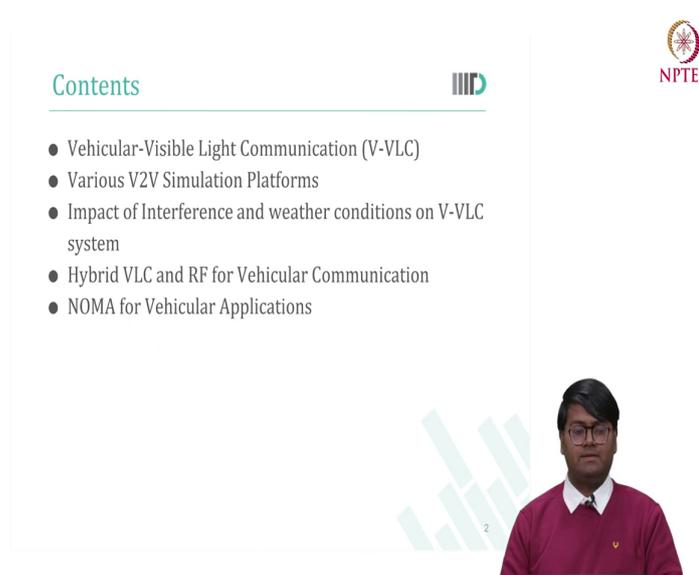


Optical Wireless Communications for Beyond 5G Networks and IoT
Prof. Guriendar Singh
Department of Electronics and Communications Engineering
Indraprastha Institute of Information Technology, Delhi

Lecture - 45
Tutorial

Hello everyone. Welcome to the course on Optical Wireless Communication for Beyond 5G Networks and IoT. My name is Guriendar Singh. I am a PhD Scholar and a Teaching Assistant under Professor Anand Srivastava, who is a course instructor of this course. In earlier modules, the basics of vehicular visible light communication have been covered in detail.

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The slide displays the following content:

- Vehicular-Visible Light Communication (V-VLC)
- Various V2V Simulation Platforms
- Impact of Interference and weather conditions on V-VLC system
- Hybrid VLC and RF for Vehicular Communication
- NOMA for Vehicular Applications

The slide also features the IITD logo, the NPTEL logo, and a small video inset of Prof. Guriendar Singh in the bottom right corner.

In this module, I am going to discuss few MATLAB based simulation exercise on vehicular-visible light communication and briefly discuss some of its use cases. I shall cover

the following contents in today's discussion. First, we will quickly recap what is vehicular VLC. Then we discuss various commonly used vehicle to vehicle simulation platforms that can be used for vehicular network simulations.

Then we will also discuss the impact of interference and weather condition on the performance of vehicular VLC system. Then we see how hybrid VLC and RF are beneficial for vehicular communication. In order to provide more reliable and massive connectivity among vehicles, we shall also discuss the concept of non orthogonal multiple access or NOMA in vehicular communication.

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NPTEL

Vehicular Visible Light Communication (V-VLC)

Car headlamps and lamp post can be used for V2V and I2V communication.

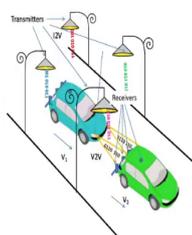


Fig 1: VLC based V2V and I2V

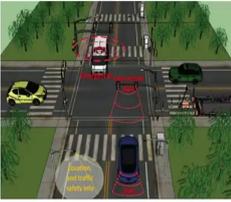


Fig 2: VLC usage scenario: road safety data transmitted using the vehicle

3



Now, this vehicular VLC can be visualized as a complementary potential candidate to the existing RF technologies. These RF technologies can be your DSRC Dedicated Short Range

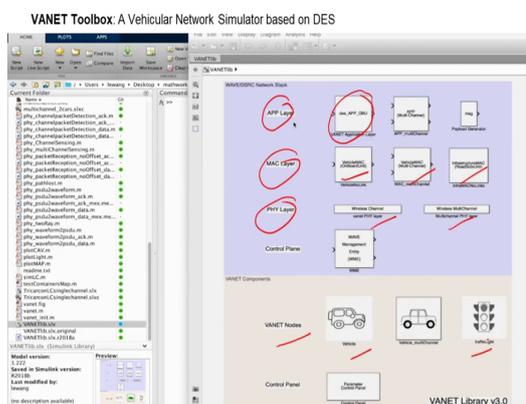
Communication or cellular V2X technologies. Vehicular VLC, it utilizes the existing vehicle headlamps LED as a transmitter and a photo detector or camera as a receiver.

As shown in this figure 1, this car headlamp and lamppost, this can be used for vehicle to vehicle V2V and infrastructure to vehicle I2V type of a communication. So, we can have two advantages. First is the road elimination and the added value is a high data rate communication, which can be achieved by using this vehicular VLC system.

Now, we see a practical use case scenario of a vehicular VLC. Now, road safety is a major issue more importantly at accident prone scenarios. For instance, your road intersection scenarios where high percentage of traffic accidents often occur. In such a scenario, your vehicular VLC offers several applications related to accident prevention such as sending your Basic Safety Messages, your BSM's, your cooperative awareness messages that alerts the vehicle about the accident happening in the surrounding.

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Various Simulation Platforms



Source: MATLAB and <https://www.ccs-labs.org/software/>

Now, I will quickly discuss various simulation platforms that are used for vehicular network simulations. First, we will briefly discuss about our VANET toolbox. So, this VANET toolbox is a vehicular network simulator, which is also a Simulink library and this library contains various network layers.

We can have your application layer; we can have your Mac layer and a physical layer. Now, in application or the APP layer, your vehicular mobility models and message creations, these are handled by your application layer. Messages like that of your lane changing messages, basic safety messages, those are generated by in the application layer.

Then this application layer, it also incorporates your various vehicular mobility models such as your lane changing model and your car following model. These are the two mobility models that enable to that enable users to simulate the lane changing and breaking actions.

Second, what we have is a MAC layer. Now, according to your IEEE 802.11p, this MAC layer, it basically use this EDCA or your Enhanced Distributed Channel Access.

Your application layer message entity, it is being transformed to a frame entity which goes through a channel contention period before being transferred to the physical layer. Now, this Reliable Data Transmission or RDT also known as the data acknowledgement, it is supported by this MAC layer.

Now, when it comes to this physical layer, then we have a DSRC or vehicular access for vehicular environment, wave standards based AWGN channel and two ray ground reflection model. So, these are the different models which are included in this physical layer. Now, all this layer, it contains the pre-built block which is independent discrete event entity.

Now, we will briefly discuss various simulation platforms that can be used for vehicular network simulation. Firstly, we will discuss about VANET toolbox. VANET toolbox is a Simulink library and this library contains major vehicular network layers. First is our application layer, MAC layer and a physical layer.

In application layer, vehicular mobility model and message creations are handled by this APP layer. Messages like a lane changing messages and basic safety messages, these are currently generated. In application layer, we make use of various vehicular mobility models such as your lane changing model and car following models. These are the two mobility models that enable user to simulate lane changing braking actions.

In MAC layer, according to your IEEE 802.11p standard, this MAC layer used this EDCA or your Enhanced Distributed Channel Access. The application layers messaging entity, it is transformed to the frame entity which goes through a channel contention period before being transferred to physical layer as a waveform entity. In MAC layer itself, your reliable data transmission or RDT also known as the data acknowledgement. It is supported by this MAC layer.

Finally coming to our physical layer, in physical layer your DSRC or vehicular access for vehicular environment, wave standards based AWGN channel and 2 ray ground reflection model are included in the physical layer. Now, all these layers contains your pre-built block. These are the various blocks. So, these are your independent discrete event entity.

So, in the MAC layer is installed on a car which is also called as an on-board unit. This Mac layer can be used for multi-channel scenarios. This MAC layer can also be used for V2I type of a communication. And this physical layer it is built for your one channel or multi-channel scenarios.

Then apart from these layers we have the VANET components such as your we can have your VANET nodes which can be your vehicle or your traffic light. This VANET node it includes all of the above layers. So, one can create vehicle to vehicle communication Simulink model using this VANET.

Now, your simulation results such as your packet delivery rate, end to end latency or cumulative distribution function this can easily be obtained using this VANET toolbox. So, this VANET toolbox is a open source on MathWorks file exchange. It can be easily downloaded freely from the MATLAB. Now, let us see few other vehicular network simulation platforms.

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The slide is titled "Various Simulation Platforms" and features the NPTEL logo in the top right corner. It lists four simulation platforms:

- VANET Toolbox:** A Vehicular Network Simulator based on DES.
- OpenC2X:** One of the first complete Open Source experimental and prototyping platform for vehicular networking solutions.
- Veins:** An open source Inter-Vehicular Communication (IVC) simulation framework composed of an event-based network simulator and a road traffic micro simulation model.
- Veins VLC:** Extends the popular vehicular networking simulator Veins with the capability to simulate Vehicular Visible Light Communication (V-VLC) alongside the default IEEE 802.11p communication.

Source: MATLAB and <https://www.ccs-labs.org/software/>

We have Open C2X which is one of the first complete open source experimental and prototyping platforms for vehicular network solution. Then we have Veins software. This Veins is an open source inter vehicular communication simulation framework, which is composed of event based network simulator and a road traffic micro simulation model.

Finally, we have what is known as the Veins VLC. Now, it is very popular for simulating vehicular VLC environment. This Veins VLC extends the popular networking simulator Veins with the capability to simulate the vehicular visible light communication along with your default IEEE 802.11p communication.

So, you have both the possibilities I am into say you can simulate VVLC your vehicular VLC along with your VRF. So, additionally the headlight and the tail light path loss models

provided by this Veins VLC. These are based on real world empirical measurement allowing the realistic simulation of this vehicular VLC environment.

