# SINR Analysis and Cell Zooming with Constant Illumination for Indoor VLC Networks

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***Abstract*—Visible Light Communication offers potential for dual purpose devices providing both wireless data and illumination; however much of the early research in the area has focused primarily on link capacity. In this work, an RF cell zooming method is adapted for VLC such that the additional requirement of constant illumination is met. This method has the potential to improve traffic distribution in multi-user environments and handover at cell edges when considering mobile users. SINR is observed and analyzed in a range of scenarios to show coverage variability when transmitters are capable of dynamically changing their signal power.**

## I. Introduction

Rapid growth in demand for wireless data transmission and ubiquitous network connectivity along with recent developments in solid state lighting and the availability of lighting devices in indoor environments have created an intersection between the wireless communications and commercial lighting industries. Visible Light Communication (VLC) offers a potential for dual use systems providing high data rate wireless connectivity and fully functional luminaire capabilities. There is a large body of research over the past few years which focuses primarily on physical layer considerations for high data rate VLC [1], [2], [3]; however the field has only recently begun observing the data link and network layers which will be necessary in order to fully integrate VLC systems. In addition to these considerations for wireless network connectivity, dual purpose VLC devices have the primary lighting requirement of providing a desired illumination in the environment.

When developing a VLC system as a network of VLC cells,[1] there are many concepts that overlap with RF cellular networks. The primary focus of this paper relates to a) layout of Access Points (APs) in VLC networks, b) traffic distribution in multi-user environments, and c) handover as mobile users traverse the environment. The concept of cell zooming has previously been proposed as a method for traffic distribution amongst RF cell towers with the objective of dynamically changing the coverage area of each cell in order to distribute user traffic amongst Base Stations (BSs) [4]. In VLC networks, a similar method can be utilized in order to distribute traffic amongst APs; however the lighting constraint in dual-use VLC systems requires that the radiation pattern and average optical output power from sources remain constant in order to provide the desired illumination. Under the assumption that output from each luminaire consists of a DC optical power, $P_{DC}$, and an average optical signal power, $P_{\text{Sig}}$, it is possible to dynamically change an AP's coverage region and improve the Signal to Interference plus Noise Ratio (SINR) at cell edges by varying the modulation depth of the signal while maintaining the average optical output power from each luminaire. Interference can be mitigated via time, code, or frequency separation of neighboring cells [5]; however it is preferable to utilize spatial separation and maximize spectrum available for devices associated with each cell.

[1]A VLC cell is defined as the area below the AP where SNR or SINR is above the required value for a specified bandwidth, bit error rate, and user range of rotation as described in Section II.

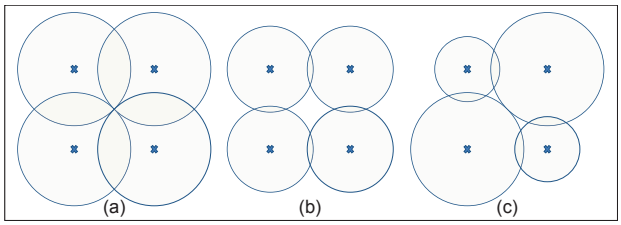


Fig. 1. Cell zooming scenarios for a conventional lighting grid.

Fig. 1 illustrates scenarios where cell zooming has the potential to improve performance based on aggregate capacity, or bandwidth density ($b/s/m^2$). The default scenario in Fig. 1 ($a$) utilizes full signal power from each AP and provides coverage throughout the environment; however the overlapping regions (cell edges) have high interference from neighboring cells. In Fig. 1 ($b$), cells reduce their signal power in order to "zoom in" and decrease interference at neighboring cells; however there is no longer continuous coverage between cells. Fig. 1 ($c$) shows a scenario where some cells zoom in and other cells zoom out in order to distribute traffic amongst APs. This can prove beneficial if many users are congregated below a specific cell or if a power user is utilizing a large portion of a cells available resources.

This work investigates the effect of system parameters on coverage and SINR. We also propose a method for VLC "Cell Zooming" that alters coverage regions of VLC APs while maintaining desired illumination. The paper is structured as follows: Section II provides an overview of VLC; including the optical communications channel, illumination constraints, and network concepts. Section III discusses cell zooming as previously proposed in the RF domain and under constraints for VLC. Section IV reviews analysis of cell zooming for VLC systems and summarizes the results. Finally, Section V provides conclusions and additional cell zooming considerations.

