2019-04

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Accepted Article – In I. Abdalla, M.B. Rahaim, and T.D.C., Little, "Investigation of Outage Probability and AP Placement for Mobile Users in Indoor VLC System Design," *Proc. 2019 IEEE Wireless Communications and Networking Conference (WCNC)*, Marrakesh, Morocco, April 15-18, 2019, https://doi.org/10.1109/WCNC.2019.8885981.

Investigation of Outage Probability and AP Placement for Mobile Users in Indoor VLC System Design

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Abstract: Providing optical wireless data access with the visible spectrum is a commercial reality. Products are available for point-to-point or point-to-multipoint solutions. However, there remain many important questions about how to successfully achieve "dual-use" systems in which both lighting and communications functions are realized. In particular, the necessary placement of lights for lighting and the characteristic of light signals to be out-of-view creates trade-offs especially when mobile devices can change their position, height, and orientation requiring cooperation with neighboring access points (APs).

In this paper, we investigate outage probability for Visible Light Communication (VLC) links in a system in which these dimensions are varied. We propose a probabilistic model characterizing where to deploy indoor VLC access points considering the impact of handover delay and user velocity. Our model demonstrates the trade-offs that lie within this problem and we also provide a closed form upper bound on outage probability that guarantees outage-free regions for devices attempting handover. The model is used to demonstrate the impact of different VLC access point cell separations and to show how user device velocity impacts outage probability.

Keywords: Visible light communications, dense networks, optical wireless communications, handover, mobile devices, outage probability.

 This work is supported in part by the Engineering Research Centers Program of the National Science Foundation under NSF Cooperative Agreement No. EEC-0812056. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

1 Introduction

With the increased adoption of electronic devices such as smart phones and internet-of-things objects, it is widely expected that both the volume and density of wireless communications will continue to increase indefinitely [1]. Meeting this demand is indeed driving the adoption of smaller and smaller networking cells and the use of heterogeneous networks.

Visible Light Communications (VLC) is one of the possible cooperative networking technologies to help offload some of the traffic from the crowded Radio Frequency (RF) spectrum. One of the many advantages of VLC systems is that it does not interfere with RF signals and can help in achieving higher aggregate rates if deployed properly [2], [3]. It is also desirable as it can be piggybacked on lighting infrastructure (power distribution, packaging, and light engine). Moreover, lighting fixtures hold a strategic location in human-occupied spaces – they are intentionally deployed to meet localized distribution of light for humans to use to see.

VLC has been studied extensively in the case of a single light and a stationary receiver. This scenario involves characterization of the source, the channel, and the receiver and yields information about the limits of what one can achieve for VLC as an access point under ideal, controlled operating conditions. Limiting factors include the beam width of the transmitter (wide vs. narrow) and similarly the FOV of a receiver. As a rule, narrow beams/FOVs yield higher SNR and thus higher potential data rates. To realize the best data rates we assume deployments with direct, line-of-sight communication with relatively narrow beam from the transmitters. This corresponds to typical downlighting fixtures deployed as lighting to realize illuminance of 300-500 lx in, for example, but not exclusively, office-type environments. Certainly other configurations such as wide beam for wide-volume connectivity are possible; however, these configurations limit frequency reuse of the optical signals.

When we consider mobile users, a single narrow beam VLC AP becomes a liability as the user can quickly exit from the illuminated area causing a loss of connectivity. But with cascaded VLC APs we have an opportunity to handover a connection to a neighboring device in order to maintain continuous or "seamless" connectivity [4].

In this context questions arise about how to intentionally design the layout of overhead dual-use APs to meet the lighting needs and to best deliver data to mobile users across a wide, diverse indoor environment. Our goal in this paper is to explore these questions and to propose new models to predict performance under a variety of design scenarios, and in particular, when a user device moves through the illuminated space. Our approach is based on the development of an outage probability model and subsequent analysis and simulation under different scenarios.