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Impact of Environmental Conditions and Interference on V-VLC

The diagram illustrates the V-VLC system architecture. On the left, a data flow starts with 'Data binary conversion' leading to 'Data encoding', which then goes through 'IP' to 'Frame building' and 'Command Signal'. These are combined and sent to a transmitter. The transmitter's output is affected by environmental conditions (represented by sun, cloud, and rain icons). The signal then passes through an 'Optical Filter' and an 'Optical System' to a 'Focal point'. From there, it goes through a 'Photodiode Amplifier' and 'Filters' to 'Signal Reconstruction', and finally 'Data decoding'.

References:

1. G. Singh, A. Srivastava, and V. A. Bohara, "Stochastic geometry based interference characterization for RF and VLC-based vehicular communication system," *IEEE System Journal*, pp. 1-11, 2020.
2. G. Singh, A. Srivastava, and V. A. Bohara, "Impact of Weather Condition and Interference on the performance of VLC based V2V Communication", *IEEE ICTON*, Angers, France, July, 2019

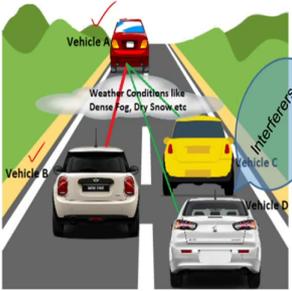
Now, next we see the impact of environmental conditions and interferences on the performance of vehicular VLC. The major difference between outdoor and indoor vehicular VLC application it arises due to influence of noise and ambient light interferences.

When compared to indoor application the outdoor applications these are mostly affected by your background solar radiations and the interferences occurring due to other sources of artificial lightning units as that of your street lights which are made up of your incandescent lamps or the fluorescent lamps.

This outdoor VLC channel these are also affected by the adverse weather conditions which include your fog, rain, heavy dust, snow, etcetera. Now, we are going to analyze the impact of environmental conditions and interferences on the performance of vehicular VLC. Now, the detailed information can be obtained from the following references. So, our interested learners can refer to these references for more detailed information's.

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System Model

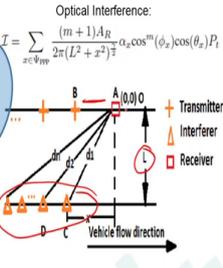


Weather Conditions + Interference

Vehicle A, Vehicle B, Vehicle C, Vehicle D

Weather Conditions like Dense Fog, Dry Snow, etc.

Interferers



Optical Interference:

$$I = \sum_{x \in \Psi_{VV}} \frac{(m+1)A_R}{2\pi(L^2+x^2)^2} \alpha_x \cos^m(\phi_x) \cos(\theta_x) P_t$$

Transmitter, Interferer, Receiver

Vehicle flow direction



Fig 3: System model. Here, Vehicle C and Vehicle D act as interferers (denoted by green solid line) for the dedicated communication link (denoted by red solid line) between Vehicle A and Vehicle B.

Fig. 4: Schematic diagram. The location of vehicles are assumed to be homogeneous poisson point process (PPP).

Now, I will briefly discuss our system model. So, this is our system model where we consider a typical V2V vehicle to vehicle communication scenario. So, we consider a one way double lane highway roadway where your communication link either RF or VLC exist between vehicle A and B.

So, this is my vehicle A and this is my vehicle B. So, the communication is happening between vehicle A and B. And vehicle B is my transmitter, which is trying to communicate

some information. Now, those information can be your speed of vehicle, traffic directions or warning messages that is. So, this vehicle A it acts as a receiver in presence of these interferers.

So, we have these interferers which are nothing but your vehicle C and vehicle D. These are these acts as an interferers to our desired communication link between my vehicle B and vehicle A. Now, a more generalized and simplified geometrical layout of the proposed scenario has been shown in this figure 4.

Now, it is assumed that the vehicle A is located at the origin O. So, this is my receiver which is located which is assumed to be located at the origin and this is my another vehicle B which is trying to communicate. And these are my interferers which are the which are responsible for causing the interference to my desired communication link between this A and B.

Now, I will quickly define some of the parameters that we used for the analysis. So, here L is your interline spacing and X it denotes the spacing the horizontal distance of the interferer from the origin. And the distance of the n th interferer to the vehicle A. So, your D_n is nothing but your distance of your n th interferer to your vehicle A and D_1 it is your from the vehicle C to vehicle A. So, that is what we call it to be a D_1 .

Now, we analyze the performance of this proposed system model using various analytical tools of stochastic geometry. Now, before we go to the stochastic geometry this is an expression for an optical interference. So, this is what is an expression for an optical interference from this interfering vehicle.

So, as discussed in your class as well. So, we have this m is your is your Lambertian order m is your Lambertian order A , A_R is your area of photo detector L is your interline spacing which we have already discussed then x is nothing but your horizontal distance between my your desired receiver and the interfering vehicle.

So, accordingly we can find out that the interference the optical interference can be given by this equation. So, again these parameters have already been discussed in the class itself in the

previous module. So, this is nothing but your angle of incidence and angle of irradiance and P_t is nothing but your transmit power of this vehicle.

So, now we are going to analyze this performance of this whole system using various analytical tools of stochastic geometry. Now, this stochastic geometry tool may be new to our new learners. So, we will invest some of the time in understanding, what is stochastic geometry.

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Stochastic Geometry



- ❑ Stochastic geometry in vehicular ad-hoc networks (VANET) can be used to determine the average transmission success rate assuming that road vehicles are spatially distributed according to a linear Poisson point process (PPP) [1].
- ❑ In vehicular networks, both vehicle distribution and road layout affect the communication performance. The locations of vehicles on one road can be modeled by a Poisson point processes (PPP) [2], [3].
- ❑ In the Euclidean plane, a Poisson line Cox point process was introduced in [3], where the vehicles are on multiple roads, modeled by a Poisson line process (PLP).

1.M. Heunggi, Stochastic geometry for wireless networks Cambridge University Press, 2012.
2.A. Al-Hourani, S. Kandeepan, and A. Jamalipour, "Stochastic geometry study on device-to-device communication as a disaster relief solution," IEEE Transactions on Vehicular Technology, vol. 65, no. 5, pp. 3005-3017, 2015.
3.Stehmetz, E., Wildemeersch, M., Quik, T.O. and Wymeersch, H., 2015, December. A stochastic geometry model for vehicular communication near intersections. In 2015 IEEE Globecom Workshops (GC-Workshp) (pp. 1-6).



So, in mathematics stochastic geometry is a study of random spatial patterns. It allows one to study the average behavior over many spatial realization for a network whose nodes are assumed to be placed according to some probability distribution. Now, this stochastic geometry can be used to characterize the randomness in this spatial distribution of the vehicle.

Now, more details of this stochastic geometry can be found out in this particular book by Martin Haenggi.

So, the interested learners can refer to this book by Martin Haenggi to have more detail explanation of various tools which can be used to model the interference using this various tools of this stochastic geometry. So, more details can be found out in this book by Martin Haenggi.

Now, in Euclidean plane we basically consider now the basic one should understand what is this Poisson line Cox process. So, I will give you just a brief introduction of what is a Poisson line Cox process. So, in a Euclidean plane we consider our doubly stochastic spatial model that captures the spatial coupling between the vehicular nodes and the roads and analyze the performance of a vehicular communication network.

We model the spatial layout of the roads by a Poisson line process what we call it to be a PLP. And the location of the nodes on each line or the road by a one dimensional Poisson point process. Thereby forming a Cox process driven by a PLP or a Poisson line Cox process. So, this is just a brief introduction to the stochastic geometry. We request our learners to refer to this book by Martin Haenggi for more detail explanation on the stochastic geometry.

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```

syms x;
f_x = @(x) mu_1 * (P_1 * (x^(m+1))) / ((L^2 +
x^2)^(m+Gamma+1/2)) * lambda;
f_x_Integral_Ans = integral(@(x) f_x(x), 0, 10000,
'ArrayValued', 1);
        
```

Monte Carlo Simulation:

```

realization=1000
for k=1:realization
    p_w=zeros(1,N);
    if S1m(1)<S1m_th
        p_u(i)=1;
    else
        p_u(i)=0;
    end
    end_outage=sum(p_u);
    P_out(k)=prob_outage;
end
P_out_avg=sum(P_out)/(realization*N);
        