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## II. Overview

### A. Optical Channel

The optical wireless channel consists of an instantaneous optical signal power, $X(t)$ [W], channel gain, $H$, detector responsivity, $R$ [A/W], and white Gaussian noise component with double-sided power spectral density $N_0$ [6]. Instantaneous optical signal power has a nonnegative constraint, $X(t) \geq 0$, and is related to average optical signal power by

$$P_{\text{Sig}} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)\, dt \tag{1}$$

Average received optical power is given by $P = HP_{\text{Sig}}$ where the channel gain consists of a Line-of-Sight (LOS) and multipath component. The LOS channel gain is defined as

$$H_{\text{LOS}} = \begin{cases} \frac{A}{d^2} R_o(\phi)\, T_s(\psi)\, g(\psi) \cos(\psi), & 0 \leq \psi \leq \Psi_c \\ 0, & \psi \geq \Psi_c \end{cases} \tag{2}$$

where $A$ is the area of the photodiode, $d$ is the distance between transmitter and receiver, $\phi$ and $\psi$ are the angles of emmittance and acceptance, $\Psi_c$ is the concentrator FOV, and $R_o()$, $T_s()$, and $g()$ are the angle-dependent radiation pattern, filter transmission, and concentrator gain, respectively.

For the purpose of this analysis, a Lambertian transmission pattern with Lambertian order, $m$, is observed such that

$$R_o(\phi) = \frac{m+1}{2\pi} \cos^m(\phi) \tag{3}$$

where $m$ is related to the semiangle at half power, $\Phi_{1/2}$, by $m = -\ln 2 / \ln\left(\cos \Phi_{1/2}\right)$. The filter transmission is set to unity, $T_s(\psi) = 1$, and a non-imaging hemispherical concentrator with internal refractive index $n$ is assumed such that $g(\psi) = n^2 / \sin^2(\Psi_c)$ for $\psi \leq \Psi_c$.

The multipath channel gain, $H_{\text{multi}}$, depends on the reflectivity of surfaces in the room and the location and orientation of the transmitter and receiver relative to these surfaces. For the purpose of this analysis, an iterative site-based model is used to obtain $H_{\text{multi}}$ [7]. The LOS channel is typically the dominant source of received signal power; however interference consists primarily of signal from the multipath channels of other APs.

Given a link with bandwidth $B$, the Signal to Noise Ratio (SNR) in the electrical domain is defined[2] as

$$SNR = \frac{(RP)^2}{BN_0} = \frac{(RHP_{\text{Sig}})^2}{\sigma^2_{\text{total}}} \tag{4}$$

where $\sigma^2_{\text{total}} = \sigma^2_{\text{shot}} + \sigma^2_{\text{thermal}}$ is the total noise variance consisting of shot noise and thermal noise components. Thermal noise variance is defined in the analysis and shot noise variance is a function of the received DC noise power, $P_n$, given by

$$\sigma^2_{\text{shot}} = 2qRP_nB \tag{5}$$

Defining a cell relative to SNR and maximum rotation, $\theta_{\text{max}}$, requires that every position in the cell meets the desired SNR value for all elevation angles, $0 \leq \theta_{\text{el}} \leq \theta_{\text{max}}$, and azimuth angles, $0 \leq \theta_{\text{az}} \leq 2\pi$. Note that a fixed position receiver will have minimum SNR when it is rotated away from the transmitter ($\psi = \phi + \theta_{\text{max}}$) if only the LOS channel is considered. This assumption does not necessarily hold when including the multipath component.

[2]This is not the conventional SNR definition ($\varepsilon_b/N_0$), as indicated in [6].

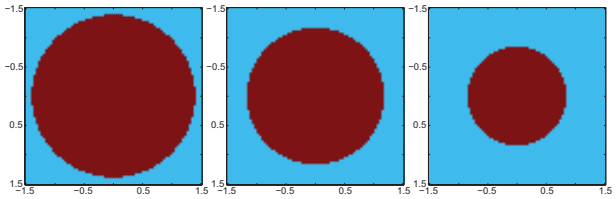

Fig. 2. Coverage regions for a 3m x 3m plane at 2m distance for requirements of $BER \leq 10^{-6}$, $B = 40$MHz, $\theta_{\text{max}} = 10°$, and signal power of 10W (*left*), 8W (*center*), and 6W (*right*).