In [5], the authors study the impact of factors that affect coverage probability of a VLC network inside an empty room, such as number of APs, room area and source height from the floor. Meanwhile, in [6], the authors propose a base station layout support system for indoor VLC that satisfies all conditions given by a user. Reference [7] investigates the communication and illumination coverage in VLC; their results show the relationship between

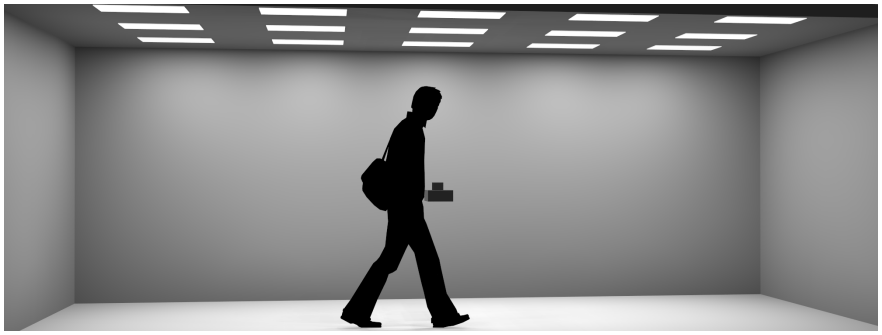

Figure 1: Illustration of a Mobile User Transiting Through Multiple VLC Cells

coverage and LED arrangements (lattice versus hexagon structures), semi-angles at half-power and heights. In reference [8], the authors propose an approach to manage handover that provides cooperation and coordination between VLC terminals in two scenarios of overlapping versus non-overlapping sources to achieve seamless connectivity. However, the previously mentioned work does not study the room layout effect in terms of handover delay. In RF, there are some works that do. For example, reference [9] analyzes handover delay and finds the minimal overlap between cells needed to achieve seamless handover. The unique contribution of our paper is the design and analysis of light/VLC AP placement based on a probabilistic handover outage model intended to mitigate handover effects. We also show trade-offs with respect to user velocity, handover delay, light placement distances, and outage probability.

The remainder of the paper is organized as follows. Section 2 describes our system model and geometry. Section 3 shows our simulation results for some design scenarios. Section 4 thoroughly discusses the trade-offs in our analysis. Section 5 concludes the paper.

2 System Model

In this section we develop a geometric model characterizing a VLC AP coverage, and how a user transits through adjacent cells. The model is the basis for identifying an exact bound and an upper bound on outage probability.

Consider the scenario illustrated in Fig. 1. Here a mobile device requires handover from cell to cell as the user moves between cells. The simplest handover technique interprets the strength of the incident signal, or Received Signal Strength (RSS). In RSS-based handover, once the signal is stronger in the new cell, the handover is initiated. It is possible to improve robustness with a variety of techniques including adding a delay in switching to achieve hysteresis to prevent a "ping pong" effect at cell edges. This delays the handover until a difference between the two signal levels is met. Meanwhile, another source of handover delay in a VLC system is the handover decision time that arises from the variable receiver orientation and field of view (FOV). Both the FOV and the orientation of a receiver towards or away from a target will impact the handover decision based on RSS alone. Lastly,

occlusions (light blockage) by the user or the environment will impact the reliability of the RSS interpretation. For our model, we define handover delay t_{HO} to account for both the handover decision time and the hysteresis delay.

2.1 System Geometry

In Fig. 2, we define S as the distance between the centers of the two light sources, which we are interested in optimizing and L which is the length of the midline J dividing the overlap region of the cells. In RSS-only-based handover RF systems this line is theoretically where the handovers are triggered because crossing it in any direction switches users to the cell that has the stronger signal within that overlap region. However, in directional systems such as VLC, it might not always be the case because the receiver orientation plays a part too in where your highest signal might come from. For the purpose of designing the room, we will consider an upward facing receiver scenario. Assume that the user crosses the line J at point m. Point m defines $l(m)$ which is the distance from the intersection of the two cells to the point m. Assuming that the user is equally likely to cross at any point on J, $l(m)$ is uniformly distributed with pdf/cdf respectively as follows:

$$f_{l(m)}(k) = \frac{1}{L}, 0 < k < L \tag{1}$$

$$F_{l(m)}(k) = \int_0^k \frac{1}{L} dx = \frac{k}{L}. \tag{2}$$

S impacts the size of the overlap region and controls L, the length of J. In our design, once the user crosses the midline, we assume they subsequently exit from the cell. The shortest path from the midline to the neighboring cell is $g(m)$. This is explained more in part B of this section. In this work, we assume all sources are the same and placed on the same plane and so their coverage range will be identical; therefore the coverage radii R are identical. It is worth noting that R depends on the receiver height within the room. D is the distance travelled by the user from point m and α is the angle that the user takes when moving out of m to exit the cell. α is uniform over π and independent of $\ell(m)$.

