Visible Light Communication and Applications

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Communication using the visible light spectrum

- 400 - 700 THz frequency range
- Spurred on by increasing prevalence and adoption of LEDs, which Are more energy efficient and longer lasting
- Results seem to indicate a potential for transmitting at a high data rate
  - Existing wifi technology caps out at gigabit wifi
  - Visible light transmission data rate can potentially go beyond 40+Gbps. [1]
- 802.15.7 standard defines the MAC and physical layers for VLC (2011)
  - 96 Mbps

Potential Advantages

- Can piggyback onto existing infrastructure
  - Converting any light fixtures into a transmitter feasible
- Untapped spectrum allocation
  - Huge, since existing RF spectrum very expensive and almost fully alloted
- Security
  - Visible light waves do not penetrate buildings or walls
  - This leads to decreased chance of possibly being intercepted by an attacker
- Potential for high data rate communication

Disadvantages

- High attenuation leads to limited coverage
  - Communication restricted essentially to line of sight and reflections
  - Creating an environment with no physical obstructions can be challenging, given dynamic applications of this technology
- Suffers from interference from other visible light transmitters
- Non-symmetric uplink-downlink conditions
  - Broadcasting from a light source to multiple mobile receivers relatively achievable, but how to do the reverse?

Visible light within building

- Usually try to utilize existing lighting systems
- There are ways to limit light sources hitting same regions
  - Trouble with multipaths
- Can create cells using individual rooms and directional lighting
  - Larger rooms require utilizing multiple access techniques
- Asymmetry of building lights being stronger than device
  - Less power on battery powered device
  - Need different color(color filter) or other lights to turn off to be effective

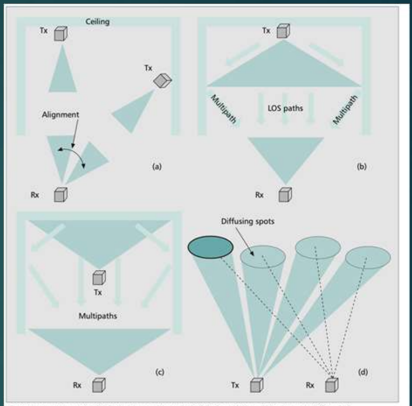


Figure 1. a) Directed-LOS link; b) non-directed-LOS link; c) diffuse link; d) quasi-diffuse link.

Types of light links

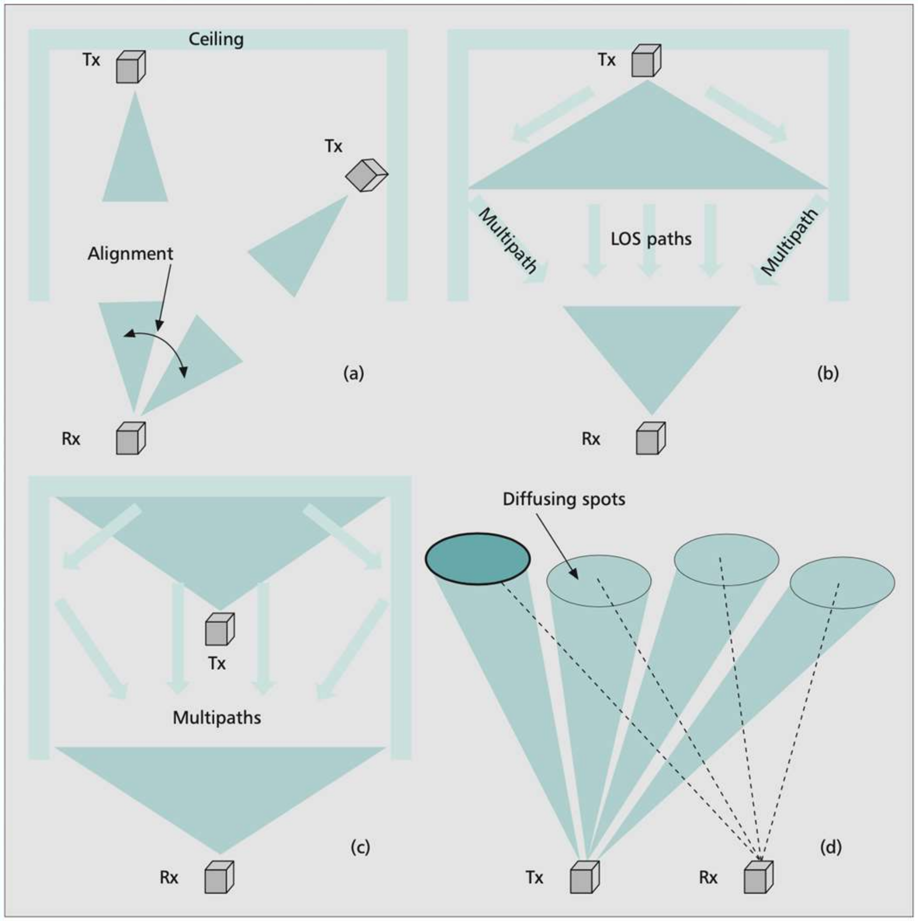
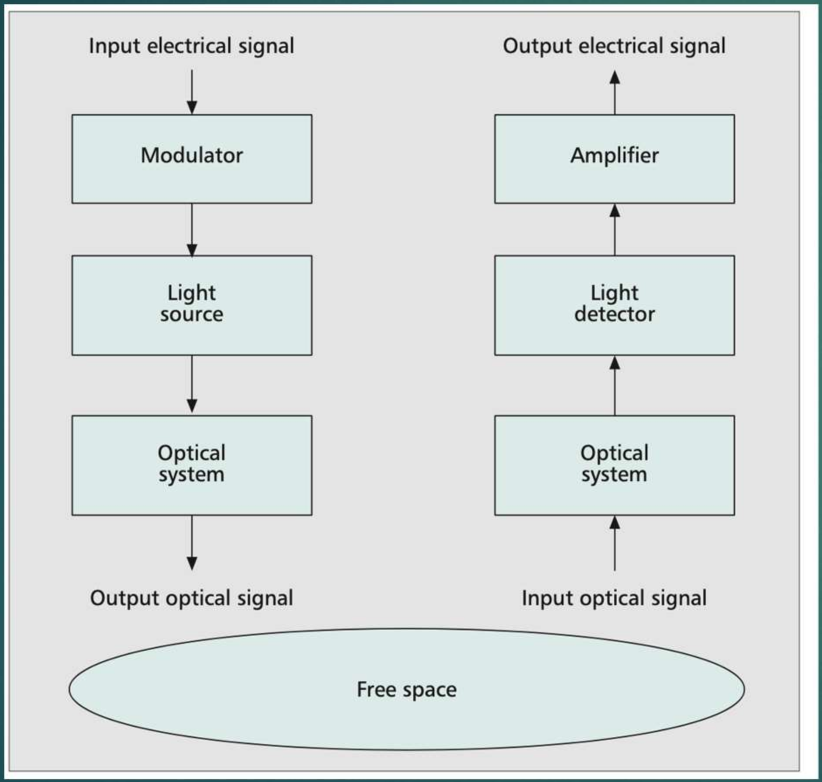


