Extending ns3 To Simulate Visible Light Communication at Network-Level

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***Abstract*—Visible light communications (VLC) describes the use of the visible spectrum for optical communications and has the potential to provide vast new wireless spectrum free from license. Most existing work on VLC focuses on the optimization of the physical medium rather than the networking context in which VLC will be deployed. Future deployments of VLC are expected to coexist with current RF technologies; complicating performance analysis of these integrated, heterogeneous systems.**

In this paper, we propose an extension of the ns3 network simulator as a means to investigate the performance of these heterogeneous RF/VLC networks. The proposed VLC module realizes physical layer models characterizing the visible spectrum mapped to various optical modulation schemes. We also consider device mobility and orientation which uniquely impact an optical receiver. We describe the adopted physical models, the structure of the ns3 model implementation, and demonstrate performance assessment for an asymmetric RF/VLC scenario. In this case, the VLC downlink and the RF (WiFi) uplink are paired using the combination of our new ns3 VLC component and existing ns3 RF modules. Simulations demonstrate how this scenario can be studied in terms of VLC SNR and BER parameters, and in the resulting network performance measured as goodput.

***Index Terms*—Visible light communication (VLC), heterogeneous networks (HetNets), network simulation, ns3.**

I. Introduction

Wireless data demand continues to grow with the adoption of mobile devices and new levels of personal media consumption, yet access to new radio spectrum is very limited and costly. Next generation wireless networks can overcome this problem through a combination of increased spectral efficiency and improved spatial reuse of this spectrum. Increasing RF spectral efficiency is costly. New techniques aim to realize diminishing gains on existing spectrum. The adoption of smaller network cells has provided some of the best recent gains on performance through network densification and spatial reuse. Nowadays 70% of mobile data traffic occurs indoors, implying a need for additional wireless capacity in indoor environments [1]. VLC is a breakout technology that has the potential to radically change the wireless landscape because it can perform well in these short-range indoor environments. VLC is unlicensed and free, supports ultra-dense deployment due to its line-of-sight property and can be combined with other network technologies such as WiFi [2]–[4]. In addition, VLC can provide both illumination and communication, immunity to interference, and highly localized emission for security purposes [5]. Due to these reasons, VLC can greatly enhance the performance of existing wireless systems.

The vast majority of VLC research to date has focused on the optimization of the physical medium. Although some initial work on the performance of hybrid RF/VLC systems has been explored [2], we have lacked robust tools to perform system performance studies that incorporate large hybrid networks involving VLC components. Current network simulators such as OPNET, ns2, ns3, OMNeT++ and NetSim have the structure to support evaluation of large scale networks; but they do not have the capability to evaluate VLC. This has motivated our work in the development of a VLC module within ns3 in order to offer an open source network-level VLC simulator.

ns3 is an open-source discrete-event network simulator that provides an open environment for network developers and researchers. The following have led us to select ns3 as the simulator in which we implement our VLC module:

- The number of ns3 users, developers, and researchers has been proliferating since 2013 [6].
- ns3 is open source and freely available for researchers interested in evaluating system level deployments.
- ns3 consists of a set of libraries and other external software libraries that can be combined together to evaluate large networks with a variety of access technologies.
- ns3 protocol entities are designed to be very close to real devices in terms of performance which allows for investigation of large networks without the need to deploy the physical system.
- ns3 mobility models can be extended to incorporate orientation, making it possible to analyze the effect of device mobility on VLC network deployments where VLC angle dependency differentiates it from RF.
- ns3 simulations support real-time schedulers that allow them to interact with real systems.

To the best of our knowledge, none of the existing work investigates large VLC deployments at or above the network layer. Shao et al. in reference [2] worked on designing and implementing a solution with a single VLC link in which the uplink challenge is resolved using an RF-VLC HetNet. References [7]–[12] study the impact of VLC deployments at the physical layer, but do not evaluate the effects of higher layer protocols. In [7] and [8], Matlab-based simulators are presented for the VLC channel. The work in [9] uses OptSim to design and simulate free-space-optical communication at signal level using only On-Off keying (OOK). In [11] and [12], indoor VLC channel simulation is done with Zemax which is a commercially-available optical and illumination design software. Ayyash et al. in reference [3] study the general coexistence of Wifi-VLC networks based system without the impact of higher layer protocols.