Some geometric relations we need in our following analysis are as follows:

- $L = \sqrt{4R^2 - S^2}$ which ties S to L, we can derive this from the right-angled triangle in Fig. 2 that consists of the vertically shaded and dotted triangles, where the hypotenuse is R and the two remaining sides are $\frac{L}{2}$ and $\frac{S}{2}$.
- $g(m) = R - \sqrt{\frac{S^2}{4} + (\frac{L}{2} - l(m))^2}$ which ties $g(m)$ to $l(m)$, this can be deduced from the dotted right angle triangle Fig. 2, with hypotenuse $R - g(m)$ and the two sides $\frac{L}{2} - l(m)$ and $\frac{S}{2}$.

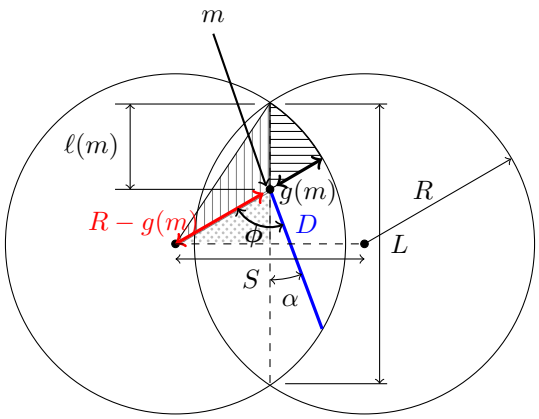

Figure 2: Two Overlapping VLC Cells

2.2 Exact Outage Probability Derivation

Given the model above, outage occurs when the user fails at achieving a seamless handover. This happens if the time it takes to establish the actual handover, we denote this by t_{HO}, is greater than the time the user takes to cross the distance from line J to his current cell's exit arc. This would cause you to lose your current connection before you get a chance to establish a new one with the cell you are headed to. Let v_u be the user's velocity.

We define $g(m)$ as the distance perpendicular to the exit arc traveled by the user within the overlap region starting at any point m on line J and ending at the tangential point at which he exits the primary cell he was connected to. From Fig. 2, we can deduce the following geometric relations:

- $\phi = \alpha + \tan^{-1}\left(\frac{S}{L-2l(m)}\right)$.

- From law of cosines, we have
  $R^2 = (R - g(m))^2 + D^2 - 2(R - g(m))Dcos(\phi)$.

Solving the last equation for D we get

$$D = (R - g(m))\left(cos(\phi) + \sqrt{cos^2(\phi) + \frac{g(m)(2R - g(m))}{(R - g(m))^2}}\right)$$

where we rejected the negative term since D is a distance.

Finally, to get the outage probability, we consider the outage of our model as:

$$\begin{aligned} P_{outage} &= P\left(t_{HO} > \frac{D}{v_u}\right) \\ &= P\left(D < t_{HO}v_u\right) \end{aligned} \tag{3}$$

where the probability is taken w.r.t $\ell(m)$ and α.

At this point we will use simulation to compute the exact outage probability (Section 4) as a closed form solution is not immediately available but will be reported in a future work.

2.3 Upper Bound on Outage Probability Derivation

In this section, we get a closed form for an upper bound to the outage probability. We design our model for the worst case scenario, which is the shortest distance from any point m to the arc of current circle, $g(m)$ as defined above. By doing so we evaluate an upper bound for the outage probability, as the shorter distance imposes a tighter constraint on the handover time. Note that, at any point m, a user can cross to the exit arc using infinite possible paths. We define the minimum path as $g(m)$. This is the path we use in our design model, meaning if you can guarantee for a certain m that there is no outage caused from traversing the minimum path generated at it ($g(m) > t_{HO}v_u$) then all paths greater than it at this point will not cause outages as well.

To get the upper bound on outage probability, we calculate the outage of our model as:

$$\begin{aligned} P_{outage} &< P\left(t_{HO} > \frac{g(m)}{v_u}\right) \\ &= P\left(t_{HO} > \frac{g(m)}{v_u}\middle| l(m) \leq \frac{L}{2}\right) P\left(l(m) \leq \frac{L}{2}\right) \\ &+ P\left(t_{HO} > \frac{g(m)}{v_u}\middle| l(m) > \frac{L}{2}\right) P\left(l(m) > \frac{L}{2}\right) \end{aligned} \tag{4}$$