```

Average Optical Interference

$$I_{VLC} = \sum_{x \in \Psi_{mw}} \frac{(m+1)A_R}{2\pi(L^2+x^2)^{\frac{m}{2}}} \alpha_x \frac{x^{m+1}}{(L^2+x^2)^{\frac{m+1}{2}}} P_i$$

$$I_{VLC}^{(a)} = \mathbb{E}_{\Psi_{mw}} \left[\sum_{x \in \Psi_{mw}} \mu_1 P_i \frac{x^{(m+1)}}{(L^2+x^2)^{\frac{m+1}{2}}} \right]$$

$$I_{VLC}^{(b)} = \int_0^\infty \mu_1 P_i \frac{x^{(m+1)}}{(L^2+x^2)^{\frac{m+1}{2}}} \lambda dx$$

$$\mu_1 = \frac{(m+1)A_R}{2\pi}$$

$$SINR_{VLC} = \frac{(R_P)_i^2}{\sigma_{total}^2 + I_{VLC}}$$

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2$$

$$E \left[\sum_x f(x) \right] = \int_0^\infty \lambda f(x) dx$$

$\hat{P}_0 = \sum_{i=1}^N SINR_i < P$



Now, I will briefly come to now we come back to our system model as where we model this optical interference. So, one can easily deduce that the optical interference it can be expressed in the following form. So, this form already we have discussed. So, this X is nothing but your Poisson distributed. So, your x is nothing but his your Poisson distributed and rest the rest are the symbols have their usual meanings.

Now, we can find out the average optical interference using this stochastic geometry tool. So, here we basically find out the expectation over this x which is Poisson distributed. So, now we make use of the Campbell's theorem of the from the stochastic geometry to find out the average optical interference.

So, briefly write the expression for the Campbell's theorem. So, we can find out the expectation when we have the we can find out the expectation for this function let us say

summation of this function and this function has the random variable x which is Poisson distributed. And if we need to find out the some expectation and if we typically consider a one dimensional homogeneous Poisson point process then this can be written as this can be expressed in form of the integral.

So, 0 to infinity and we have this $\lambda \int f(x) dx$. This is for one dimensional Poisson point process. This is what we have written over here to find out the average optical interferences. So, if you refer to our system model, we have the optical interferences are nothing but the summation of all the optical powers from the interfering vehicles.

So, we have the summation over all the optical powers. And this summation can be expressed in an integral form using this Campbell's theorem in stochastic geometry. So, this is what we have in these are the constants. So, now the basic purpose here is now how to implement these equations in MATLAB.

So, you can implement these equations in MATLAB using this `syms` function. So, in MATLAB this `syms` or the symbolic this can be this `syms` it list the names of all the symbolic scalar variables functions, matrix variables, matrix functions and array in MATLAB workspace. So, here x is my symbolic variable.

Now, we can find out the average optical received power using these using this integral function in the MATLAB and this is how we find out the average optical interference in using the MATLAB. So, these equations can be numerically computed in MATLAB using this `syms` function where we declare this the variable as a symbolic variable and depending upon the distribution of that function then we can implement this average optical interference.

Then we perform this Monte Carlo simulations to obtain my outage or the any other performance matrix like that of your outage or the ber. So, how do we compute this SINR the signal to interference plus noise ratio? So, this is what is our desired signal power and this is my interference or the optical interference instantaneous optical interference and the sigma square total is nothing but my summation of your shot noise and thermal noise.

So, this is about how we analyze our system model. So, this Monte Carlo simulations these are performed by averaging over 1000 realizations of this Poisson point process and the channel fading parameters. So, it may be noted that the vehicles these are deployed over a length of 10 kilometers.

So, this is where the summation this infinity is nothing but the stretch the road stretch what we are considering. So, this we have considered to be around 10 kilometers. So, this we assume that this vehicles they are deployed over a length of 10 kilometer and we find out the interference at the origin and preserve. And they we the scenario is repeated for at least 10,000 time in order to obtain the statistics of the interference.

Now, given our simulation settings we further calculate this signal to interference plus noise ratio as per this relation. And we count the number of times your SINRs the signal to interference ratio signal is not larger than the SINR threshold. So, this is how we compute the outage probability.

So, in order to calculate my outage probability, we need to calculate the number of times your SINR, it is less than some it is less than some SINR threshold let us say β . So, we count that number of times for which this signal to interference plus noise ratio is not larger than the SINR threshold β .

And accordingly, we find out the simulated outage probability by finding out the number of time this SINR it is not larger than the threshold. And we divide it with the total number of simulation runs. This is how we find out the outage probability.

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Modelling Optical Interference

TABLE I
SYSTEM MODEL PARAMETERS

```

syms x;
f_x = @(x) mu_1 * (P_t * (x^(m+1))) / ((L^2 +
x^2)^(m+Gamma+1/2)) * lambda;
f_x_Integral_Ans = integral(@(x) f_x(x), 0, 10000,
'ArrayValued', 1);

```

Monte Carlo Simulation:

```

realization=1000
for k=1:realization
p_w=zeros(1,N);
if Slnr(1)<Slnr_th
p_u(i)=1;
else
p_u(i)=0;
end
end
prob_outage=sum(p_u);
P_out(k)=prob_outage;
end
f_out(fg)=sum(f_out)./ (realization*N);
end

```

Parameter	Symbol	Value
Lambertian Order	m	2, 4 and 6
PD active detection area	A_d	1.2 mm ²
Transmission power for RF	P_t^r	33 dBm [34]
Transmission power for VLC	P_t^v	36.5 dBm
Responsivity of the PD	R	0.58 A/W [2]
Electronic charge	e	1.6×10^{-19} C
Noise variance	σ_n^2	-99 dBm
Boltzmann's constant	k_B	1.38×10^{-23} JK
Absolute temperature	T_k	298° K
System Bandwidth	B_s	2 MHz [2]
Transmitter antenna gain	G_t	3dBi
Receiver antenna gain	G_r	3dBi
Visibility parameter light fog	V	0.1 km
Visibility parameter dense fog	V	0.05 km
Attenuation coefficient under light fog	β	39.4 dB/km [45]
Attenuation coefficient under dense fog	β	78.8 dB/km [45]
Attenuation coefficient under dry snow (snow rate=10 mm/hr)	$\beta_{dry\ snow}$	131 dB/km [45]
Inter-line spacing	L	10 m

Now, I will quickly discuss. So, these are the simulation parameters, these are the simulation parameters which are being used for simulating our vehicular environment. So, we have considered this Lambertian order to vary for different vary from 2, 4 and 6 the area of photo detector it is assumed to be 1.2 millimeter square. And interestingly the transmit power for this RF we have assumed it to be 33 dBm and for VLC we have considered it to be a 36.5 dBm.

So, these are the practical these values have been taken from the practical vehicular scenario. And moreover, the transmission powers for RF and VLC cannot be the same as these are the two different technologies. So, they have the different transmit power. Rest the these are the different variables, then we will discuss about this attenuation coefficient beta, the visibility parameters and these parameters we are going to discuss in the upcoming slides.

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VLC Interference Reduction: VLC attocell



Like small cell concept for RF, the optical access point (AP) is referred to as VLC attocell. The optical attocell not only improves indoor coverage, but since it does not generate any additional interference, it is able to enhance the capacity of the RF wireless networks [1].

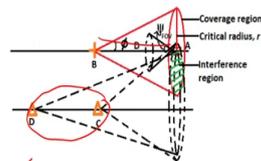


Fig 5: Reference scenario illustrating coverage and interference region using VLC attocells. Here, R and D denotes radius of VLC attocell under coverage region of desired vehicle and communication-range, respectively.

1. C. Chen, I. Muhammad, D. Tsonev, H. Haas, "Analysis of downlink transmission in DCO-OFDM-based optical attocell networks", Proc. IEEE Global Commun. Conf., pp. 2072-2077, Dec. 2014.
2. Surampudi, A. and Ganti, R.K., 2018. Interference Characterization in Downlink Li-Fi Optical Attocell Networks. *Journal of Lightwave Technology*, 36(16), pp.3211-3228.

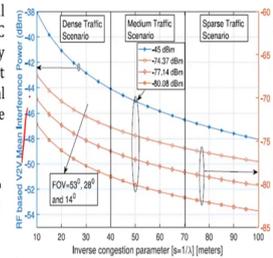


Fig 6: Mean Interference variation with inverse congestion parameter for VRF communication ($\alpha = 2$) and V-VLC with Lambertian Order, $m = 4$ with different FOV of receiver



So, depending upon the simulation parameter settings, now we see the simulation results for average optical interference and the effect of reducing the FOV on average interference power in case of vehicular VLC. Typically, the received signal as well as the interference model it can considers a full FOV of 180 degree at the PD receiver which leads to a worst case bound on the interference.

So, for a typical receiver the received interference power as well as the received signal power it heavily depends on the FOV of the receiver. Moreover, if we consider a full FOV of the PD it assumes that the interference are interferers are always within the FOV of the desired receiver. So, which may not be true always and hence it over estimate the total interference for a given scenario.

Now, by reducing the FOV of the receiver one can minimize the impact of interference from the interferers. So, we can easily see that from this figure 5 that the impact of reducing the FOV of the receiver on the average optical power experienced at the typical receiver can be observed from this figure 5.

So, we have this is our desired communication link and these are my interferers. So, we can minimize the impact of interferers by reducing the FOV of the receiver. So, this is also can be visualized in the form of results. So, on the right hand side we have this VLC based mean interference power and on the left hand side we have the RF based mean interference power.

So, we can easily see the impact of reducing the FOV on the performance of this vehicular visible light communication. More you decrease the FOV of the receiver the impact of average interference power it is less. Then we also see that the optical interference what is being observed in case of vehicular VLC it is less as compared to the RF based mean interference power.

So, these are the main takeaways from these results. So, we have already told you how to calculate the average optical power using the numerical computation. So, those can be implemented in the MATLAB and we will get these simulation results under those given simulation parameter settings.

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Fog and Visibility

NPTEL

The meteorological visibility parameter, V data in order to characterize the density of fog. Mathematically, it can be modeled by Kim's model as:

$$V(\text{km}) = \frac{10 \log_{10} T_{th} \left(\frac{\lambda}{\lambda_0} \right)}{\beta_k}$$

$\delta =$	1.6	for $V > 50$ km
	1.3	for $6 \text{ km} < V < 50$ km
	$0.16V + 0.34$	for $1 \text{ km} < V < 6$ km
	$V - 0.5$	for $0.5 \text{ km} < V < 1$ km
	0	for $V < 0.5$ km



So, now let us discuss how weather conditions in particular fog it affects the performance of vehicular VLC. Let us formally define, what is fog? So, the meteorological definition of fog is given by a parameter known as the visibility parameter. This visibility parameter it is basically used for defining your fog. The very fundamental law to measure the fog density indirectly depends on the basis of the visibility parameter.

The now, mathematically the visibility parameter can be modeled by Kim's model and it is given by this particular equation. So, now in this equation we have beta lambda which is nothing but your atmospheric attenuation coefficient and t_h is your visual or the transmittance threshold.

So, we define the visibility parameter V as the distance as the distance at which the visual contrast or the transmittance of an object drops to a certain value of the visual or the

transmission threshold level of the original visual contrast along with the propagation path. So, now here this is how we define the visibility parameter.

This lambda naught in this particular equation is your maximum spectral spectrum of the solar band and delta this is your delta, delta is your particle size, size related coefficient and its value is given by this. For different values of V we have this different values of lambda. Now, let us see a MATLAB code for simulating the attenuation against the visibility using this Kim model.

(Refer Slide Time: 36:01)

Fog and Visibility

The meteorological visibility parameter, V data in order to characterize the density of fog. Mathematically, it can be modeled by Kim's model as:

Fig 7: Kim model for visibility for T_m of 2% and a range of wavelengths

