

Impact of Receiver FOV and Orientation on Dense Optical Networks

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Abstract—As the technical feasibility of indoor Optical Wireless Communications becomes established, a variety of new system challenges emerge in the quest for higher and denser data rates when employing lighting, or luminaires, for VLC. Supporting device mobility is one such challenge wherein a mobile device equipped with an optical receiver will transit a field of optical access points (APs) and will require one or more handovers between APs. Of course, the nature of the handovers is dependent on the behavior of the user and the design constraints for the placement of the luminaires/APs within the indoor space.

In this paper we focus on modeling a parameterized system for studying the handover performance for mobile users with different receiver characteristics including field of view (FOV) and orientation with respect to overhead APs. Results indicate the utility of our system models for characterizing handover performance for a reference indoor space and AP placement. We also describe several handover strategies providing performance gains in terms of reducing the number and frequency of handovers for a user in the system. Lastly, we show the linkage between a wide FOV and a narrow FOV in terms of optimizing system performance. In the future we expect to drive simulations based on representative mobility behavior derived from empirical models of user behavior in an indoor space.

Index Terms—LiFi, multi-cell lighting, visible light communications, handover, testbeds

I. INTRODUCTION

Visible Light Communication (VLC) is a promising technology to realize new capacity in wireless networks. The increasing data demand coupled with the scarcity of RF spectrum resources motivates the exploration of under-utilized spectrum resources such as visible light, millimeter wave, and infrared. With the advancement in solid state lighting, Light Emitting Diodes (LEDs) are considered a satisfactory option for signal modulation that is cost effective and eye-safe. Illumination-grade LEDs can be combined in luminaires in various combinations to meet different lighting needs. For example to deliver 300–500 lux at table-top in indoor office lighting. These levels also satisfy delivery of signals at high SNR [1]. Most importantly, VLC does not interfere with existing RF systems. This means that VLC/RF hybrid systems are capable of achieving very high aggregate data rates [2]. We expect in the near future to have indoor areas covered with VLC APs that will utilize the lights in a room for dual use

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(illumination and communication) through specialized drivers to these light sources [3].

With the increase in use of wireless devices and increased data demand, it is reasonable to assume scenarios emerging that require very high density of small cells to provide coverage for the users occupying a room [4], [5]. Having many VLC small cells will help in offloading crowded WiFi traffic and improving the aggregated system throughput, but not without some challenges. These include interference between cells, fast handovers, and blockage. All of which depend on a variety of system parameters – how design a room, how you space the lighting sources, where a receiver lies within the room and its FOV, just to mention a few.



Fig. 1: Testbed Comprised of 3x5 Lighting Array Using VLC-Enabled Commercial Lighting

Most previous work in the literature studying mobility in VLC systems does not study the effect of orientation, which is crucial to understanding how the system will behave in a practical deployment. In [6], the authors consider mobility and handover overheads through solving a load balancing problem by introducing the college admission model in a matching theory, while in [7], the authors study load balancing in a hybrid Light-Fidelity (Li-Fi)/Wireless Fidelity (Wi-Fi) network taking into account user mobility and handover signaling overheads. In [8], the authors propose two soft handover schemes, one power-based and the other frequency-based to improve the performance of users at cell boundaries. However in the papers mentioned above, the effect of receiver orientation are not addressed. In [9], the authors study the effects of receiver orientation and location on the performance of a wearable VLC device; they analyze their system performance through outage probability and discuss a relation between the impact of receiver orientation and data rates. In our paper, we

investigate how user mobility, receiver FOV and orientation affect the received signal strength (RSS) and use the resulting SNR profile to perform a handover analysis, and suggest new handover algorithms that show how the variables in the system come in to play to change the handover algorithm output.

The remainder of the paper is organized as follows. Section II describes our system model and the testbed we use to measure data. Section III explores our simulation results for selected handover algorithms. Section IV discusses the orientation and FOV effects. Section V concludes the paper.

II. SYSTEM MODEL

A. Testbed Configuration

Our testbed at Boston University (Fig. 1) contains a 3×5 grid of off-the-shelf CREE luminaires (#CR22-32L-35K-S) with dimensions of $46 \text{ cm} \times 24 \text{ cm}$. The grid dimensions are $427 \text{ cm} \times 162 \text{ cm}$ ($x \times y$). The luminaires are positioned from the center with increments of 0.7 m in the x -axis and 0.5 m in the y -axis at a height of 2.1 m from the floor.