From symmetry of the arc, eqn. (4) equals

$$2P\left(t_{HO} > \frac{g(m)}{v_u}\middle| l(m) \leq \frac{L}{2}\right) P\left(l(m) \leq \frac{L}{2}\right)$$

Using the fact that

$$P\left(l(m) \leq \frac{L}{2}\right) = P\left(l(m) > \frac{L}{2}\right) = \frac{1}{2}$$

It follows

$$
\begin{aligned}
P_{outage} &< P\left(t_{HO} > \frac{g(m)}{v_u}\middle| l(m) \leq \frac{L}{2}\right) \\
&= P\left(g(m) < t_{HO}v_u \middle| l(m) \leq \frac{L}{2}\right) \\
&= P\left(l(m) < \frac{L}{2} - \sqrt{(R - t_{HO}v_u)^2 - \frac{S^2}{4}}\right) \\
&= F_{l(m)}\left(\frac{L}{2} - \sqrt{(R - t_{HO}v_u)^2 - \frac{S^2}{4}}\right) \\
&= \frac{\frac{L}{2} - \sqrt{(R - t_{HO}v_u)^2 - \frac{S^2}{4}}}{L/2} \\
&= 1 - \sqrt{\frac{(R - t_{HO}v_u)^2 - \frac{S^2}{4}}{R^2 - \frac{S^2}{4}}}
\end{aligned} \tag{5}
$$

This result captures the design tradeoffs for dual-use VLC including light spacing. The closer the lights are together the more overlap exists and therefore there is less probability of outage; but this is also dependent on the speed of the user and the actual handover time. This model provides a guaranteed outage-free region and small regions where there could be possible outages, such as the region horizontally shaded in Fig. 2. Note that from the symmetry of the shape, another outage region occurs at the mirror of this region on the bottom of the arc. This region shows the area where you can possibly get lines shorter than $t_{HO}v_u$. This approach designs for the worst case scenario; it is possible to guarantee not to cross a certain outage probability determined in advance. Using the formula derived above one can deduce where to place the APs, by determining S, for a predefined tolerable outage probability (discussed more in section 4). Some simple examples show you the expected outcomes such as, if the two sources were at the maximum allowed separation distance which is $S = 2(R - t_{HO}v_u)$ in this model, you get an upper bound of 1 on the outage probability. On the other hand, for the case where you allow the two sources to completely overlap, $S = 0$, because this is an upper bound you will not get zero for the outage probability but the the minimum possible outage you get would be $\frac{t_{HO}v_u}{R}$.

Main differences between the exact outage and the upper bounds are: (1) We were able to get a closed form for the outage probability upper bound and this bound gives the designer regions of guaranteed outage free zones.
(2) The exact formula does not guarantee outage free regions.

The following section shows some numerical examples for the upper bound outage model. Section 4 shows the results of both the exact probability and its upper bound and allows for a closer analysis of the tradeoffs involved in the overall system.

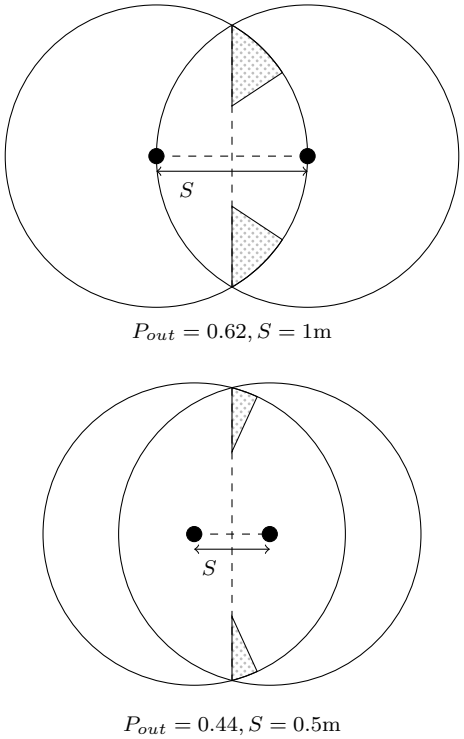

Figure 3: Possible outage regions at $t_{HO} = 0.2$ Sec for different S

3 Simulation Results for Outage Upper Bound

For our simulations, we assume practical numbers for the parameters. We let the coverage radius $R = 1\ m$ and $v_u = 2\ m/sec$ which is an upper bound on the user velocity indoors. We note that there are several regimes for indoor mobility when there is overlapping coverage: (1) quasi-static slower users with low or intermittent velocity in which there is ample time to address handover, (2) faster users with very high velocity that are best supported by omnidirectional media (RF), and (3) the intermediate ones which hope to exploit the availability of the VLC channels without handover to RF.