Considering a channel with NRZ On-Off Keying (OOK) modulation, bit-error rate (BER) of the channel is defined as $BER = Q\left(\sqrt{SNR}\right)$ where $Q()$ is the tail probability of the standard normal distribution. Given fixed requirements for $(B, BER, \theta_{\text{max}})$, the overall coverage at a plane below the transmitter varies dependent on the signal power as shown in Fig. 2. In this case, total noise variance is assumed to be a constant, $\sigma^2_{\text{total}} = 5 \cdot 10^{-15}$. The coverage area will also vary as the receiver moves towards or away from the receiver plane; however for the purpose of this analysis a fixed plane is assumed. Variation in location on the X and Y planes will typically be larger than that in the Z plane.

### B. Illumination

Illumination from a VLC device is based on its average optical output power,

$$P_{\text{ave},i} = P_{\text{DC},i} + P_{\text{Sig},i} \tag{6}$$

where $i$ represents the specified AP. The surface irradiance [W/m$^2$] at the receiver plane is defined as

$$I_{\text{rad},i} = \frac{P_{\text{ave},i} T(\phi) \cos(\phi)}{d^2} \tag{7}$$

where $\phi$ is used in the cosine function because the surface is parallel to the transmit plane and APs are assumed to be pointing downwards. Reflected light is ignored in the irradiance calculation since the LOS path is the dominant source. The sum of all irradiance values are used to calculate surface illuminance (lum/m$^2$ or lux), defined as

$$I_{\text{lux}} = \left(\sum_i I_{\text{rad},i}\right) \cdot 683 \frac{\text{lum}}{\text{W}} \int_{380\text{nm}}^{720\text{nm}} S(\lambda)\, V(\lambda)\, d\lambda \tag{8}$$

where $S(\lambda)$ is the spectral power distribution (SPD) of the source and $V(\lambda)$ is the eye sensitivity function. The desired illuminance at a working surface is typically 400 lux.

### C. Network Considerations

Since the primary benefit of VLC is spatial reuse leading to improved bandwidth density, it is important to consider the interaction between various VLC channels in a network with many VLC APs. Interference can be mitigated in scenarios where diversity receivers or imaging receivers isolate individual channels [8]; however the optics required for such isolation

can be cost prohibitive and channel selection increases the complexity of the receiver design. In a conventional VLC network with devices utilizing non-imaging architecture, interference between devices becomes more prevelant. SINR is the relative metric of interest when considering simultaneous use of resources at nearby APs and is defined as

$$SINR = \frac{(RHP_{\text{Sig},x})^2}{\left(R\sum_{i\neq x} H_i P_{\text{Sig},i}\right)^2 + \sigma^2_{\text{total}}} \quad (9)$$

where $x$ represents the associated AP and $H_i P_{\text{Sig},i}$ is the average received power from the $i$th interfering AP [5]. Similar to the calculations for SNR, a minimum SINR must be achieved corresponding to the modulation scheme in order to decode the signal with a minimum desired BER [5].

System layout and receiver FOV must also be considered to provide the best coverage in a network of VLC APs. Ideally, a single AP will be in the receiver FOV at all times in order to minimize interference; however, the FOV should also be large enough that a LOS path is available to a receiver at the center of four APs. Placing the same receiver directed upwards in the center of two neighboring APs will put both APs in its FOV, which implies that providing full coverage from a grid of VLC enabled luminaires requires overlapping coverage regions.

The problem can be mitigated by using frequency partitioning as shown in Fig. 3. Available bandwidth is divided into $K$ slots[3] and neighboring cells utilize separate frequencies to eliminate interference at overlapping regions. When $K = 4$, receiver FOV can be set such that an upward facing receiver has at least one AP in the FOV at all locations and two interfering APs will never be in the LOS of the receiver at the same time. If there are no interfering APs with a LOS path, the dominant interference signal comes from the multipath channels. Essentially, optimal SINR[4] at any location in an environment can be catagorized by the three scenarios[5] described below. These scenarios are shown[6] in Figs. 4 and 5 and are discussed in Section IV.

- **LOS, Multipath:** In the case where a LOS signal exists without any interferers in the receiver FOV, signal power is generally orders of magnitude larger than interference power - equating to high SINR.
- **Multipath, Multipath:** When no LOS signal exists, the numerator in Eq. 9 is low and SINR is poor.
- **LOS, LOS:** When signal and interferer are both LOS, the denominator in Eq. 9 is high and SINR is poor.

The optimal SINR is at a minimum when the received signal power is near or lower than that of the total received power from interferers. Given a mobile receiver and fixed rotation, this generally occurs at transition regions (cell edges). When determining which channel to associate with, this is typically the region where a receiver will initiate a horizontal handover (HHO) to another AP or a vertical handover (VHO) to another media such as RF in a heterogeneous network. The ability to zoom in and out allows the network to dynamically change these handover regions as described in Section V.