Our optical receiver is an avalanche photodiode (ThorLabs unit (#APD120A2)) positioned on a servo so that we may dynamically alter its elevation angle between the following set of fixed values $\{45^\circ, 60^\circ, 75^\circ, 90^\circ\}$. We also employ a lens tube of internal diameter measured to be 25.64 mm with a length of 33.5 mm . When mounted on the receiver surface, the lens tube changes the FOV from 90° to 20.89° . The presence or absence of the tube allows exploration of wide vs. narrow FOV settings. We use no lens in this particular study, therefore, the optical gain of the lens tube is 1.

We are interested in measuring RSS at many points in our grid to fully analyze the system and validate our model. We fix the receiver's height at 0.63 m from the floor and carry out our experiments for 8 points along the y -axis and 18 points along the x -axis for all angle tilts and both FOVs mentioned above.

We use four Universal Software Radio Peripherals (USRPs) to uniquely control the 15 luminaires. Modulation is achieved by a custom flowgraph using the GNURadio (software-radio toolkit [10]) to transmit sinusoids of unique frequency for each transmitter in order to distinguish between signals. The sinusoids range from 100 kHz to 800 kHz with 50 kHz difference between adjacent signals. At the receive side, the photodiode is connected to another USRP which realizes a flowgraph to capture the RSS measurements.

B. Channel Model

Our system model depends on many parameters that relate to its surroundings including our lab dimensions, the location of the light sources, the distances between the sources, light intensity, the vertical distance between the transmitter and receiver, and the ambient light conditions. We employ black curtains around our test space to mitigate ambient light inputs, minimize reflections, and to allow for repeatability of our results.

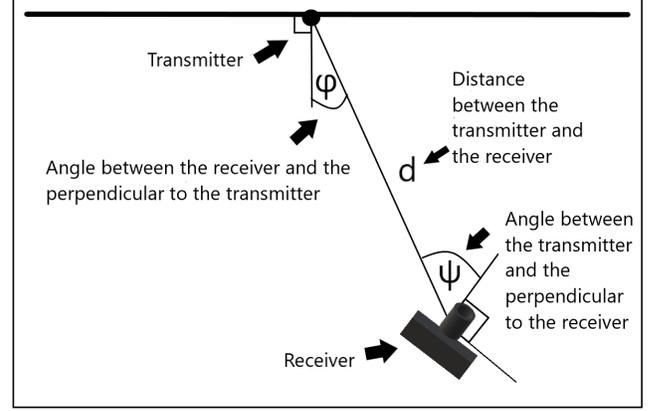


Fig. 2: Device Orientation

The Line of Sight (LOS) optical channel DC gain [11] is defined

$$H_{DC}(\phi_i, \psi_i, d_i) = \frac{P_r^{(i)}}{P_t^{(i)}} = \frac{G_T(\phi_i)G_R(\psi_i)}{d_i^2}, \quad (1)$$

where $P_t^{(i)}$ and $P_r^{(i)}$ are the power transmitted and received from the i -th transmitter, respectively. The transmitter gain (i.e., G_T) and the receiver gain (i.e., G_R) are defined

$$G_T(\phi) = \frac{m+1}{2\pi} \cos^m(\phi) \quad (2)$$

and

$$G_R(\psi) = \begin{cases} A \cos(\psi) & \psi < \Psi_C \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

respectively. We model a Lambertian emission with order m and use a photodetector with area A and no filter or optical lens. Ψ_C is the receiver's FOV, while ϕ_i is the angle between the receiver and the line perpendicular to the transmitter, ψ_i is the angle between the transmitter and the perpendicular line to the receiver, and d_i is the distance between the receiver and the i -th transmitter, as is shown in Fig. 2. While most available works make the simplifying assumption that $\phi = \psi$, we believe it is crucial to explore the effect of orientation on the quality of communication and will not be equating them.

We consider signal transmission via Intensity Modulation with Direct Detection (IM/DD). Considering the conversion between the electrical and optical domains, the amplitudes of the received $A_y^{(i)}$ and transmitted $A_x^{(i)}$ electrical signals are related as follows:

$$\frac{A_y^{(i)}}{A_x^{(i)}} = \begin{cases} \frac{C_T C_R (m+1)}{2\pi d_i^2} \cos^m(\phi_i) \cos(\psi_i) & \psi < \Psi_C \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

where C_T and C_R are the proportionality constants that account for the fixed parameters within the system that relate to the transmitter and receiver gains. We observe the electrical power from each of the unique frequency sinusoidal signals

in order to calculate amplitude and, accordingly, the peak-peak optical power. We can directly relate the received optical power to the received amplitude as optical power is directly proportional to current in the optical domain. It is worth noting that our model can accommodate different settings, the lab model is just an operating point.