In Figures 3 and 4, the user is assumed to be moving from cell 1 (left) to cell 2 (right), the dotted regions show the possible outage regions for two scenarios in which the lights are spaced at 0.5 m versus at 1 m while $t_{HO} = 0.2$ s and $t_{HO} = 0.1$ s respectively. It is clear that spacing the sources too far from each other strongly affects the outage probability but what also plays a vital role is the handover time t_{HO} where in Fig. 4 when it decreased to 0.1 s for the same S values as in Fig. 3, we realized much better results and the difference in outage probability was much closer than in Fig. 3, results are listed in Table 1. We can calculate the minimum outage probability for each of these scenarios and they are 0.4 for Fig. 3 and 0.2 for Fig. 4. This will change with user velocity as well. In these cases we only show the worst case scenarios. One can also show improved performance with a source with a wider coverage region.

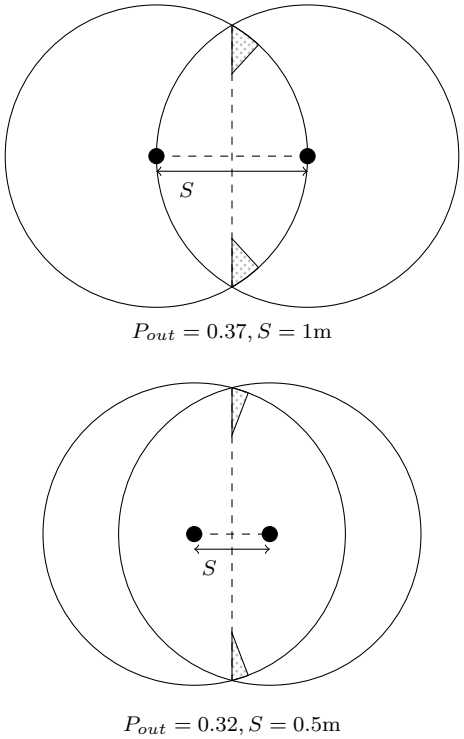

Figure 4: Possible outage regions at $t_{HO} = 0.1$ Sec for different S

Table 1: Numerical results

	At $t_{HO} = 0.2$ s	At $t_{HO} = 0.1$ s
S	0.5 m	0.5 m
P_{outage}	0.44	0.32
S	1 m	1 m
P_{outage}	0.68	0.37

The key observation from these results is the importance of lighting placement with respect to user mobility (speed) and the resulting handover delays.

4 Analysis of Trade-Offs

We discuss possible applications of the proposed model in this section and show the results for both the exact and upper bound on the outage probability.

Impact of Source Coverage Radius R on Outage Probability Suppose a lighting system is constrained to use legacy wiring, i.e., the VLC fixtures are constrained to use

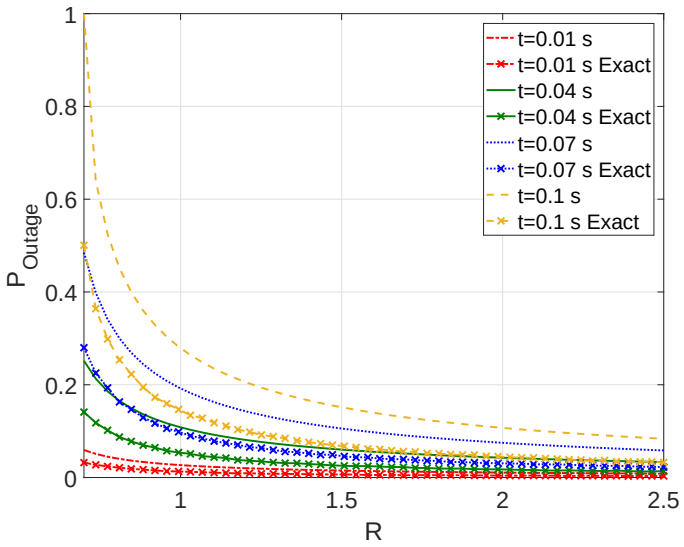

Figure 5: Impact of Source Coverage on Outage Probability for Fixed S and v_u

pre-existing locations. Here we let $S = 1\ m$ and a user velocity of $v_u = 2\ m/s$. Fig. 5 shows options of possible coverage radii R at the receiver plane. Here it is possible to select the light sources to realize desired performance. The results also show how performance is affected by different handover delays. Fig. 5 shows that with the increase in R while maintaining a low t_{HO},you get better performance in terms of outage probability.