The advantage of our work is that we provide an openly available VLC simulator to study the impact of large-scale VLC deployments at and above the network layer.

We propose a new module, "VLC-M," as an extension of the ns3 core libraries. The module consists of classes and examples for investigating VLC-based networks. The module contains a VLC channel model, VLC mobility model, VLC helpers, and example scripts. Helpers are implemented to control large-scale VLC networks while the VLC channel and mobility models incorporate distinct characteristics of VLC. In evaluation, we present results of test scripts using various modulation schemes such as Variable Pulse Position Modulation (VPPM), Pulse Amplitude Modulation (PAM), and OOK. We evaluate the quality of data transmission through SNR, BER and goodput over an asymmetric RF/VLC link.

The rest of the paper is organized as follows: Section II presents a conceptual overview of ns3. Section III introduces our VLC channel model. The design requirements and principles of the VLC module using ns3 are in section IV. Section V provides the method for merging our module into ns3 and simulation experiments are presented in section VI. We conclude in section VII.

II. NS3 Conceptual Overview

ns3 and its predecessors realize a widely used network simulator based on discrete event simulation that has evolved over the last 20 years. ns3 is open-source under GNU GPLv2 license. ns3 is very rich; here we provide an overview of the components of ns3 and begin to illustrate how our VLC module is achieved with these abstractions.

The core abstractions within ns3 are as follows: **(1)** Node: representation of a network device (mobile terminal or access point) where different functionality can be added such as protocol stacks, peripheral cards, or mobility functions. **(2)** Net-Device: installed inside a node and acts as a peripheral card or Network Interface Card (NIC). Net-devices allow a node to use a specific channel. **(3)** Channel: represents the communication channel in which data flows between nodes. Channels connect to nodes via Net-Devices and may be used by multiple nodes. **(4)** Helpers: used to manage large networks that consist of many nodes, channels and Net-Devices. **(5)** Application: represents basic abstraction that generates some activities to be simulated. These abstractions are composed (interconnected) to realize a network instantiaton in ns3. In terms of basic function, ns3 provides models of how network packets flow and a simulation engine for users to proceed with experiments. In addition, ns3 uses utilities to analyze packet traces; one of which generates packet capture (pcap) trace files. New modules can also be added and used with the existing ns3 libraries. ns3 supports the development of new components using C++ or Python. In our work we have opted to use C++.

In order to create a new module in ns3, we use the ns3 python create-module tool (*create-module.py*), which is a script provided by ns3 to initiate a module skeleton and create directories. The VLC module skeleton and directories are shown in Figure 1. The module structure comprises six directories: model, helper, examples, test, Doc and Wscript. The **model** directory contains the source and headers files of the VLC module classes. These include VLC channel, VLC propagation loss, VLC mobility, and modulation scheme classes for error rate evaluation as a function of SNR which is dependent on the modulation and coding scheme used. The **helper** directory is used to hold the VLC module helpers. The purpose of the helper in ns3 is to simplify the creation of complicated networks. Topology helper allows the assignment of IP addresses to a set of nodes or to perform similar tasks on a container consisting of node, Net-Device, and channel objects. Conceptually, helpers are to organize code into a structure easily understood by anyone familiar with ns3. **Examples** directory holds samples on how to use the module. The **Test** directory contains files used to verify the correctness of the module's implementation and the **DOC** directory contains documentation files to explain how the module works and the scope and limitation of the module. **Wscript** directory is used to combine the new module with ns3 by introducing it to the ns3 build system (i.e., Waf).

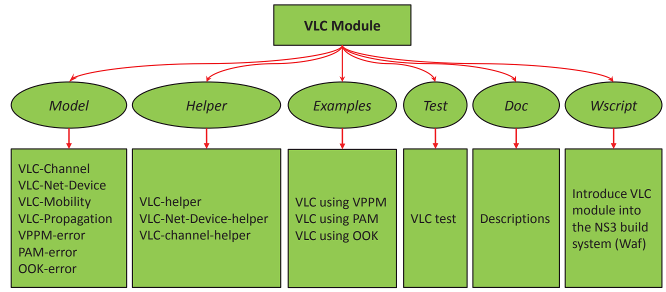


Fig. 1: VLC module structure.