```

Visibility=0.1:0.1:50;
for i=1:length(Visibility)
V=Visibility(i);
if (V >= 50)
q=-1;
elseif (V >=6) && (V < 50)
q=-1.3;
elseif (V >=1) && (V < 6)
q=0.16*V+0.34;
elseif (V >=0.5) && (V < 1)
q=V-0.5;
else
q=0;
end
Att_coeff(i)=(3.91/V^q)*(wavl/550)^-q;
Att_coeff_dB_km(i)=10*Att_coeff(i)/log(10);
end
                    
```

Fog → light fog (V=1km)
 → Dense fog (V=0.5km)

So, this is a simple MATLAB code which is used for simulating the attenuation against the visibility. So, we vary the visibility from 0.0 to 50 kilometers. Then we implement what is what we have defined earlier as a delta. So, for different visibility under different visibility

conditions when your V is greater than 50 then your delta or your delta is nothing but your 1.6.

Then if your V is greater than 6 and also it is less than 50 then your q or your delta is nothing but your 1.3 and if your visibility is greater than 1 kilometer and less than 6 kilometer then we implement this delta function.

And in other cases when we have the visibility parameter greater than 0.5 kilometer and less than 1 kilometer then we implement a delta to be from V minus 0.05. Then this is how we implement the attenuation coefficient and we obtain the attenuation coefficient in dB kilometers. So, finally, what we obtain is the following result.

So, this is the attenuation as a function of visibility. This attenuation against visibility has been drawn for various range of wavelengths say for instance 690 nanometer, 830 nanometer 1550 nanometers. So, the performance the attenuation curve for all these wavelengths are more or less the same. The behavior of this attenuation it is more or less the same.

Now, the for the visibility greater than 5 kilometer the attenuation is very low. It is also evident from this curve itself. So, we see that when your visibility is very low which is a typically a case of your fog. So, your fog which is characterized as your light fog or your density or your dense fog.

We can define this light fog by this visibility parameter when your visibility is approximately 1 kilometer and the dense fog is characterized by this visibility parameter when you have V equal to 0.5 kilometers. So, this is how we have defined this fog. So, we see that when you have the visibility in the range 0 to 1 kilometer then your attenuation is very high. This is what is in the case of vehicular VLC. So, there is a means great attenuation in vehicular VLC in presence of this fog conditions.

(Refer Slide Time: 39:19)

Probability of Successful Transmission



- Irrespective of traffic scenario, the probability of successful transmission for V-VLC communication under normal atmospheric condition outperforms V-RF communication for a given threshold power.

$$\begin{aligned}
 P_s &= \mathbb{P}(S/N/R \geq \zeta) \\
 &= \mathbb{P}\left(\mathcal{I}(V.L.C.B.F) \leq \frac{\zeta}{\sigma_t^2}\right) \\
 &= \mathcal{I}_x\left(\frac{\zeta}{\sigma_t^2}\right) \\
 &= \xi_c
 \end{aligned}$$

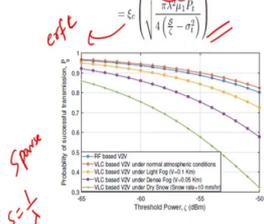


Fig. 10. Probability of successful transmission over a range of threshold power for Sparse traffic scenario when inverse congestion parameter is 50 m.

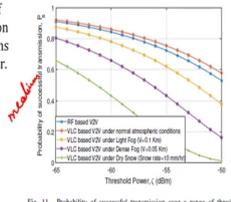


Fig. 11. Probability of successful transmission over a range of threshold power for Medium traffic scenario when inverse congestion parameter is 20.

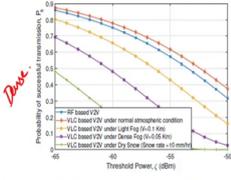


Fig. 12. Probability of successful transmission over a range of threshold power for Dense traffic scenario when inverse congestion parameter is 12.5.

Singh, A. Srivastava, and V.A. Bohara, "Stochastic Geometry Based Interference Characterization of RF and VLC Based Vehicular Communication System", IEEE System Journal, vol. 15, no. 2, pp. 2035-2045, 2021.



Now, we will quickly see some of the results where we examine the cumulative effect of interference as well as your weather condition on probability of successful transmission. So, this is the this is how we define the probability of successful transmission. It is basically the complement of your outage probability.

Now, this can be expressed in the form of the CDF function, which is evaluated at under these condition. Your S, S is nothing but your desired signal power and this zeta is your SINR threshold power and this sigma square t is your total noise variance. So, finally, what we obtain is that the probability of successful transmission it can be expressed analytically by this expression in terms of your zeta C is nothing but your complimentary error function. This is my complimentary error function.

So, the details of this analytical expression have been discussed in the this paper. So, the interested learners can refer to this reference for the details of how we obtain this probability of successful transmission in terms of your complimentary error functions. So, now interestingly these figures, figure 10 to 12, this shows the probability of successful transmission variation over a range of threshold power for VRF and vehicular V LC under various environmental deterrence for 3 different traffic scenarios.

We have typically considered sparse traffic scenario; we have considered medium traffic scenario and your dense traffic scenario. Now, one can define this, we can one can characterize this different traffic medium using this parameter what we call it as inverse congestion period parameter. This in traffic flow theory this inverse congestion parameter it is related to the vehicular density. It is defined as the inverse of the vehicular density.

So, here your inverse congestion parameter is 50 meters. So, your so it is basically nothing but we can also say that the distance between the two consecutive vehicles, the consecutive vehicle it is 50 meters. In other word we can also say that the vehicular density is nothing but your 0.2, 0.02.

So, this is for different, this is how. So, this is when so the sparse is characterized when your inverse congestion parameter is 50 meters and the medium traffic scenario it is characterized when your inverse congestion parameter is 20. And we when we decrease this inverse congestion parameter to 12.5 then we can have a dense traffic scenario.

So, now irrespective of all these traffic scenario we observe that the probability of successful transmission for vehicular VLC communication under normal atmospheric conditions it outperforms VRF communication for a given threshold power. So, in all the condition we see that irrespective of whether it is a sparse, medium or a dense traffic scenario your vehicular VLC under normal atmospheric conditions it outperforms your VRF.

But when it comes to your environmental condition such as that of your light fog and dense fog then your VRF under no fading condition it outperforms my vehicular VLC under

different environmental conditions such as that of your light fog dense fog and dry snow conditions. So, these are the things we have covered. So, again you can obtain this results using the tools of stochastic geometry.

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Vehicle Headlamp Radiation Pattern

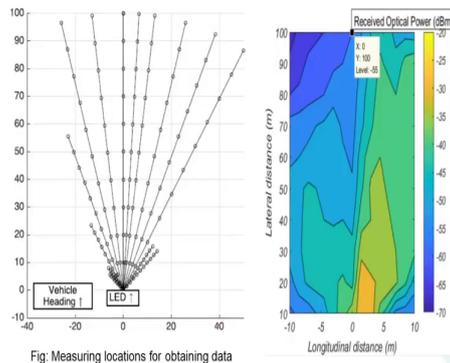


Fig: Measuring locations for obtaining data

$$P_r = \frac{(m+1)A_R}{2\pi D^2} \cos^m(\phi) \cos(\theta_R) P_t$$



Now, we see how to obtain a realistic radiation pattern of a vehicle headlamp. So, this is the slide where we want to highlight how we can obtain the vehicle headlamp radiation pattern. So, this optical powers actually this is your vehicle headlamp which is assumed to be at the origin and we measure the optical powers at different locations.

So, these are the different locations actually marked by the circles. So, we calculate the optical power at different locations. So, the optical powers, which are measured at the different locations these are the data is being fed to the MATLAB.

(Refer Slide Time: 45:20)

Vehicle Headlamp Radiation Pattern

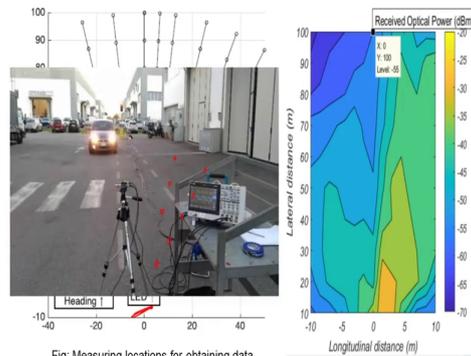


Fig: Measuring locations for obtaining data

$$P_r = \frac{(m+1)A_R}{2\pi D^2} \cos^m(\phi) \cos(\theta_R) P_t$$

12

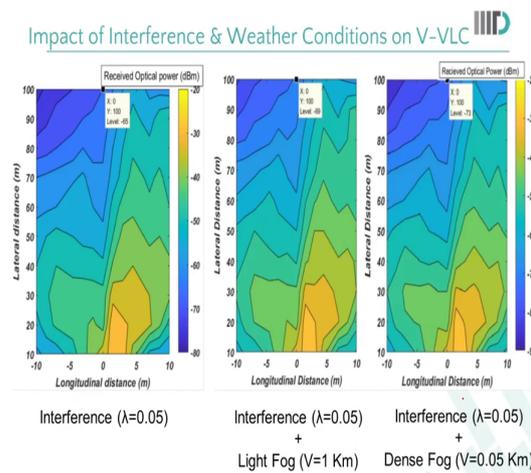
So, so this is basically the experimental setup which is used for simulating which is used for getting this vehicle headlamp radiation pattern. So, as you can see in this experimental setup. So, we measure this optical received power at the different locations. In that way we obtain a realistic radiation pattern from a car headlamp. So, this is basically the car headlamp radiation pattern.

So, we utilize the MATLAB surf command to obtain the radiation pattern of this headlight. So, interestingly if you observe this radiation pattern then it is little asymmetric in nature. So, this figure basically shows a clear asymmetry in radiation pattern from a single headlight.

And as you know this Lemberation model it basically assumes the vehicle LED headlamp to be a axially symmetric radiation pattern. So, from this practical setup and these results what we can conclude is that the Lemberation channel model is not valid for vehicular VLC. And

recently researchers have come up with various models such as Gaussian angular model and asymmetric empirical model for simulating the realistic vehicular VLC radiation pattern.

(Refer Slide Time: 47:09)



Now, these figure shows the modified headlamp optical radiation power under the influence of interference as well as weather conditions. So, we see that at a distance of a 100 meter, we observe that when we consider only the impact of interference then the average optical received power at a distance of 100 meter from a transmitter is 65 dBm. One can observe that when we consider the impact of light fog as well as the interference then your receive of the average optical received power the it is at a distance of 100 meter it reduces to minus 69 dBm. And when we consider the dense fog and your interference on the impact on the radiation pattern of this vehicular VLC headlamp then it drops to minus 73 dBm. So, we can easily see the impact of fog conditions and interference on the headlamp radiation pattern.

(Refer Slide Time: 48:42)



Heterogeneous Visible Light and Radio Frequency for Vehicular Applications

G.Singh, A. Srivastava, V.A.Bohara, Zilong L., M.N. Rahim, and G. Ghatak, "Heterogeneous Visible Light and Radio Communication for Improving Safety Message Dissemination at Road Intersection", *IEEE Transaction on Intelligent Transportation System*, Feb, 2022.