Impact of Source Separation Distance S on Outage Probability This scenario deals with having a fixed $R = 1\ m$, assuming $v_u = 2\ m/s$ and trying to find how to place your lights to achieve the outage probability that you can tolerate. Fig. 6 shows the relationship among the parameters and the outage probability; by increasing S, the outage probability increases but when the handover time t_{HO} decreases, the performance quality increases.

Impact of Handover Time t_{HO} on Outage Probability This case constrains room dimensions. Here we assume that the sources are in place and we seek a bound on the performance of the system, allowing study of how to optimize the handover delay based on the required performance. Fig. 7 shows, for a fixed $R = 1\ m$ and $S = 0.5\ m$, how the handover delay and user velocity play an important role in deciding how the system will perform. Of course, the lower your handover time or the lower the user velocity, the lower your outage probability.

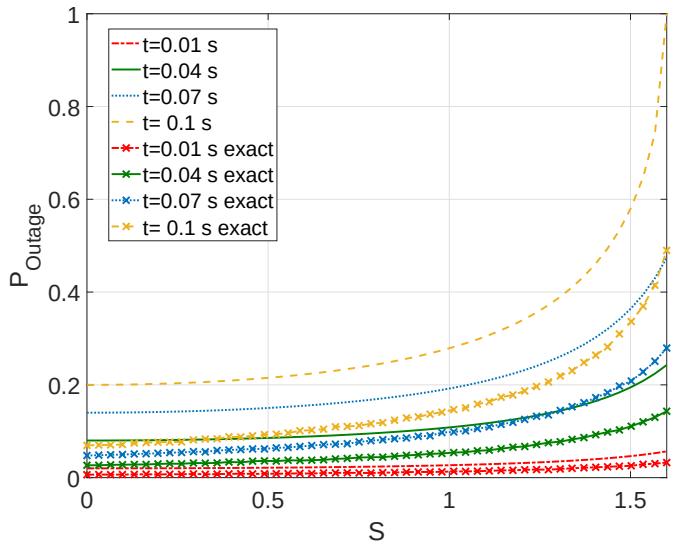

Figure 6: Impact of Source Separation Distance on Outage Probability for Fixed R and v_u