III. Analytical Modeling of VLC Channel

As mentioned earlier, there is a great deal of existing work on VLC physical channel models and modulation techniques adapted specifically for the optical channel. There are many to explore in the context of network analysis. Here we describe the VLC channel model that we have adopted for the ns3 VLC module. VLC is implemented with intensity modulation and direct detection (IM/DD) such that the signal is represented by variations in the instantaneous optical power and the received optical signal is directly converted to an electrical current. We assume that the optical transmitter has maximum optical power constraint, C, and the source (optical emitter) produces an instantaneous optical power, $X(t)$, in $watts$ constrained by $0 \leq X(t) \leq C$. Since optical intensity is non-negative, a DC bias is incorporated into the signal. In a dual-use lighting and communication VLC system we have an illumination constraint that specifies average optical power. In order to achieve a specified average transmitted optical power, the signal may not necessarily utilize the entire range of the source. Accordingly, we define $min(X(t))$ and $max(X(t))$ as the minimum and maximum optical power and define the instantaneous optical signal power as $x(t) = X(t) - min(X(t))$.

Average optical power and average optical signal power are therefore defined as $E[X(t)]$ and $E[x(t)]$, respectively.

A. VLC Channel Model

When considering a dominant line-of-sight (LOS) path in a VLC system, the received optical power is represented by the product of the transmitted optical power and the DC channel gain [13]. A primary difference between VLC and RF is that VLC channel gain is highly dependent on the angle of radiance, ϕ, and angle of incidence, ψ. Assuming a Lambertian emission pattern, the VLC channel gain is defined as:

$$H = \frac{(m_l+1)A}{2\pi d^2} \cos^{m_l}(\phi) T_s(\psi) g(\psi) \cos(\psi) \tag{1}$$

where m_l is Lambertian order, A is photodetector area (m^2), d is distance between transmitter and receiver (m), T_s is optical filter gain, and $g(\psi)$ is the gain of the receiver optics. For an optical concentrator, $g(\psi)$ is given by [14], [15]:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin(\psi_{con})^2} & \psi \leq \psi_{con} \\ 0 & \text{else} \end{cases} \tag{2}$$

where n and ψ_{con} are the refractive index and photodetector field-of-view, respectively. The Lambertian order is given by $m_l = -(\ln 2)/(\ln \cos(\Phi_{1/2}))$ where $\Phi_{1/2}$ is the transmitter semi-angle at half power [14], [15]. Given the channel gain of a link and the characteristics of the transmitted optical signal, we can calculate the received optical signal power and associated characteristics.

B. VLC Performance Model

Channel quality is evaluated by computing the signal to noise ratio (SNR). The performance of a link is evaluated in terms of bit error rate (BER) which is a function of the SNR for a specified modulation scheme. Optical SNR compares the average received signal to the background noise [15]:

$$SNR = \frac{(P_r R)^2}{\sigma_n^2} \tag{3}$$

where P_r, R and σ_n^2 are the average received optical signal power, responsivity (A/W) and total noise variance, respectively. The responsivity is a function of the photosensor's response to the spectral power distribution of the received light. The aggregate noise variance is the sum of the shot noise variance and the thermal noise variance [15].

$$\sigma_n^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \tag{4}$$

$$\sigma_{shot}^2 = 2qRP_rB + 2qI_BI_2B \tag{5}$$

$$\sigma_{thermal}^2 = \frac{8\pi k T_k C_{pd} A I_2 B^2}{G_{ol}} + \frac{16\pi^2 k T_k \Gamma C_{pd}^2 A^2 I_3 B^3}{g_m} \tag{6}$$

Here, q is electronic charge, B is noise bandwidth, I_B is background current. I_2 is the noise-bandwidth factor which we set as I_2 = 0.5620 [16]. The thermal noise variance in equation (6) represents the feedback-resistor noise and the FET channel noise. K is Boltzmann's constant, T_k is the absolute temperature, G_{ol} is the open-loop voltage gain, C_{pd} is the fixed capacitance of a photo detector per unit area, Γ is the FET channel noise factor, g_m is the FET transconductance, and I_3 = 0.0868 [17].