C. Metrics/Conditions

There are many metrics to consider; however, in this paper we focus on the problem of providing continuous connectivity for a user walking in a room, while maintaining a lower bound on bit error rate (BER) and trying to reduce the number of handovers experienced. It is favorable to minimize number of handovers in a system while ensuring a required quality of service, as handovers usually introduce delays, can cause toggling effects and affect the overall system performance. The metrics we analyze are Total number of Handovers (THO) which is the sum of vertical (VHO) and Horizontal Handovers (HHO). A VHO happens when the VLC system cannot provide the minimum SNR needed to attain the desired BER and so the user is switched to the RF system, meanwhile HHO is triggered between VLC APs based on your location/orientation. We also calculate the average rate for our user to monitor how each algorithm's reduction of THO affects it and what tradeoffs occur. For average rate, we discretize the path that the user takes, get the instantaneous rate through Eqn. (7) and then get the average of all the points evaluated.

We modulate our signal using On-Off-Keying (OOK); the Signal to Noise Ratio (SNR) is calculated using:

$$\text{SNR} = \frac{\text{SignalPower}}{\text{NoisePower}} = \frac{(RP_t H_{DC})^2}{N_0 B} \quad (5)$$

where R is the responsivity of the receiver, N_0 is the noise power spectral density and B is the receiver bandwidth. We are able to measure noise variance in the lab when we are not transmitting, dividing our measurement by B we realize N_0 (values in Table I). For OOK, the BER is defined as

$$\text{BER} = Q(\sqrt{\text{SNR}}) \quad (6)$$

Using the previous equations, we are then able to evaluate a minimum SNR threshold that maintains the desired BER using OOK.

In a more general sense, we evaluate the achievable rate as

$$R = B \log(1 + \text{SNR}) \quad (7)$$

D. Model vs. Data

The main difference between the model and the system is that the model assumes a point source, while our actual sources were rectangular luminaires. In our error analysis shown in Fig. 3 and 4, which show the CDF of the absolute error between the simulated and measured optical power, it is clear that in spite of this assumption, the data and the model follow the same trend with negligible error.

Based on our confidence in the model, we are able to simulate different scenarios and handover algorithms and test

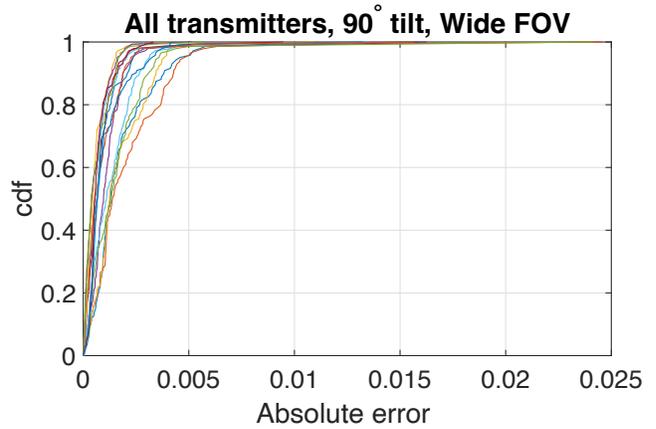


Fig. 3: CDF of Absolute Error Between Simulated and Measured Received Optical Power When $FOV = 90^\circ$

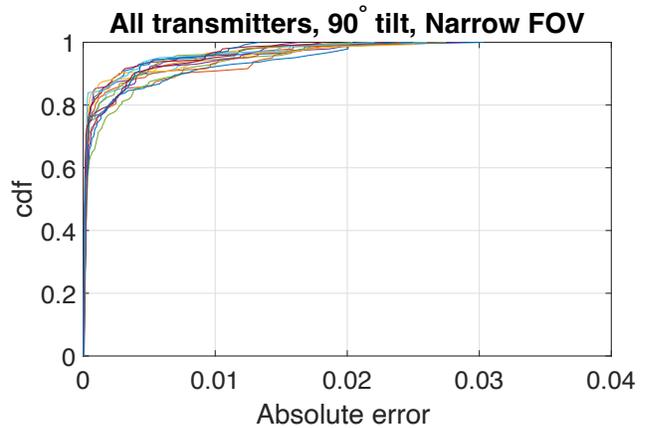


Fig. 4: CDF of Absolute Error Between Simulated and Measured Received Optical Power When $FOV = 20.89^\circ$

their performance against one another based on the metrics defined above.