[3]Ideal frequency separation is assumed such that there is no overlap in frequency and APs using different frequency slots do not interfere.

[4]Optimal SINR is defined as the SINR associated with the transmitter providing highest received optical signal power.

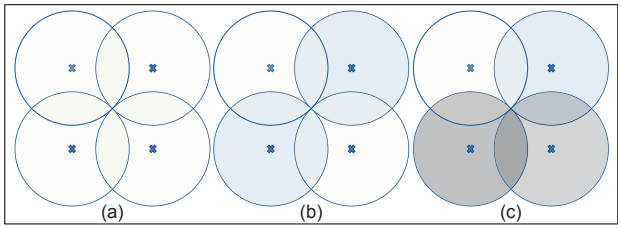


Fig. 3. Frequency partitioning of cells with a) full reuse ($K = 1$), b) two channel partitioning ($K = 2$), and c) four channel partitioning ($K = 4$).

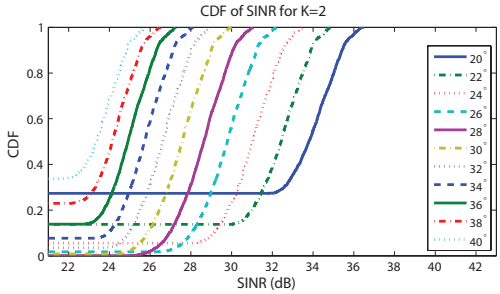


Fig. 4. CDF of SINR values at a plane 2m below the transmitters for $K = 2$ and various concentrator FOVs. When FOV $= 28°$, nearly 100% of the plane has SINR above 25dB; however smaller FOV leads to an increasing percentage where no APs have a LOS path and larger FOV leads to an increasing percentage where interfering APs have a LOS path.

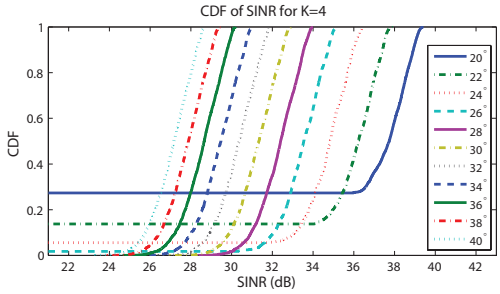


Fig. 5. CDF of SINR values at 2m below the transmitters for $K = 4$ and various concentrator FOVs. Comparing to Fig. 4, FOVs smaller than $28°$ still lead to locations without a LOS path to an AP; however FOVs larger than $28°$ do not immediately lead to locations where interfering APs have a LOS path because APs surrounding the primary are non-interfering.

## III. Cell Zooming

### A. RF Cell Zooming

In RF cellular networks, implementation of the cell zooming technique is done by either physically adjusting the antenna tilt or dynamic power adjustment of the transmit signal. Centralized and distributed algorithms have also been presented to dynamically adjust cell size according to traffic load fluctuations [4]. Since RF networks don't have the additional average power requirement of dual-use VLC systems, energy efficiency is also proposed as a cell zooming benefit considering cells that

[5]Given the definition of optimal SINR, the scenario of a multipath signal and LOS interference is invalid in most cases. The defined cases are also only relevant when noise is not the dominant factor in the denominator of Eq. 9.

[6]Values below 20dB are not shown as there is no change from 5dB to 20dB and values less than 5dB are considered non-ideal for communication.

TABLE I. SIMULATION PARAMETERS

| | | |
|---|---|---|
| Average Transmit Power | $P_{\text{ave}}$ | 5.5W |
| Luminaire Semiangle | $\Phi_{1/2}$ | $60^\circ$ |
| Bandwidth | $B$ | 40MHz |
| Photodiode Area | $A$ | $1\text{mm}^2$ |
| Concentrator FOV | $\Psi_c$ | $28^\circ$ |
| Refractive Index | $n$ | 1.5 |
| Responsivity | $R$ | 0.28 |
| Thermal Noise Variance | $\sigma^2_{\text{thermal}}$ | $10^{-15}\text{A}^2$ |

operate in a sleep mode when all devices they are supporting can be offloaded to other cells.