Now, let us see how hybrid visible light and radio frequency can be beneficial for vehicular application. This concept of heterogeneous or coexistence of VLC and IREF has been widely explored in an indoor environment.

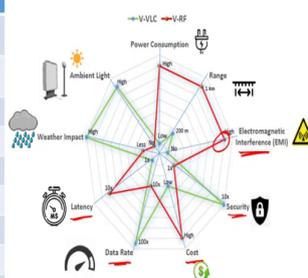
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Hybrid VLC-RF Vehicular Communication Systems



□ Hybrid V-VLC/V-RF systems can utilize complimentary advantages of standalone V-VLC and standalone V-RF systems.

Parameters	V-VLC	V-RF
Power Consumption	Low	High
Communication Range	Low (upto 200 m)	High (upto 1 Km)
EMI	No	Sensitive
Security	High	Low
Cost	Low	High
Data rate	High	Low
Latency	Low	High
Weather Impact	Sensitive	Negligible
Ambient Light	Sensitive	No affect



Performance trade-offs of conventional VLC and RF based V2X communication systems.



So, likewise your indoor scenario in vehicular environmental as well hybrid VLC-RF system can utilize the complementary advantages of standalone VLC and standalone RF system. So, as we see from this spider diagram, we see the pros and cons of a this VLC and RF based communication V2X communication system.

So, when it comes to the power consumption this vehicular VLC has lower power consumption as compared to this VRF. And the communication range supported by vehicular VLC is low that is typically around 200 meters, while for vehicular radio frequency communication is up to 1 kilometer.

And when we consider the impact of electromagnetic interferences then the electromagnet the impact of electromagnetic interference is more significant in case of VRF. However, in vehicular VLC we have no electromagnetic interference impact. When it comes to the

security because of its line of sight nature we say that vehicular VLC is highly secure as compared to my vehicular radio frequency communication.

When we see the cost, we can say that since you make use of the existing infrastructure this vehicular VLC it is more economically viable as compared to your vehicular radio frequency communication. Then as we discussed earlier that this vehicular VLC it supports high data rate communication.

So, we say that in terms of providing high data rate your vehicular VLC it is far better as compared to your vehicular RF. When we considered the latency in particular end to end latency then your vehicular VLC it offers lower end to end latency as compared to your vehicular radio frequency communication.

As we have seen in the previous slides that there is a significant impact of a weather condition on the performance of vehicular VLC. So, your vehicular VLC is more sensitive to the weather condition and there is very negligible impact of this weather impact of on this vehicular radio frequency communication. When it comes to the impact of solar radiations or the solar radiance on the performance of VLC then the there is it is the vehicular VLC it is more sensitive to this ambient light sources.

However, there is no effect of this ambient light on the performance of vehicular radio frequency. In nutshell what we see here is that we have the pros and cons of both these technologies and hybrid VLC and RF makes use of the better of both these worlds. So, we can make use of hybrid VLC-RF system for vehicular application as well for different scenarios. Let us see how where these hybrid VLC-RF can be applied in case of an outdoor scenario.

(Refer Slide Time: 53:18)

Hybrid VLC-RF V2X Systems

There are five primary scenarios in which VLC can complement and strengthen RF communication in V2X networks:

Fig: Illustration of a generic hybrid RF-VLC communication in a vehicular network.

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So, this slide is basically where we introduce the various hybrid RF VLC communication in a vehicular network. So, as shown in this figure there are five scenarios in which VLC can complement and strengthen your RF communication in V2X network. First is your vehicle to vehicle communication which can happen via this front light and the back lights. Secondly, we can also have U2V, UAV to vehicle type of a communication. This is the scenario then we can also have vehicle to vehicle through reconfigurable intelligence surfaces or an RIS.

So, these are this RIS or the reconfigurable intelligence surfaces this may be a new concept to our learners. So, I will briefly discuss what is this reconfigurable intelligence surfaces makes use of numerous materials, which can be used for altering the phase amplitude and the polarization of the incident signal wave to a desired user.

So, this the common place where this a reconfigurable intelligence surface can be employed is at the road intersection. So, we see that this vehicle cannot communicate with this vehicle. So, this can be or we can say that that there is a blocked line of sight communication between these two vehicles.

This is my blocked line of sight communication. So, now in order to improve the communication reliability we can make use of the reconfigurable intelligence surfaces on the buildings at the road intersection. So, this can improve the communication reliability between the vehicles which are in the blocked line of sight.

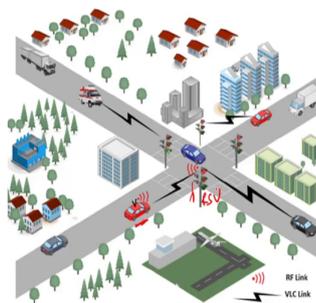
Next what we have is the V2X or vehicle to everything communication via traffic lights. So, this traffic light also can be useful. These traffic lights these are these can also be useful for communicating the basic safety messages or your cooperative awareness messages to alert the vehicle about the accident happening around the surrounding in the surrounding environment.

Next, we also have what is known as V2X communication via street lights. So, this street lights they also have some information, those information can be given to these vehicles through this vehicular VLC. And in turn this street light can be connected to my centralized base station through an back-haul RF link. So, these are the various scenarios where the a hybrid VLC or RF can be utilized in case of our vehicular communication. I think we will stop here. (Refer Slide Time: 57:03)

Hybrid RF/VLC at Road Intersection



Both VLC and IEEE 802.11p transceivers are assumed integrated on board and can be used separately (also called standalone V-VLC or V-RF network) or jointly (also called Hybrid V-VLC/V-RF network).



✓ Fig. Illustration of safety message dissemination in a vehicular network at road intersection. A desired vehicle can communicate with RSU via VLC or RF link.



Now, we briefly discuss the potential benefit of employing hybrid VLC and RF at road intersection. Hybrid RF VLC is capable of significantly improving the safety at road intersection where frequent accidents often occur. At road intersection the surrounding high-rise buildings roadside installation or sign boards may block the line of sight communication among the vehicles.

As shown in this figure we consider a desired vehicle close to intersection to carry the critical road information which needs to be immediately communicated to this roadside unit. Both the

visible light communication and IEEE 802.11p trans receivers they are assumed to be integrated on board and can be used separately what we call as a standalone vehicular VLC or vehicular RF network.

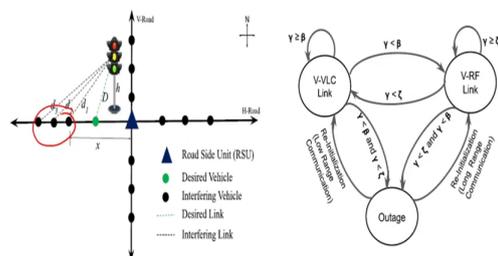
When we jointly use both VLC as well as your IEEE 802.11p trans receivers then we say it to be a hybrid vehicular VLC vehicular RF network. Now, the roadside unit it is assumed to be positioned at the crossroads. The roadside unit for IEEE 802.11p are already installed while the roadside units for VLC can be considered integrated in the road lamps or the traffic light.

When vehicular VLC is addressed the communication between the vehicle and the roadside unit happen through the head or the rear LED headlamp, while the reception at the roadside unit is carried out through the photo detector. So, this is basically the figure where we show how the safety message dissemination in a vehicular network occurs at the road intersection.

So, the communication between this vehicle and this RSU this is RSU it can happen either through a standalone VLC or a standalone RF or the combination of both what we call it as hybrid VLC-RF network.

(Refer Slide Time: 59:58)

System Model



✓ Fig. Abstraction used for modelling. The desired vehicle is marked in green circle, while RSU is marked in triangle, is assumed to be located at the center of road intersection.

✓ Fig. Transition diagram of hybrid V-VLC/V-RF network configuration.

We plot outage probability of hybrid V-VLC and V-RF using various analytical tools of stochastic geometry.

✓ Singh, A., Srivastava, V.A., Bohara, Zilong L., M.N. Rahim, and G. Ghatak, "Heterogeneous Visible Light and Radio Communication for Improving Safety Message Dissemination at Road Intersection", IEEE Transaction on Intelligent Transportation System, Feb. 2022.



Now, this figure portrays a generalized and a simplified abstraction model of the proposed scenario. Now, all the links can either be my visible light communication which we call it as a standalone vehicular VLC network or an RF link what we call it to be as standalone RF network. Both VLC as well as RF link are assumed to be available for hybrid vehicular VLC, vehicular radio frequency network configuration.

Now, we see here in this figure that the vehicles on the horizontal road H and vertical road V represented by the black circles these vehicles they transmit coherently and the and causes interference at the RSU. Figure 4 shows this figure, this figure shows the transition diagram of a hard switching based hybrid vehicular VLC vehicular RF network configuration.

So, an outage occurs when both vehicular VLC and vehicular RF fall into an outage. The real re-initialization is decided depending upon the distance between the desired vehicle and the

roadside unit. In general, unlike our vehicular radio frequency your vehicular VLC network is reliable option for low communication range. So, for more details you can also refer to our paper. Now, we plot the outage probability of hybrid vehicular VLC and vehicular RF using various analytical tools of stochastic geometry.

(Refer Slide Time: 62:15)