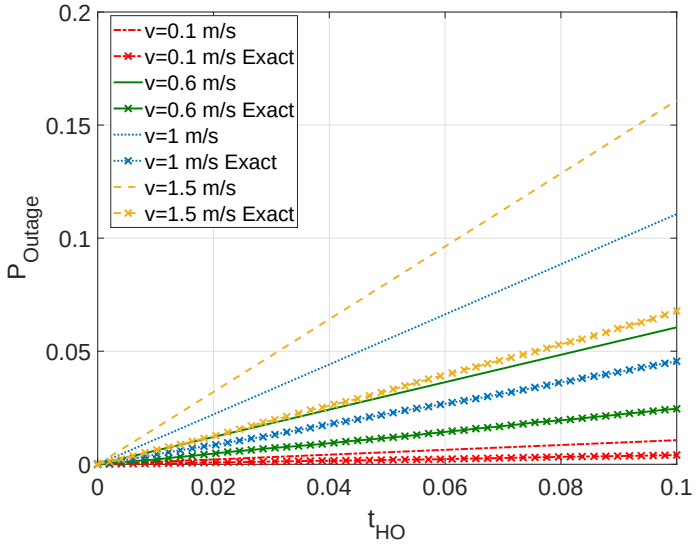

Figure 7: Impact of Handover Time on Outage Probability for Fixed R and S

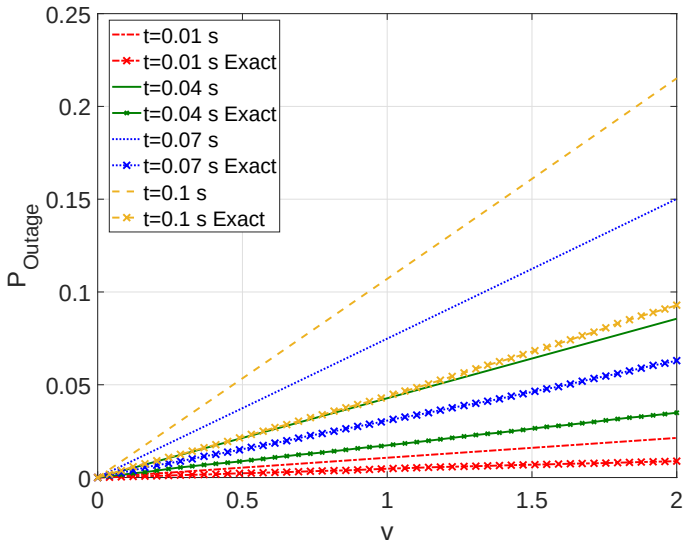

Figure 8: Impact of User Velocity on Outage Probability for Fixed R and S

Impact of user velocity v_u on Outage Probability This case follows from the case above ($R = 1\ m$ and $S = 0.5\ m$) and is just to show that the impact of user velocity is close to the impact of handover time, confirming that the lower the user velocity, the lower the outage probability.

Exact Versus Upper Bound Figures [5 - 8] show that the upper bound is tight at lower handover times or lower velocities and then the higher t_{HO} or v_u get the more the bound becomes loose.

5 Conclusion

Optical wireless access points using the visible spectrum have the promise of providing both lighting and dense networking. Lighting requirements usually dictate providing a mix of broad, glare-free light and direct, line-of-sight spot lighting, which are not ideal for VLC. Dual-use systems must reconcile these requirements in overall system design and operation as both the lighting and user mobility are considered, especially when devices move through the lighting field.

In this paper, we investigated the impact of device mobility in a dual-use system with a focus on data outage probability due to lighting design parameters. We develop a probabilistic model that provides an exact outage probability and derive a closed form upper bound on outage probability under the constraint of outage-free zones. The models are used to show how design parameters affect system performance and illustrate tradeoffs for dual-use

VLC system and lighting designers.

References

[1] D. Evans, "The internet of things how the next evolution of the internet is changing everything," Jan 2011.

[2] M. B. Rahaim and T. D. C. Little, "Toward practical integration of dual-use VLC within 5G networks," *IEEE Wireless Communications*, vol. 22, no. 4, pp. 97–103, Aug 2015. [Online]. Available: https://doi.org/10.1109/MWC.2015.7224733

[3] M. B. Rahaim, J. Morrison, and T. D. C. Little, "Beam control for indoor FSO and dynamic dual-use VLC lighting systems," *Journal of Communications and Information Networks*, vol. 2, no. 4, pp. 11–27, 2017. [Online]. Available: https://doi.org/10.1007/s41650-017-0041-7

[4] T. D. C. Little, M. B. Rahaim, I. Abdalla, L. E. W., R. Mcallister, and A. M. Vegni, "A multi-cell lighting testbed for VLC and VLP," in *2018 Global LIFI Congress (GLC)*, Feb 2018, pp. 1–6. [Online]. Available: https://doi.org/10.23919/GLC.2018.8319111

[5] A. Vavoulas, H. G. Sandalidis, T. A. Tsiftsis, and N. Vaiopoulos, "Coverage aspects of indoor VLC networks," *J. Lightwave Technol.*, vol. 33, no. 23, pp. 4915–4921, Dec 2015. [Online]. Available: http://jlt.osa.org/abstract.cfm?URI=jlt-33-23-4915

[6] I. Miya and Y. Kajikawa, "Base station layout support system for indoor visible light communication," in *2010 10th International Symposium on Communications and Information Technologies*, Oct 2010, pp. 661–666.

[7] J.-H. Liu, Q. Li, and X.-Y. Zhang, "Cellular coverage optimization for indoor visible light communication and illumination networks," *Journal of Communications*, vol. 9, no. 11, pp. 891–898, November 2014.

[8] A. M. Vegni and T. D. C. Little, "Handover in VLC systems with cooperating mobile devices," in *2012 International Conference on Computing, Networking and Communications (ICNC)*, Jan 2012, pp. 126–130. [Online]. Available: https://doi.org/10.1109/ICCNC.2012.6167395

[9] M. Emmelmann, "Influence of velocity on the handover delay associated with a radio-signal-measurement-based handover decision," in *VTC-2005-Fall. 2005 IEEE 62nd Vehicular Technology Conference, 2005.*, vol. 4, Sept 2005, pp. 2282–2286.