### B. VLC Cell Zooming

The method proposed in this analysis observes a VLC network with similar objectives to those mentioned above. As with the RF channel, VLC cell size can potentially be changed by adjusting the output power or physically changing the radiation pattern [9]; however the additional requirement of constant illumination is also considered in the method we present here. Equations 7 and 8 indicate that a constant illumination can be provided as long as $P_{\text{ave}}$ remains constant for all transmitters. Assuming the upper limit on instantaneous optical power is such that full modulation depth is available at any desired average output power, the average signal power for the $i$th device is constrained by

$$0 \leq P_{\text{Sig},i} = P_{\text{ave},i} - P_{\text{DC},i} \leq P_{\text{ave},i} \tag{10}$$

Given these constraints, $P_{\text{Sig}}$ can be selected and $P_{\text{DC}}$ can be calculated in order to maintain constant illumination. Equation 9 shows that SINR at a specified location can be improved by increasing $P_{\text{Sig},x}$ and decreasing $P_{\text{Sig}}$ of nearby transmitters. Section IV analyzes instances where doing so can potentially optimize aggregate performance.

## IV. RESULTS AND ANALYSIS

In order to show the benefit of cell zooming, we have analyzed SINR in multiple simulations with parameter values defined in Table I. Noise power, $P_n$, is approximated as the average received power from all transmitters, SPD of a cool white LED is defined for $S(\lambda)$, surface reflectivity for multipath response is set as 80%, and the receiver is assumed to be directed upwards such that $\theta_{\text{max}} = 0$. SINR is observed at a plane located 2m below the transmitters which are placed in a grid layout with devices located 1.5m apart in both the X and Y directions. Transmitter placement and average power levels are set such that illumination of 400 lux is met throughout the central portion of the room.

The first scenario demonstrates a default condition where all transmitters utilize full modulation depth for maximum signal power. Fig. 6 compares various frequency partitioning cases for the default scenario and Fig. 7 shows the SINR in the environment when $K = 2$ and $K = 4$. SINR drops below 5dB when interfering APs are in the FOV of the receiver, which can be seen in 45% of the room for the full reuse case and for a

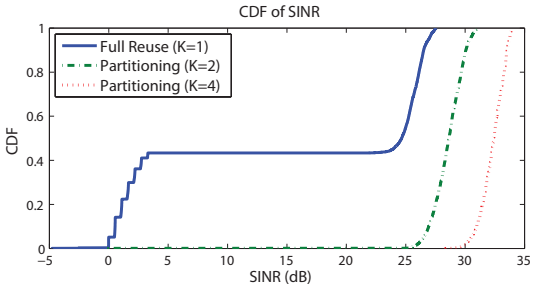


Fig. 6. SINR distribution for various frequency partitioning scenarios.

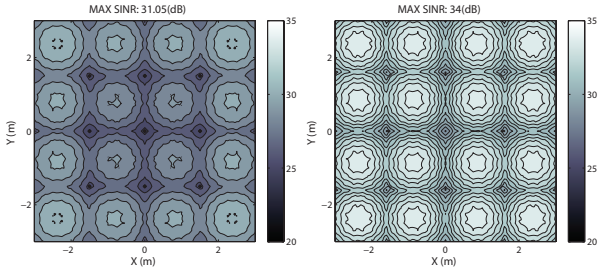


Fig. 7. SINR for the default case when $K = 2$ (*left*) and $K = 4$ (*right*).

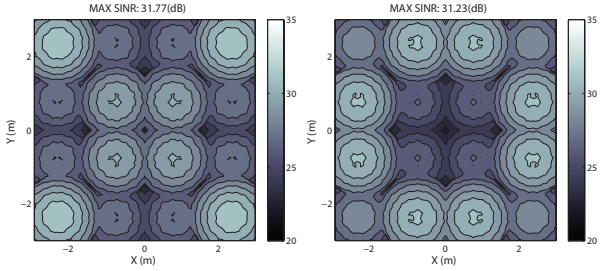


Fig. 8. Comparison of SINR for the cell zooming cases when $K = 2$.

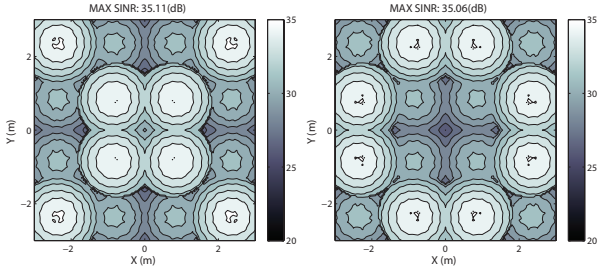


Fig. 9. Comparison of SINR for the cell zooming cases when $K = 4$.

very small percentage of the room when $K = 2$ (these values, which occur at the center points between four transmitters, are not shown in the color axis of Figures 7 and 8).