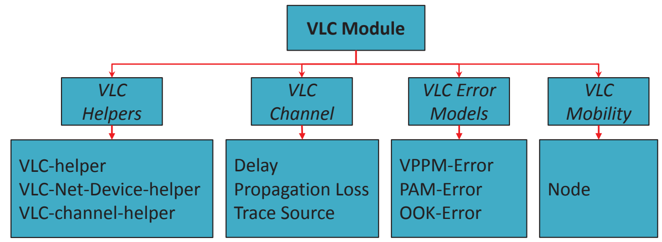


Fig. 2: Implemented VLC Module.

The BER is evaluated according to the value of SNR and the specified modulation scheme. For the VPPM scheme,

$$BER_{\text{VPPM}} = \begin{cases} Q\left(\sqrt{\frac{SNR}{2b\alpha}}\right) & \alpha \leq 0.5 \\ Q\left(\sqrt{\frac{SNR(1-\alpha)}{2b\alpha^2}}\right) & \alpha \geq 0.5 \end{cases} \tag{7}$$

where α represents the duty cycle of the VPPM signal, b is a factor relating noise bandwidth to signal bandwidth, and $Q(x)$ is the tail probability of the standard normal distribution. The Symbol Error Rate (SER) for PAM is computed by:

$$SER_{\text{PAM}} = \frac{2(M-1)}{M} Q\left(\frac{\sqrt{SNR}}{(M-1)}\right) \tag{8}$$

where M is the modulation order. We also consider OOK which is a subset of the PAM scheme where $M = 2$.

Network performance is evaluated in terms of goodput at the client. Goodput is defined as the ratio of delivered amount of information in bits to the total delivery time, given by

$$goodput = \frac{8 \cdot p \cdot N_{rx}}{T} \tag{9}$$

where p is the packet size in bytes and N_{rx} is the number of received packets over a period of T seconds.

IV. Design Requirements and Principles

In this section, we describe the ns3 VLC module implementation. The VLC module is presented in Figure 2 and contains the following objects: VLC helpers, VLC channel, VLC error models, and VLC mobility models.

A. VLC Helper Classes

In order to easily create larger complex systems, we implemented three helper classes. Our helper directory is comprised of **VLC helper**, VLC **Channel helper** and VLC **Net-Device helper**. The VLC helper handles the whole VLC system. This helper manages methods that relate the channel to the Net-Device and performs tasks such as creating Net-Devices and channels using ns3 smart-pointers. It also enables system protocols such as IP addresses, queues, etc. The VLC channel helper is an extension of the existing ns3 point-to-point helper but with more methods to control aspects of the VLC channel. The VLC channel helper manages the connection between the

VLC channel and the Net-Device, Node and Queue classes. In ns3, the channel is connected to the node through the VLC Net-Device. We control this connection using the VLC channel helper. It also enables the addition of features such as propagation loss and delay attributes when creating a VLC channel. The VLC Net-Device helper handles the connection between the node and the channel. Also, it is used to address the link between the Net-Device and the above ns3 classes. In addition, we used the VLC Net-Device helper to connect our error model and the ns3 queue class to the Net-Device.

B. VLC Channel Class

The VLC channel class represents an instance of a VLC channel and captures the unique optical characteristics required for accurate simulation. In our case we enhanced the ns3 point-to-point channel by attaching to it the VLC propagation model. The current channel is an extension of the ns3 channel class that provides more flexibility for users to modify it depending on their research requirement. Figure 2 shows the attributes of the VLC channel: **Delay**, **Propagation loss**, and **Trace source**. Delay represents the transmission delay through the channel. Propagation loss is a pointer to the desired propagation loss model. Trace source indicates transmission of packets through the VLC channel.

The average received optical signal power, P_r, is the product of the transmitted optical signal power and the channel gain defined in (1). It is computed using the transmitter and receiver net device properties and the VLC channel model. The transmitted power, Lambertian order, filter gain, photodetector area, receiver field of view, and refractive index are properties used to evaluate the channel gain. With additional parameters for noise, the received SNR is evaluated as in equation (3). Noise parameters include photodetector area, temperature, and electrical filter bandwidth. Noise is calculated using equations (4), (5) and (6). For more flexibility, these attributes are accessible by the user and can be modified to easily investigate their effects on the P_r, SNR, and network performance.