III. HANDOVER ANALYSIS AND SIMULATION RESULTS

In studying handover, our objective is to have seamless connectivity while not sacrificing rate or throughput performance. Imagine the following scenario, for a person walking through a room, in this case our lab. What is the nature of RSS for a user carried device? What if the device is tilted, and how does the FOV of the device impact performance?

Motivated by this scenario, we answer most of these questions with Fig. 5 which shows the SNR of received signals from the single transmitter no. 8 in our lab for different tilts and compares the wide FOV (top) to the narrow FOV (bottom). Of course with the RSS from all of the 15 transmitters, we will get many combinations of possible handovers based on all the possible curves due to tilt, FOV and location. This highlights the impact of orientation and FOV and how strongly they affect the seamlessness of the user connectivity and play a key role in analyzing handover schemes.

TABLE I: Simulation Parameters

BER threshold	10^{-3}
B	5×10^7
N_o without lens tube	1.25×10^{-11}
$C_T C_R$	1.4
N_o with lens tube	3.75×10^{-12}
Frequency	100 kHz

Next, we propose two handover algorithms and compare them with a traditional 'connect to the maximum RSS' algorithm (we refer to this as Max algorithm) and see how these algorithms reduce number of handovers and affect the user average rate. We will see the impact of FOV and orientation with just three algorithms. Since we are mainly interested in assessing that impact, for now we assume negligible handover delay and will analyze delay in future work. We tested the following algorithms:

- **Max algorithm:** is an RSS based algorithm where the receiver is always trying to connect to the strongest signal it can detect. It serves as our baseline scheme wherein we expect a lot of handovers because the algorithm only cares about following the envelope of the SNR profile.
- **Hold algorithm:** is an RSS based thresholding algorithm where the receiver tries to keep connected to the access point (AP) that it is connected to for as long as it can while the received signal is greater than the threshold constraint. Then when the received signal is about to go below the threshold it connects to the highest signal detected and holds on to it in the manner mentioned above.
- **Best Next algorithm:** is a predictive algorithm in which the receiver compares the past SNR value with the present, predicting the slope of measured SNR changes. The handover is executed when the receiver finds an increasing slope.

Note that different thresholds generate different handover outputs. For both, Hold and Best Next, if a low threshold is imposed on a system, one can expect fewer handovers because you can connect to the same transmitter for a longer time as long as it can provide the needed quality of service. Meanwhile, if the threshold is high, the system will keep trying to provide the BER requirement and may need to produce more handovers and of course might end up not able to support the required threshold. The BER threshold we considered along with our simulation parameters are given in Table I. In the table, we also show that for the simulations, we normalized the $C_T C_R$ values we used to the $C_T C_R$ of one of the luminaires due to an artifact of the CREE luminaires that they have a frequency response that decreases as frequency increases.

