover difficulty in V2IVLC is due to the fact that the handover delay might consume a large portion of the dwell time of the vehicle, which is the result of the combination of the fast movement of the vehicle and the small size of each cell. In the case that the network is stable, the handover delay only takes a small portion of the dwell time, and hence the vehicle has plenty of time to switch to the next cell. However, when the network is unstable, the handover delay might be very long compared to the dwell time and this could lead to a missed handover. The ratio of the handover delay to the dwell time of the vehicle in each cell is shown in Fig. 16. It can be seen that the handover-delay/dwell-time ratio is dependent on the speed of the vehicle. The average handover-delay ratio, which is approximately the handover-delay ratio in the case of a stable network, varied within a region of a few percent. However, the maximum handover-delay ratio in the case of an unstable network can rise higher than 15 % when the vehicle is moving at high speeds.

The effects of vehicle speed on the signal quality are shown in Fig. 17. In the simulation, the missing handover threshold in the probabilistic algorithm is set to 10^{-4} and 10^{-5}. It can be seen that as the vehicle speed increases, the BER increases regardless the type of handover algorithm. This is because as the vehicle speed increases, the vehicle need to switch to the next cell at early time when the remaining distance is still long, which results in the low BER.

The average BER achieved by the probabilistic-handover algorithm and its deterministic counterpart is shown in Fig. 18. It can be seen that the BER of the probabilistic approach is dependent on the missing handover-rate threshold that is predetermined in the algorithm. More specifically, the BER achieved by the probabilistic algorithm gets lower if the threshold is increased. On the other hand, the BER achieved by the deterministic algorithm has a fixed value, which is higher than the BER achieved by the probabilistic algorithm with the missing handover rate threshold ranging from $10^{-4}\%$ to 1%. The reason for the high BER of the deterministic algorithm is that the deterministic algorithm takes into account the maximum values of all parameters. Therefore, the switching time would be chosen at a point that is too soon, and this leads to an unnecessarily low signal quality.

VI. CONCLUSION

Handover is one of the most challenging problems in V2IVLC systems. This is due to many reasons, including the small size of each street-light cell, the fast movement of the vehicle, and the changing pattern of the signals from the current and the target cells. A work on the solving of the handover problem in V2IVLC does not exist in the literature, while the existing handover algorithms for the cellular network cannot be applied to V2IVLC due to the differences between the two systems. This paper elucidates the handover problem in V2IVLC, pointing out that the handover procedure in V2IVLC includes the following two phases: handover decision and handover execution. Between the two phases, the handover decision requires an algorithm to determine the switching time of the handover, which is a very difficult task since a switching time that is either too soon or too late negatively affects the systemic performance. While a too-late switching time is likely to lead to a missed handover, a too-soon switching time might degrade the signal quality. Further, a simple deterministic algorithm would only try to minimize the missing handover rate without any regard for the degradation of the signal quality.

This paper proposes a distance-based probabilistic algorithm that takes into account both the missing handover rate and the signal quality for the selection of the switching time. The result of the proposed algorithm is the highest achievable signal quality with a guaranteed missing handover rate. The performance of the proposed algorithm is verified through simulations, and the results show that the proposed algorithm can provide a high signal quality within a given missing handover rate.

APPENDIX
MISSING HANDOVER PROBABILITY CALCULATION

The missing handover probability is calculated as:

$$\begin{aligned} P_{HOmiss} &= P(Z > Y) \\ &= \int_{y=0}^{\infty} P(Y = y) \times P(Z > y)\,\partial y \\ &= \int_{y=0}^{\infty} P(Y = y) \times \int_{z=y}^{\infty} P(Z = z)\partial z \partial y \\ &= \int_{y=0}^{\infty}\int_{z=y}^{\infty} Y_{X=x}(y) \times Z_{X=x}(z)\partial z \partial y \end{aligned}$$

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