C. VLC Error Model Classes

VLC link performance is studied using VPPM, PAM and OOK modulation. To achieve this using ns3, we introduced error models into the receiver's Net-Device to compute the BER for each scheme. The error model class consists of models for each modulation scheme. Each error model consists of the the signal parameters (i.e., α and M for VPPM and PAM, respectively). The BER is evaluated according to the value of the SNR and the specified modulation scheme.

1) Error Model in VPPM Modulation: To determine packet drops, we use the DoCurrupt command in ns3. If a generated random number is less than the packet error rate (PER), the simulator rejects the packet delivery. VPPM PER is

$$PER_{\text{VPPM}} = 1 - (1 - BER_{\text{VPPM}})^{8*p} \tag{10}$$

where p is the packet size and equation (7) and (9) are used to compute BER and goodput.

2) Error Model in PAM Modulation: Nearly the same procedure for VPPM is followed for PAM; however the PER must account for the number of bits per symbol.

$$PER_{\text{PAM}} = 1 - (1 - SER_{\text{PAM}})^{\frac{8*p}{\log 2(M)}} \tag{11}$$

Here, equation (8) is used to calculate SER. Recall that OOK is a subset of the PAM scheme with $M = 2$ such that SER and BER are equivalent.

D. VLC Mobility Class

The VLC mobility model is inherited from the ns3 mobility class where; however we include the orientation of the transmitter and the receiver devices. Therefore, users can evaluate the effect of orientation on the link and network performance. The VLC mobility model includes attributes for **azimuth**, **elevation** and **position**. Azimuth represents the left and right rotation of the device. Elevation represents the up and down rotation of the device and position represents the device location. These attributes are used within the transmitter, receiver Net-Devices and the channel model to determine the angle of incidence and the angle of radiance. The mobility model is linked to the ns3 node class.

V. Combining VLC into ns3

ns3 uses Waf build system to build new modules. Waf is based on Python build system and it exists on top of all ns3 modules. To integrate VLC module into the ns3 libraries, we need to inform Waf. We used the Wscript directory in Figure 1 to notify the Waf build system of the existence of the VLC module by declaring all the source and public header files. Therefore, the VLC module can be built using ns3 Waf build system such that it is combined and linked to the ns3 libraries.

VI. Simulator Experiment

To show the efficacy of our NS models we demonstrate the use of the system via an example scenario. We built a small network consisting of four nodes. The model with next-hop addresses is shown in Figure 3. We used static routing to enforce packets flow in one direction across the network. Packets flow out from node1 (Wi-Fi AP) through a point-to-point connection to node2 (Relay A), from node2 to node3 (Relay B) using VLC link, then from node3 to node4 (Mobile Terminal) through a point-to-point connection. The same process is repeated in the uplink but using Wi-Fi for the connection between Relay B and Relay A. We run the simulator using ns3 and collect the data across the VLC link. We then plotted the collected data using gnuplot.

A. Simulation Settings

We consider the scenario illustrated in Figure 3 to run our simulator. The connection between node1 (Wi-Fi AP) and node2 (Relay A) is a point-to-point connection with $2ms$ delay and data rate of 200 $Mbps$. The uplink between node3 and node2 is represented using the existing ns3 WiFi model. The last connection between node3 and node4 (Mobile Terminal) is point to point with data rate of 200 $Mbps$ and $2ms$ delay.