```

syms x s;
f_x=@(x,s) exp(-k.*2.*(s.*(x.^2.*m+2)))/(k.^2.*D.^(-2.*(m+1)).*(h.^2+x.^2).^(m+Gamma+1));
IntegratingFunction=@(x,s) 1-f_x(x,s);
f_x_Integral_Ans=@(s) integral(@(x)IntegratingFunction(x,s),0,10000,'ArrayValued',1);
L_ws_1=@(s) exp(-zeta.*(Lambda_01)*f_x_Integral_Ans(s));
Summation_b_1=0;
Summation_b_2=0;
Summation_b_3=0;
for b=0:B
    B_C_b=nchoosek(B,b);
    Summation_c_1=0;
    Summation_c_2=0;
    Summation_c_3=0;
    for c=0:C+b
        D_c=1+double(c==0);
        s_Current=(A+2*pi*c*1)/(2*(Beta*(-1)));
        Term_1=(-1)^c/D_c*real(L_ws_1(s_Current))/s_Current;
        Summation_c_1=Summation_c_1+Term_1;
    end
    Summation_b_1=Summation_b_1+(B_C_b*Summation_c_1);
end
P_Out_1_VLC=1-(PreTerm_Summation_b_1*Summation_b_1);
        
```

L_W(s) =

$$\exp\left[-\frac{\lambda}{s} \int_0^\infty \left(1 - \exp\left(-\frac{z \lambda^2 \lambda^{m+1}}{z_0 (\lambda^2 + z^2)^{m+3}}\right)\right) dz\right]$$

ALOHA MAC $\lambda_{MAC} = P \lambda$

$$P_{out,VLC}(\beta) \approx 1 - \frac{2^{-\beta} \exp(\frac{\beta}{2})}{\beta^{-1}} \sum_{b=0}^{\beta} \binom{\beta}{b} \sum_{c=0}^{C+b} \frac{(-1)^c}{D_c} \times \text{Re}\left(\frac{L_{ws}(s)}{s}\right)$$

VLC

$$P_{out,Hyb}(\beta, \zeta) \geq P_{out,VLC}(\beta) P_{out,RF}(\zeta)$$

$\hat{P}_0 = \sum \frac{\sin \kappa \rho}{\rho}$



✓ Singh A, Srivastava, V A, Bohara, Zong, M M, Bhat, S, G, Ghatak, "Heterogeneous Visible Light and Radio Communication for Improving Safety Message Dissemination at Road Intersection", IEEE Transaction on Intelligent Transportation System, Feb, 2022.

So, this is our MATLAB code to calculate the outage probability associated with the vehicular VLC. So, this is an analytical expression for outage probability associated with the vehicular VLC.

The details of this equation can be found out in this reference. The interested learners can refer to the following reference for this equation. So, in this equation for outage probability we see that we have a term what we call it as a Laplace transform of the random variable W. This Laplace transform of random variable W is given by this equation.

So, this is my Laplace transform of random variable W . So, here what we see is the term λMAC . Now, the MAC protocol governs the amount of interference experienced at the receiver. We can minimize the impact of interference by employing a suitable MAC protocol. Say for instance V if we employ ALOHA MAC protocol, ALOHA MAC protocol then this λMAC is nothing but the product of the access probability which is given by ρ and λ , which is our vehicular density.

Now, the access probability ρ , it is the probability during which it access the channel most of the time your channel is idle. So, it is the probability when a particular interfering vehicle it access the channel. So, that is what we defined by the parameter what we call it to as a access probability ρ .

So, now as done before we can also implement this particular Laplace transform of random variable W numerically in MATLAB using this `syms` function. We have already discussed, what is a `syms` function in the MATLAB. So, this is used to declare our variable symbolic variable. So, here my symbolic variables are nothing but x and s . So, we can implement this equation numerically in MATLAB using this `syms` function.

So, finally, what we have is the equation which shows what Laplace transform of the random variable W . Now, in order to compute numerically this equation of outage probability for VLC this is a simple MATLAB code. So, this preterm here preterm summation b is given by this mathematical form. The rest of the thing is implemented over here. We have this parameters which are also known as the controlling parameters.

So, the error estimation can be controlled using this parameter A , B and C . So, we implement this particular outage expression using these simple MATLAB code programming. So, the details of this all these equations how we obtain this outage probability can be found out in this particular reference.

Now, assuming this vehicular VLC and RF to be statistically independent we say that the outage probability associated with the hybrid vehicular VLC vehicular RF is given as the

product of the two outage probability, the outage probability associated with the VLC and the outage probability associated with the RF.

So, you can implement this you can implement numerically these equation and you can verify your analytical results using the simulation results. Again, in order to obtain the simulation results we need to compute what we call it as a signal to interference plus noise ratio. We compare it with some SINR threshold, we count the number of times your SINR threshold is less than some SINR threshold say β and then we compute the outage probability as what we have done previously.

We divide we count the number of times the this SINR in order to calculate my outage, we count the number of time this SINR it is it is less than some threshold to the total number of simulation results. So, in this way we calculate the outage, this is the way how do we calculate the simulation results.

(Refer Slide Time: 68:23)

Outage Performance Comparison



The framework can be customized to capture the performance of a desired vehicle in various network configurations such as

- ❖ Standalone V-RF
- ❖ Standalone V-VLC
- ❖ Hybrid V-VLC/V-RF

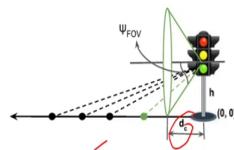


Figure: Illustration of critical distance, d_c .

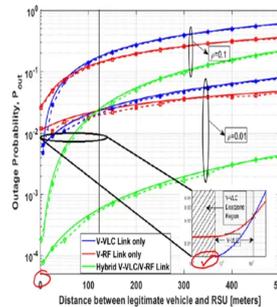


Figure: Comparison of analytical (solid line) and simulation (dashed line) results for outage probability, P_{out} versus distance for V-VLC link only (blue), V-RF link only (red) and hybrid V-VLC/V-RF Link (green) with CSMA CA protocol.

Singh, G., Srivastava, A., Bohara, V., Liu, Z., Rahim, M.N. and Ghatak, G., "Heterogeneous Visible Light and Radio Communication for Improving Safety Message Dissemination at Road Intersection" [submitted to IEEE Transaction on Intelligent Transportation System]



So, now I am quickly going to discuss few simulation results of outage probability of for standalone vehicular radio frequency link, vehicular VLC link and hybrid vehicular VLC RF link with CSMA or carrier sense multiple access with collision avoidance protocol. So, we can observe from this figure that when the desired transmitter location from the roadside unit increases the outage probability also increases.

Also, the outage performance of standalone vehicular VLC link is comparatively better than the standalone vehicular radio frequency. This is true for low communication range. It can also be observed that for access probability 0.01 the outage performance of standalone vehicular VLC is better as compared to vehicular radio frequency link.

When my desired transmitter location is less than 120 meters. However, when the standalone RF this standalone RF is more reliable option when my desired transmitter location is greater

than 120 meter. Now, in irrespective of the distance we observe that my hybrid vehicular VLC vehicular RF link it always outperforms standalone vehicular VLC and vehicular RF link.

Now, as shown in this figure this vehicular VLC it suffers from it suffers interference from vehicles on the same lane. There exist a critical distance d_c below which my vehicular VLC becomes unoperationalble which we refer to as a dead zone region for vehicular VLC.

Actually, I am discussing about a region over here there is very small region where this vehicular VLC becomes unoperationalble. That is the death the distance that critical distance is what we call it as a the distance below which your vehicular VLC becomes unoperationalble and the region what we call it has a dead zone region.

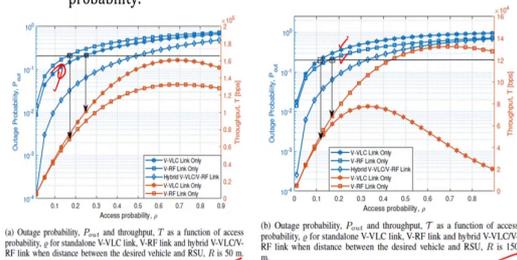
So, in such a case so, this is the region I am talking about. So, in this particular region your vehicular radio frequency communication is the only feasible solution of communication between my desired vehicle and the radio side roadside unit.

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Impact of Access Probability



- With increase in access probability, outage probability increases due to the availability of more interferers.
- Throughput first increases (due to more active transmitters) with increase in access probability and then decreases (due to extensive amount of interference), leading to an optimal value of access probability.



Next one can also plot the outage probability as a function of access probability for two different distance between the transmitter and the receiver. So, we have typically shown the impact of varying the access probability on the outage performance for different network configuration.