The default scenario is also observed in Figures 4 and 5 for various values of $\Psi_c$. As the FOV decreases, the concentrator gain is increased and SINR improves as long as the associated AP is in view. If the FOV is too small ($\Psi_c < 26^\circ$), some locations have no APs with a LOS channel (Multipath/Multipath scenario) and a drastic drop-off in SINR occurs because of

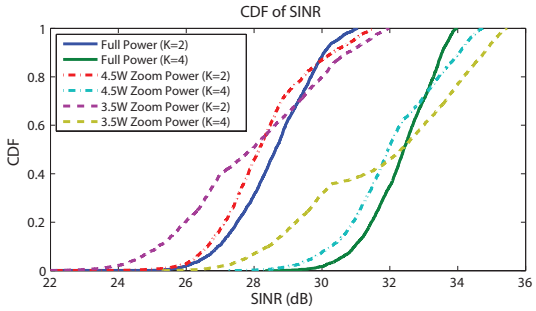


Fig. 10. Distribution of SINR values in the environment for the case where edge APs have various signal powers.

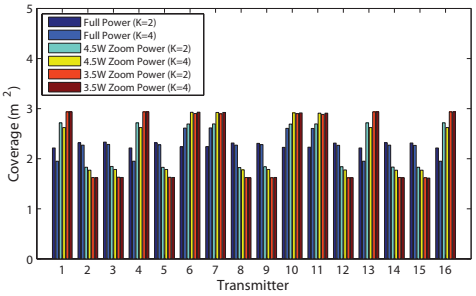


Fig. 11. Comparison of coverage per transmitter for the case where edge APs have various signal powers.

the low signal power. If the FOV is too large ($\Psi_c > 30°$ for $K = 2$), multiple APs with shared resources have a LOS channel to the receiver (LOS/LOS scenario) and the SINR drops off because average interference power is high. Although the optimal FOV for a specified plane can be determined in the system design, a similar effect occurs as you move the receiver plane either closer to or further from the transmit plane.

Figures 8 and 9 show SINR in the environment when cell zooming is used with frequency partitioning of $K = 2$ and $K = 4$, respectively. In both cases, $P_{\text{Sig}}$ is reduced to 4W at various APs to reduce their coverage regions and extend the coverage regions of other APs. In the first scenario, edge APs use reduced power such that the central and diagonal APs have larger coverage area. In the second scenario, central and diagonal APs use reduced power such that edge APs have larger coverage area. This displays how cell zooming allows the network to dynamically change the high SINR regions by updating which transmitters are sending at low signal power and which are sending at high signal power.

Figures 10 and 11 observe the case where $K = \{2, 4\}$ and the signal power of the edge APs are varied. Fig. 10 shows that SINR performance improves at some areas of the room and declines at others when signal power of select transmitters is reduced. Fig. 11 shows the coverage of each AP for the various zoom levels. When full signal power is used throughout, coverage is evenly distributed with approximately $2.2\text{m}^2$ per AP. When the signal power of edge APs is reduced to 4.5W, coverage varies from $1.8\text{m}^2$ to $2.9\text{m}^2$. When it is reduced to 3.5W, coverage varies from $1.6\text{m}^2$ to $2.9\text{m}^2$ with more APs covering $2.9\text{m}^2$. Reducing signal power at select APs improves SINR below full power APs and at cell edges while SINR directly below the reduced power APs is decreased.

## V. Conclusions

We have shown the ability to dynamically alter cell coverage regions and SINR distribution in the environment while maintaining constant illumination. This capability has two major benefits. First, traffic can be evenly distributed amongst APs by mapping the coverage regions to the spatial distribution of users. Second, increasing cell size allows a mobile user to remain associated with a cell for a longer period, minimizing overhead from handover. It is also shown that a 2W increase in signal power from neighboring APs can effect SINR by 2-3dB, therefore a user will see decreased performance if another user is associated with a neighboring AP. In a heterogeneous system, this implies that it may be beneficial for the network to initiate a VHO to transfer the second user to an alternative media or to keep a new user on the alternative media rather than transferring to an unused VLC cell.

As dual-use VLC systems are developed, it is important to consider network cooperation for environments with many users. This includes a combination of static devices and mobile users, creating a variable environment which requires dynamic distribution of resources amongst cells in order to optimally accommodate network traffic. Cell zooming provides an opportunity to rearrange cell coverage regions in the network while maintaining the illumination required by the lighting system.

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