TABLE I: Parameters for Simulation

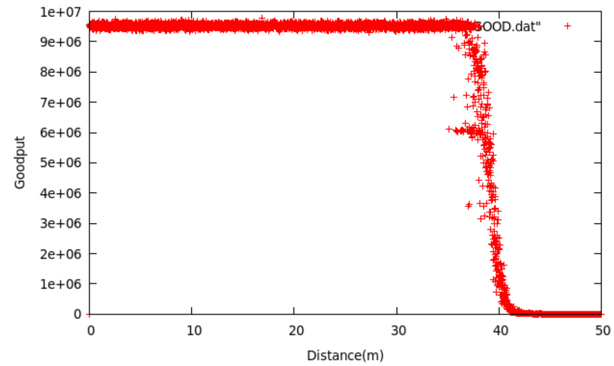
Parameter	Value
Transmited Power, P_t	48.573(dbm)
Lambertian Order Semiangle, $\Phi_{1/2}$	$70°$
Filter Gain, T_s	1
Boltzmann's constant, k	$1.3806e^{-23}$ J/K
Noise bandwidth factor, I_2	0.562
Background current I_B	$5100^{-6}\ A$
Open-loop voltage gain, G_{ol}	10
fixed capacitance of photo,C_{pd}	$112pF/cm^2$
Field-effect transistor (FET) transconductance (gm)	30 ms
electronic charge, q	$1.60217e^{-19}\ C$
I_3	0.0868
PhotoDetectorArea, A	$1.0e^{-4}\ m^2$
Refractive Index, n	1.5
field of view, ψ_{con}	$70°$
Transmiter coordinate	(0.0,0.0,50.0)
Transmiter Azimuth	(0.0)
Transmiter Elevation	(180.0)
Receiver coordinate	(0.0,0.0,dist)
Receiver Azimuth	(0.0)
Receiver Elevation	(0.0)
α	0.85
Bandwidth factor, B	10
lower wavelength, λ_{min}	$380nm$
upper wavelength, λ_{max}	$380nm$
Distance, d	50 m
Absolute temperature, T_k	295
Temperature,T	5000
FET channel noise factor,Γ	1.5
PAM, M	4
Electric filter bandwidth	$5e^6\ b/s$

The downlink between node2 (Relay A) and node3 (Relay B) is the designed VLC connection using the parameters provided in Table I. To study the VLC link at network layer, we created two moving nodes corresponding to a transmitter and receiver using the VLC mobility model inside node2 (Relay A) and node3 (Relay B) respectively. The VLC channel in Figure 3 was implemented using VLC channel helper. We increased the distance between the source and destination from 0 to 50 meters. The quantity of transmitted data is 1MB, where each packet carries 1040 bytes using a TCP connection.

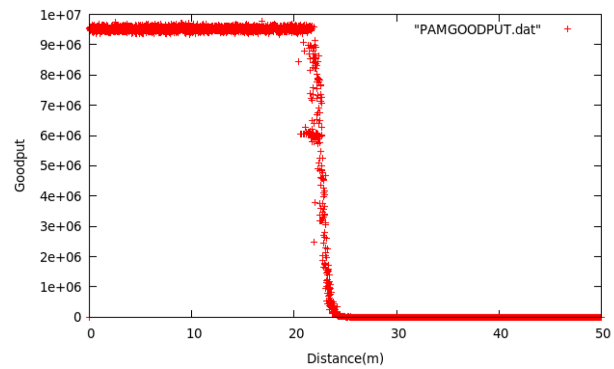
B. Simulation Results

The goodput results for VPPM, 4-PAM and OOK modulation schemes are illustrated in Figures 4a, 4b and 4c, respectively. In Figure 4a the goodput is shown versus increasing distance between the transmitter and receiver. The results show that the goodput is very high, reaching $9 * 10^6$ bytes when the distance between the receiver and transmitter is less than 38 meters. None of the packets were retransmitted. The goodput decreases sharply beyond 38 meters. This is noted by high retransmission activity, resulting in collapse of VLC link to the point where goodput reaches zero. In Figure 4b the VLC link starts to breakdown at $\approx 25\ m$ while this does not happen for VPPM until the receiver is $\approx 38m$ away from the transmitter. From the result VPPM outperform PAM in term of long distance communication. The OOK case, shown in Figure 4c, performs poorly in terms of goodput as compared to the other two schemes. The VLC link starts to deteriorate at $\approx 12m$ between the source and the destination.