We have shown the results for different distances when my R is 50 meters and when my R is 150 meters. So, here we see that with an increase in the access probability the outage probability increases due to the availability of more interferers. Also, the throughput first increases due to more active transmitters with increase in the access probability and then it decreases.

So, for the throughput if you observe the trend first it increases and then decreases. So, there is some optimal value of the access probability at which you have the maximum throughput.

So, we should note here that the throughput of my hybrid VLC-RF system depends on the maximum throughput offered by either standalone vehicular VLC or a standalone VRF system.

In order to ensure a certain quality of service one must also guarantee on outage performance as well. With an outage probability below 20 percent when the distance between my desired vehicle and roadside unit which is 50 meter then the optimal value of access probability for standalone VLC is 0.25 and it results in a throughput of about 100 Kbps.

However, when we increase the distance that is when my R is 150 meters the opposite trends are observed. So, as expected your hybrid VLC-RF it always outperforms the standalone VLC or an RF in terms of outage performance.

So, for R less than 50 meters we observe that my vehicular VLC is performing better as compared my vehicular VLC it is performing better as compared to my vehicular RF, but when my distance is 150 meter the opposite trends are observed your VRF it is performing better as compared to my VLC. So, we can say that your vehicular VLC is suitable for low communication range while your vehicular RF it is more applicable for long range communication.

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NOMA for Vehicular Applications

Singh G, Srivastava A, Bohara V A, and Liu Z. "Downlink Performance of Optical Power Domain NOMA for Beyond 5G Enabled V2X Networks", *IEEE Open Journal of Vehicular Technology*, May, 2021.



Now, in order to provide vehicles with reliable, ubiquitous and massive connectivity an appropriate multiple-access scheme must be adopted. An appealing multiple-access scheme referred to as Non Orthogonal Multiple Access NOMA has been gaining significant research attention in vehicular networks among accommodation and industry. In earlier modules the basics of NOMA has already been covered. Now, let us see a simple MATLAB exercise on NOMA.

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Power Domain NOMA: 2-User Scenario



$$y_1 = h_1 x + w_1$$

$$= h_1 \sqrt{P} (\sqrt{\alpha_1} x_1 + \sqrt{\alpha_2} x_2) + w_1$$

$$= \underbrace{h_1 \sqrt{P} \sqrt{\alpha_1} x_1}_{\text{desired \& dominating}} + \underbrace{h_1 \sqrt{P} \sqrt{\alpha_2} x_2}_{\text{Interference \& low power}} + w_1$$

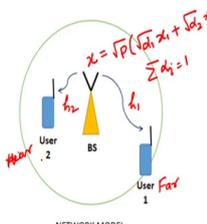
\hat{x}_1

$$y_2 = h_2 x + w_2$$

$$= h_2 \sqrt{P} (\sqrt{\alpha_1} x_1 + \sqrt{\alpha_2} x_2) + w_2$$

$$= \underbrace{h_2 \sqrt{P} \sqrt{\alpha_1} x_1}_{\text{Interference \& dominating}} + \underbrace{h_2 \sqrt{P} \sqrt{\alpha_2} x_2}_{\text{desired \& low power}} + w_2$$

\hat{x}_2



NETWORK MODEL

$\alpha_1 > \alpha_2$

So, this is a simple scenario where we consider a base station communicating to the 2 user. This is a downlink scenario where we consider two user, user 1 and user 2. User 1 is my far user and user 2 is my near user. And the channel between the base station and user 1 is given by let us say h_1 and the channel between base station and user 2 let us say to be h_2 .

In case of power domain NOMA different powers these are allocated to the different users. Now, at the base station power domain NOMA utilizes the superposition coding. Meaning the symbol which is transmitted from this base station is a superimposition of the message intended for user 1 and user 2.

Let us say the message for user 1 is x_1 and the message for user 2 be x_2 . Then at the base station the signal which is transmitted is given by. Kindly note here your P is your transmit

power of your base station α_1 and α_2 these are the power allocation factors associated with user 1 and user 2 respectively.

Now, the basic property of these power allocation coefficient is simple that my summation of all the power coefficients α_i should be 1. So, here my α_1 and α_2 should be unity the summation of α_1 and α_2 should be unity. Not necessary that the NOMA can be applied only for two users this the concept of NOMA can be extended for multiple users as well.

Now, if we look at the received signal for my far user and near user. So, mathematically we can write that the received signal at user 1 is given by $h_1 x + w_1$. So, your w_1 is nothing but your AWGN noise additive white Gaussian noise h_1 is the channel between my base station and user 1.

So, if we further simplify this received signal, we can obtain h_1 . So, this is my noise component. This is my desired and dominating part. Now, let me come to this point as well how I define it to be a dominating. This is nothing but my interference and it has got a low power.

So, how do we define it to be a dominating and low power? So, it is basically for far user now more power is allocated for the far user because it has to travel a longer distance. So, the power which is assigned to the far user is indeed more as compared to the near user. So, here for this case your α_1 is greater than my α_2 . My α_1 is greater than my α_2 that is the power allocation factor associated with user 1 is greater than the power allocation factor associated with user 2.

So, provided this condition we see that my this component this component is more dominating and the other term can be regarded as a interference and also it has got a low power. So, as far as the decoding for user 1 is concerned we can easily decode our signal for user 1. Rather we can better estimate my message for user 1.

So, we can directly since you have this condition that your power allocation factor for user 1 is greater than user 2 we can easily decode the user 1 signal, that is we can easily estimate my the message for user 1. But, if you consider the received signal power for user 2 then it is given as $h_2^2 x_2 + w_2$, you can further simplify h_2^2 root.

So, here we have this as an interference and which is more dominating due to this condition. And this is my desired signal and it has got a low power and this is nothing but my AWGN noise this is nothing but my noise.

So, what we can conclude here that the user 2 must perform what we call as a Successive Interference Cancellation, SIC decoding. So, before decoding its own signal my user 2 the near user has to perform the SIC decoding and this signal interference cancellation it is carried out as follows. So, your y_2 is directly decoded to obtain your message signal x_1 or rather an estimate of x_1 that is what we call it as a \hat{x}_1 first we obtain the estimate of message signal \hat{x}_1 from y_2 .

Then we subtract y_2 from this estimate we compute this estimate to we compute this estimate. So, this $y_2 - \hat{x}_1$ is decoded this is nothing but my y_2 dash. So, this y_2 dash it is decoded to obtain an estimate of x_2 . This is how we perform the successive interference cancellation at user 1, user 2.

So, user so, this is the performance of a power domain NOMA, how the power domain NOMA is employed for a 2 user scenario. Now, let us quickly see a simple MATLAB code which basically show the power domain NOMA performance for a 2 user scenario.

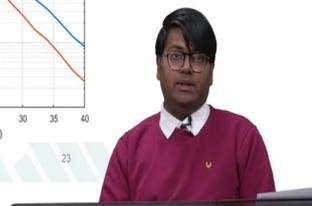
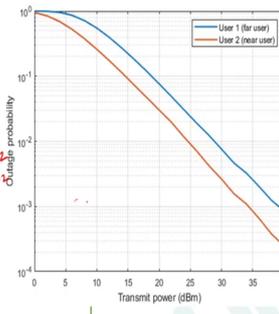
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Power Domain NOMA: 2-User Scenario



```

clear variables; close all; N = 10^5;
d1 = 1000; d2 = 500; %Distances of users from base station (BS)
a1 = 0.75; a2 = 0.25; %Power allocation factors
eta = 4; %Path loss exponent
%Generate rayleigh fading coefficient for both users
h1 = sqrt(d1^-eta)*(randn(1,N)+1i*randn(1,N))/sqrt(2);
h2 = sqrt(d2^-eta)*(randn(1,N)+1i*randn(1,N))/sqrt(2);
g1 = (abs(h1))^2;
g2 = (abs(h2))^2;
P1 = 0.240; %Transmit power in dBm
pt = (10^-3)*10.^(P1/10); %Transmit power in linear scale
BW = 10^6; %System bandwidth
No = 174 * 10*log10(BW); %Noise power (dBm)
no = (10^-3)*10.^(No/10); %Noise power (linear scale)
p = length(P1);
p1 = zeros(1,length(P1));
p2 = zeros(1,length(P1));
rate1 = 1; rate2 = 2; %Target rate of users in bps/hz
for u = 1:p
    %Calculate SNRs
    gamma_1 = a1^rate1*(g1./(a2^rate1*(g1+no)));
    gamma_2 = a1^rate1*(g2./(a2^rate1*(g2+no)));
    %Check for outage
    for k = 1:N
        if R1(k) < rate1
            p1(u) = p1(u)+1;
        end
        if (R2(k) < rate1)||(R2(k) < rate2)
            p2(u) = p2(u)+1;
        end
    end
end
out1 = p1/N;
out2 = p2/N;
    