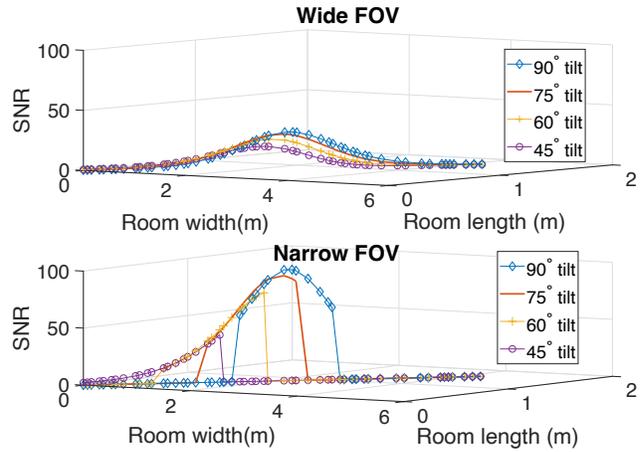


Fig. 5: SNR Profile from Tx no. 8 for Different Tilts and FOVs

TABLE II: Diagonal Scenario at FOV = 20.89°

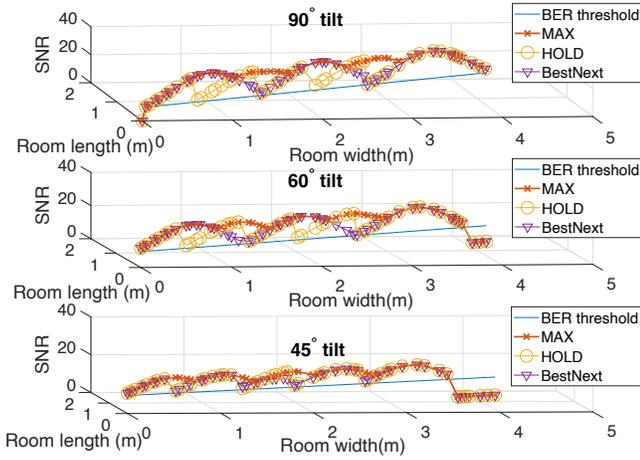
	Tilt (°)	Average rate (Mbps)	THO	VHO
Max	90	193.87	8	2
Hold	90	192.04	6	2
BestNext	90	190.1	6	2
Max	60	164.81	7	1
Hold	60	139.86	3	1
BestNext	60	139.19	3	1
Max	45	125.94	7	1
Hold	45	114.71	4	1
BestNext	45	114.04	4	1

In Figures 6a and 6b, we show how designing algorithms can exploit what we saw in Fig.5 by highlighting the performances of the three algorithms mentioned above.

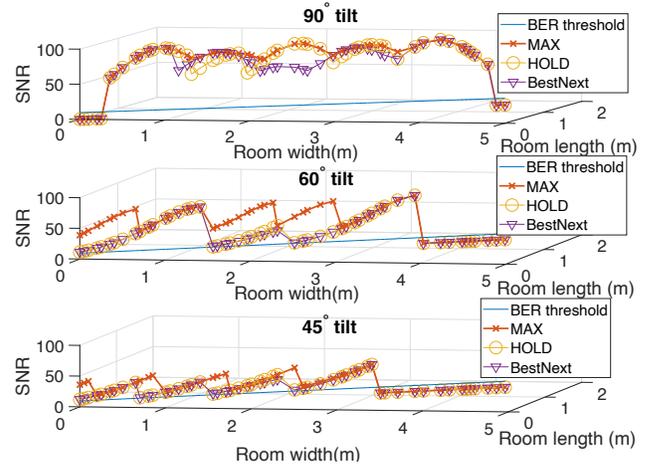
Tables II and III show how each algorithm performs in terms of the metrics we study for different tilts and FOV for the scenarios of Fig. 6b and 6a respectively. Table IV shows the results for a random walk case where we simulate a receiver that moves in a random walk pattern for 1,000 steps within the lab. We notice from the numerous results generated that BestNext outperforms the other two techniques when the receiver elevation angle is 90° in terms of fewest number

TABLE III: For the Diagonal Scenario at FOV = 90°

	Tilt (°)	Average rate (Mbps)	THO	VHO
Max	90	157.35	7	1
Hold	90	146.35	5	1
BestNext	90	149.69	3	1
Max	60	143.5	7	1
Hold	60	135.56	5	1
BestNext	60	136.85	3	1
Max	45	122.75	7	1
Hold	45	119.41	5	1
BestNext	45	119.04	5	1



(a) Handover Algorithm Outputs for Different Tilts When Entering the Room From the Right and Walking a Diagonal, for $FOV = 90^\circ$



(b) Handover Algorithm Outputs for Different Tilts When Entering the Room From the Right and Walking a Diagonal, for $FOV = 20.89^\circ$

TABLE IV: For the a Random Walk Scenario at $FOV = 90^\circ$

	Tilt ($^\circ$)	Average rate (Mbps)	THO	VHO
Max	90	155.32	100	7
Hold	90	147.94	14	7
BestNext	90	148.68	12	7
Max	60	130.6	122	24
Hold	60	126.08	36	24
BestNext	60	124.72	41	24
Max	45	106.89	98	10
Hold	45	104.5	19	10
BestNext	45	104.5	19	10

of handovers while maintaining a reasonable average rate for the user. In comparison, BestNext is based on following the highest slope when connectivity is about to be lost, so with a smaller FOV the curve is no longer the full lambertian and so there are no guarantees that it will outperform Hold. But it still performs better than the Max algorithm in terms of number of handovers. Overall, Max is always better in terms of average rate but is mostly worst in terms of number of handovers. The superior performance of Hold and BestNext depend on the FOV and the tilt of the receiver. However, when the receiver is directly underneath the luminaires, they tend to give almost the same performance.