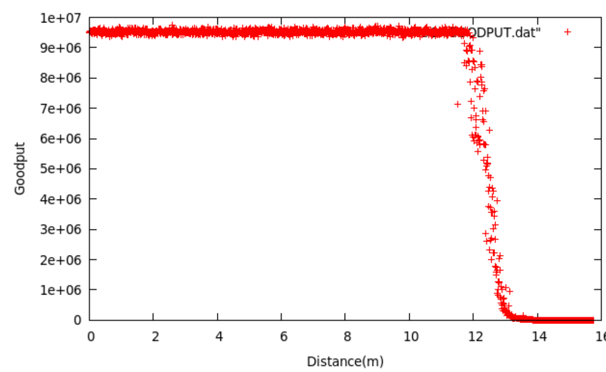
The BER for VPPM, PAM and OOK schemes are shown



(a) VPPM-Goodput



(b) PAM-Goodput



(c) OOK-Goodput

Fig. 4: Simulation results: Goodput

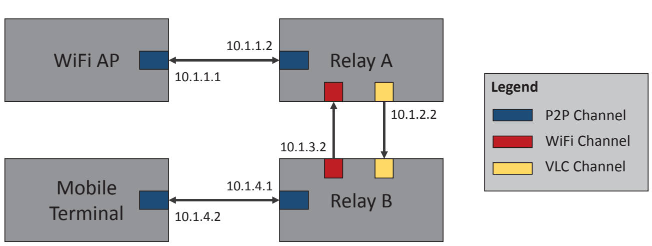
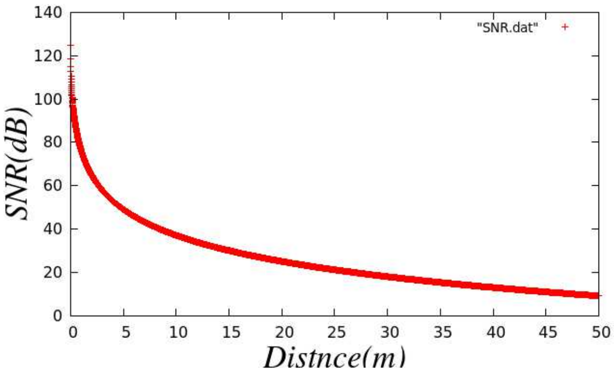
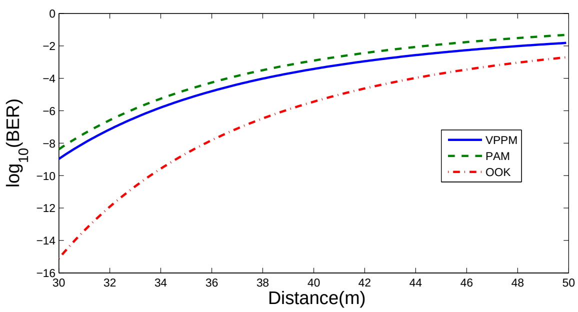


Fig. 3: Simulated example.



(a) SNR vs Distance



(b) BER vs Distance

Fig. 5: Simulation results: SNR and BER

in Figure 5b. The results show that OOK has lower BER than VPPM and PAM but increases sharply as distance increases. This causes the link to collapse faster than the other schemes. VPPM has higher BER than OOK because in our scheme we set α (duty cycle) $= 0.85$ while if $\alpha = 0.5$ then VPPM will perform similar to OOK in term of BER. 4-PAM has the highest BER among the rest. The reason is that it transmits more bits than VPPM and OOK which results in more error when the distance increases. The system SNR is presented in Figure 5a. When the distance increases, the optical power decreases according to equation (1) which leads to reduction of the SNR value to $\approx 16\ dB$ at a distance of 50 meters.

VII. Conclusion and Future Vision

VLC is experiencing growing interest as a physical medium for gaining new spectrum for wireless communications. In this paper we have proposed and demonstrated how various VLC physical layer modulation techniques and a baseline channel model can be simulated in the context of a larger model of a hybrid network system. Our approach is to adopt existing VLC channel and modulation techniques into a novel instance of NS to enable studies of hybrid RF/VLC systems under most operating conditions. Using the proposed NS VLC modules we explored the BER and Goodput of VPPM, PAM and OOK in simulations designed to show the utility of the tool. The simulation results results show that OOK has lower BER but drastically increasing as distance increase comparing to VPPM and PAM. Future work will include enhancements including the use of orthogonal frequency division multiplexing (OFDM) and consideration for multipath effects due to reflections. We also anticipate dissemination of the work as open source. It is our hope that this work will lead to new system simulations that will further enhance VLC as a viable new wireless networking technology.

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