```



So, this is a simple MATLAB code where we consider a downlink transmission from a base station to the 2 vehicular nodes. So, first we declare the values of some parameters. Let us say the distances are d_1 is your 1000, d_2 is your near user which is at 500 meters from the base station and then we set these power allocation factors. This has been arbitrarily chosen. Later we will also see that the benefits of NOMA can only be employed if we optimally choose this power allocation factors.

But for this particular case we have considered the power allocation factors to be 0.75 for user 1 and 0.25 for user 2. Now, we want to we want a plot of a outage probability as a function of transmit power. So, we first initialize a range of transmit power from 0 dBm to 40 dBm. Then we set our system bandwidth as 1 megahertz.

Then we calculate the thermal noise power as N_{naught} is the thermal noise power can be calculated using this formula where K is your Boltzmann's constant temperature, T is your temperature and B is your system bandwidth. So, next we have to generate the Rayleigh fading coefficients h_1 and h_2 to simulate the channel between the two users and this can be done using the following MATLAB code.

So, these are the MATLAB codes which are used to generate the Rayleigh fading coefficients for both the users. In order to plot the outage probability, we first need to set the target rate for each user. So, for user 1 we set the target rate as 1 bits per second per hertz and for user 2 we set the target rate as 2 bits per second per hertz.

Now, we count the number of times the values calculated. We calculate the SNR's using these MATLAB commands. Once these SNR's are computed we can easily calculate the rate associated with these SNR. So, this is for user 1 SNR you can easily compute my R_1 the rate which is associated with the user 1 and the rate which is associated in decoding the user 1 signal at user 2 is defined by R_{12} .

Then from γ_2 or the SNR associated with the user 2 we can compute the rate associated with the user 2. So, these are the instantaneous rates. We compare these instantaneous rates with the rates which we have said before what we call as a rate threshold. So, we count the number of times the rate falls below the target rate and take the average.

So, this can be implemented using these commands. And finally, we compute the outage associated with user 1 and user 2 by dividing it over the number of simulation runs. Finally, what we obtain is the following result. This is the result for this is the result for outage performance for user 1 and user 2 as a function of transmit power. So, we see here that the outage performance of user 2 it is better as compared to my user 1. Similarly, the learners can also plot the BER curves for the two user scenario.

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System Model



- We consider uni-directional traffic stream wherein either VLC or RF downlink exists between vehicles and Road Side Unit (RSU) (mounted on LED traffic lamp)
- We assume that a light source (e.g., traffic lamp post) sends a message to destination nodes through visible light. However, such VLC transmission is subject to interference originated from neighbouring vehicles that are located on the roads.



Fig: Typical I2V and V2V-VLC scenario.

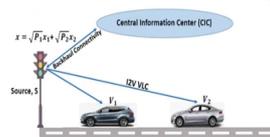


Fig: OPD NOMA based V2X system model.

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Now, let us extend the notion of non orthogonal multiple access in optical domain. What we call as Optical Power Domain NOMA or OPD NOMA. So, in this particular system model we consider a unidirectional traffic stream wherein either NOMA enabled VLC or RF downlink exist between the roadside unit and vehicle as depicted in this figure. Now, we assume that the light source which can be your traffic lamp post it sends a message to the destination nodes through the visible light.

However, such VLC transmissions are subject to interferences originating from the neighboring vehicles. At the transmitter side as shown in this particular figure, the light source it transmits the composite signal which is a superposition of desired optical signals of user pairs with different power allocation.

We consider the presence of this Central Information Center, what we call it as CIC that collects and keep track of some key system information say for instance the location and speed of each vehicle, road condition or basic safety masses dissemination. Now, the communication between the LED traffic light and central information center is established via a backhaul connectivity and to the vehicle through free space optical wireless transmission.

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Performance Analysis



- We specifically consider interference limited scenario wherein two vehicular nodes, V_1 and V_2 are selected to perform NOMA jointly since asking all the vehicles in network to participate is not preferable in practice.
- We compare the performance of OPD NOMA based V2X with conventional RF based V2X network using various analytical tools of stochastic geometry.

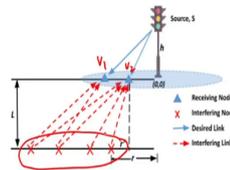


Fig: Abstraction used for modelling. The desired vehicles are marked in triangle, while interferers are marked in cross marks. Here, L and h denotes the inter lane distance and height of traffic lamp respectively.



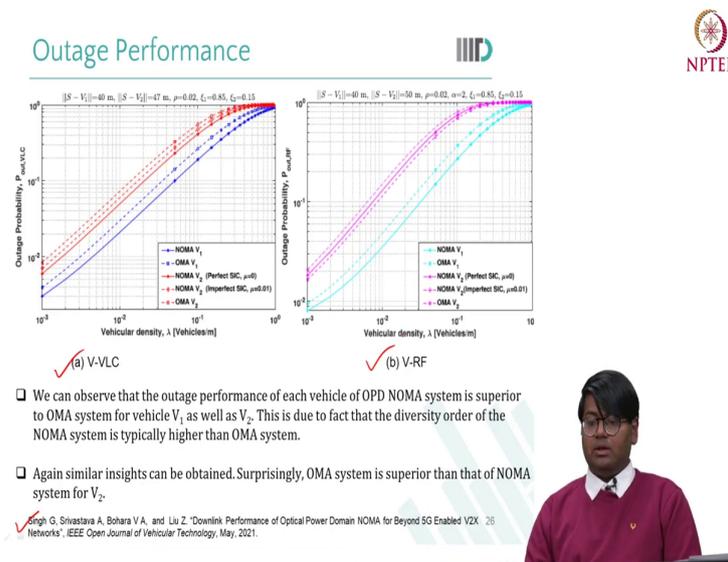
Now, for ease of understanding we have shown in this figure the systematic the schematic layout of the proposed system model. We consider a set of interfering vehicles which are distributed according to one dimensional homogeneous point process. So, these are my users V_1 , V_2 which are my desired vehicular nodes and these are my interfering vehicles.

So, we consider the interference limited scenario where these two vehicular nodes are selected to perform NOMA. And we compare the performance of this optical power domain

NOMA with conventional RF based V2X network using various analytical tools of stochastic geometry.

Now, for this for analysis of such a system we have assumed a low speed mobility model where we assume that the interfering vehicles they do not move or move slowly. That is their positions remain the same during two consecutive time duration. And for time being we have neglected the impact of Doppler shift and time varying impacts effects of your vehicle to vehicle and vehicle to infrastructure channel on the performance of optical power domain NOMA.

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So, as shown previously here also we plot the outage performance for my vehicular VLC and vehicular radio frequency communication. So, we calculate the signal to interference ratio at the vehicular node V 1 and vehicular node V 2 and calculate the outage probability associated

with the vehicular node V 1 and V 2 using similar approach as what we did in case of hybrid RF VLC.

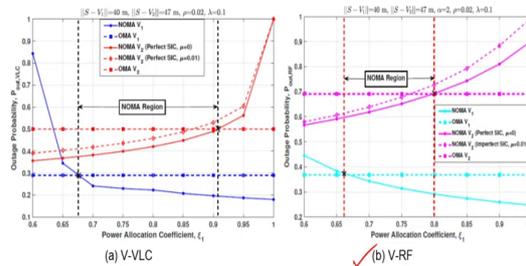
Now, I leave this as a simulation exercise to our learners to plot the outage probability as a function of vehicular density using MATLAB. One can refer to the following reference for detailed analytical equations and simulation parameters. So, you can refer to this reference for detailed analytical equations. And we can perform you can verify your analytical results with the simulation results. And the way we perform the simulation is similar as what we have done what we have seen previously.

So, finally, under our given simulation settings we can observe the following outage performance of my optical power domain NOMA and your conventional VRF based NOMA. So, from these figures we observe that my optical power domain NOMA performs better as compared to my vehicular radio frequency communication.

So, we observe that this outage performance of my OPD NOMA is superior to this OMA system as well. So, this is mainly because of the fact that the diversity order of the NOMA system it is typically higher than the OMA system.

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Impact of Power Allocation Coefficient



- If we compare OPD NOMA and OMA outage performance, both users exhibit superior NOMA performance over OMA system when $\xi_1 \in [0.67, 0.91]$.
- The benefit of V-RF NOMA over OMA system can be exploited when $\xi_1 \in [0.66, 0.8]$.



Next, we also plot the outage probability as a function of power allocation coefficient. As I mentioned earlier that my power allocation coefficient has to be selected optimally in order to enjoy the benefits of optical power domain NOMA. So, in these results also we see that the benefits of optical power domain NOMA can be obtained only for specific range of power allocation coefficient.

When my power of allocation coefficient is in this range, we see that the NOMA performance is better as compared to my OMA system Orthogonal Multiple Access system. And for the VRF case specifically the benefits of vehicular radio frequency NOMA over OMA system can only be exploited when my power allocation coefficient is in this interval.

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Conclusion



- ❖ We analyzed the performance of V-VLC systems in presence of interference as well as different environmental deterrents.
- ❖ We have shown the potential benefit of employing hybrid V-VLC/V-RF configuration for improving BSMs dissemination at road intersection over standalone V-VLC or V-RF network.
- ❖ We also explored the optical power domain non orthogonal multiple access (OPD-NOMA) for VLC based vehicle-to-everything (V2X) networks.



So, finally, in this module we analyzed the performance of vehicular VLC system in presence of interference as well as different environmental conditions. We concluded that irrespective of any traffic scenario the performance of vehicular VLC communication under normal atmospheric condition always outperforms vehicular radio frequency communication. However, the performance of vehicular radio frequency communication is comparatively better than vehicular VLC under various environmental condition.

Then we have also illustrated vehicle headlamp illumination patterns in presence of interference under different environmental conditions. Then secondly, we have also shown the potential benefit of employing hybrid vehicular VLC vehicular RF configuration for improving basic safety message dissemination at road intersection over standalone vehicular VLC or vehicular RF network.

And depending upon the transmitter location it is found that the standalone vehicular VLC and vehicular RF exhibit complementary roles in terms of outage probability. The presented framework also showed the limitation of standalone vehicular VLC over VRF communication when the distance between my desired vehicle and radios and my roadside unit is less than the critical distance defined for vehicular VLC.

Finally, we also explored the optical power domain non orthogonal multiple access for VLC based vehicle to everything network. We compare the performance of proposed downlink OPD NOMA based V2X network to RF NOMA and showed that the OPD NOMA based V2X network offers improved performance in terms of outage probability.

So, for any query you can always get in touch with me through my mail ID. So, this is my mail ID. For latest updates and ongoing research activity. In the field of visible light communication at triple IT Delhi you can visit us at the following website.

Thank you.