IV. ORIENTATION AND FOV EFFECTS

1) *The FOV Effect:* Our data and simulation results validate many ideas we expected, specifically:

- If the device is stationary and the receiver is at a good angle of reception, having a smaller FOV is an advantage and provides better signal quality.
- If the device is moving, a wider FOV allows detection of more signals and potential connections, and thus will have fewer holes in connectivity.

The use of a lens tube decreases the noise floor and therefore increases signal quality; but also increases the potential for holes in connectivity. Removing the tube

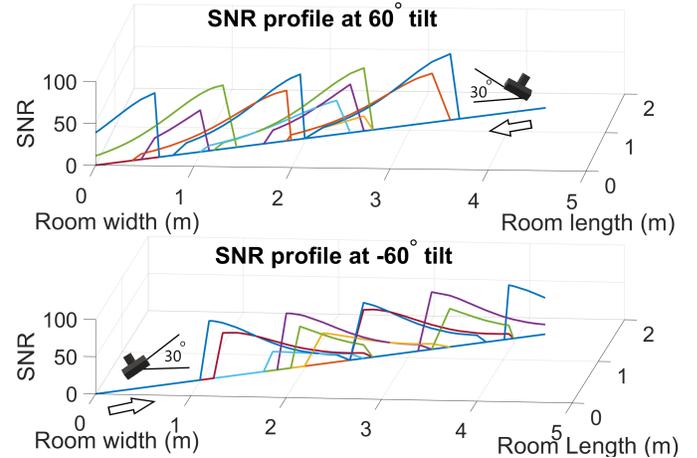


Fig. 7: Effect of Orientation on SNR Profile

provides better connectivity but lower overall SNR.

2) *The Orientation Effect:* In RF-only networks we do not face the same challenges concerning orientation; however, one point worth mentioning in the VLC scenario is an illustration of how the SNR profile is different on entering a room from different directions. For example, Fig. 7 illustrates a diagonal transit of the working space in the lab. The figure shows the SNR profile for mobility with a 60° (30° away from the horizontal surface) tilted device, with narrow FOV, entering the room from different sides and walking diagonally across the room. The resultant handover output for the two scenarios are quite different due to direction of transit and the opposing orientations of the receiver.

We also notice that angular changes can trigger handovers depending on their severity. While conventional omnidirectional systems have VHOs and HHOs due to translational

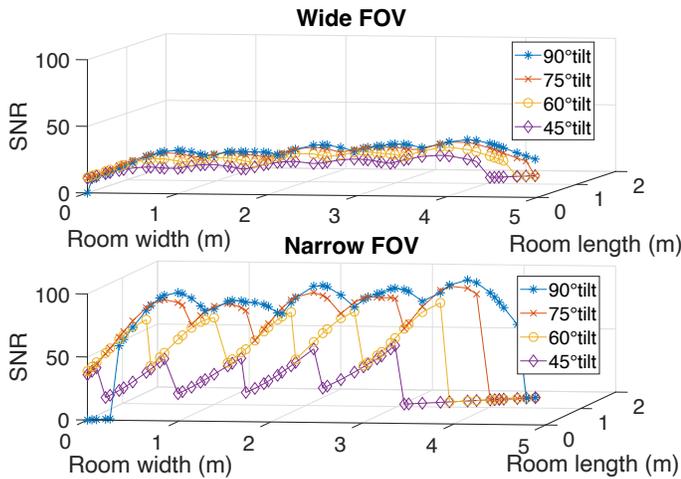


Fig. 8: Max Algorithm for Different Tilts

motion, orientation in directional systems can cause an angular handover that can trigger VHOs and HHOs due to rotational motion depending on the surrounding SNR values and the SNR threshold required.

Figure 8 shows the effect of different tilts on the output of the Max algorithm and shows how the receiver FOV impacts the user device SNR.

V. CONCLUSION

Visible light communications is now an established technology for providing indoor optical wireless access and has the potential to support very dense placement of access points for servicing mobile devices. In this paper we investigate the parameters impacting system performance in a dense network of VLC access points including receiver orientation and field of view. We develop a system model to characterize and simulate an indoor space. In a set of experiments using the model, we establish how the FOV impacts the design of handover techniques necessary to ensure seamless communication as a mobile device transits through the lighting array. In particular, the benefits of a wide FOV are the ability for a receiver to identify upcoming APs during mobility; and the advantages of a narrow FOV are when a receiver is static or quasi-static. Our model has been validated against a physical testbed and is sufficiently general to characterize a variety of indoor space specifications. We anticipate performing additional work to optimize handover techniques addressing latency, buffering, and system signal blockage.

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