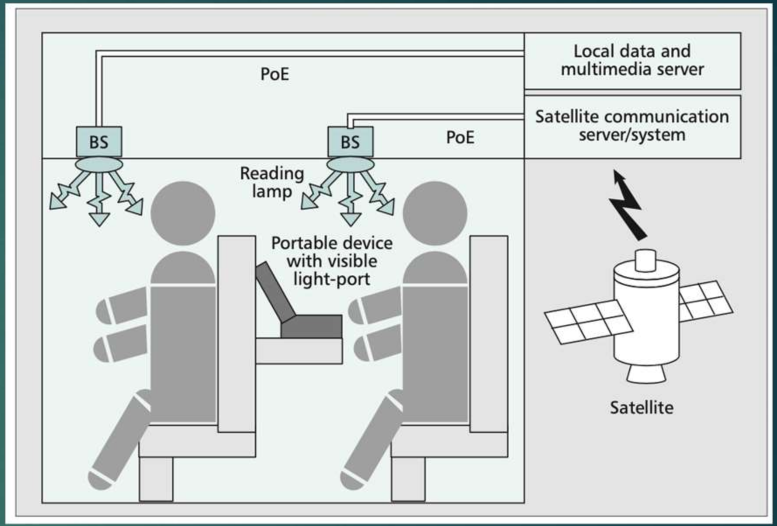
Figure 1. *a) Directed-LOS link; b) non-directed-LOS link; c) diffuse link; d) quasi-diffuse link.*

Basic idea of operation



Individual light station

- Used for airplanes or trains
- Reading lamp sufficiently blocked from others
  - Spatial multiplexing
- Works very well for downloads
  - Using light for device to base station would be power intensive
- Probably would work best for large downloads with regular Wifi covering communication



Transmission Techniques

- On-off keying(OOK)
  - Easiest implementation for existing light infrastructure
  - Simply turn on and off light to signal 1 and 0 bits
- Pulse-position modulation(PPM)
  - The deration of the pulse denotes what bit is being sent
  - Requires time synchronization between device and base station
- Multiple Access
  - OFDM, FDMA, CDMA, and TDMA are used

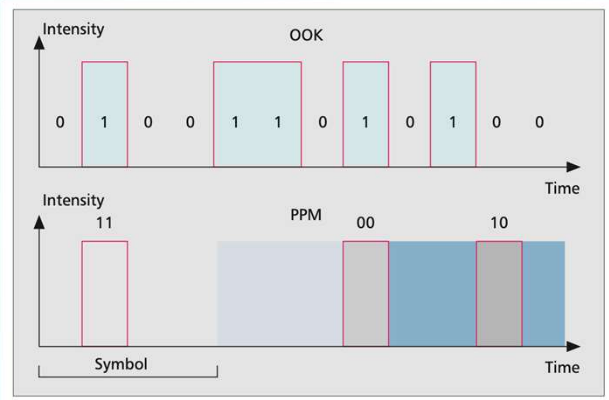


Figure 4. *Demonstrating SC pulsed modulation schemes, OOK and PPM.*

Example light based transmission system

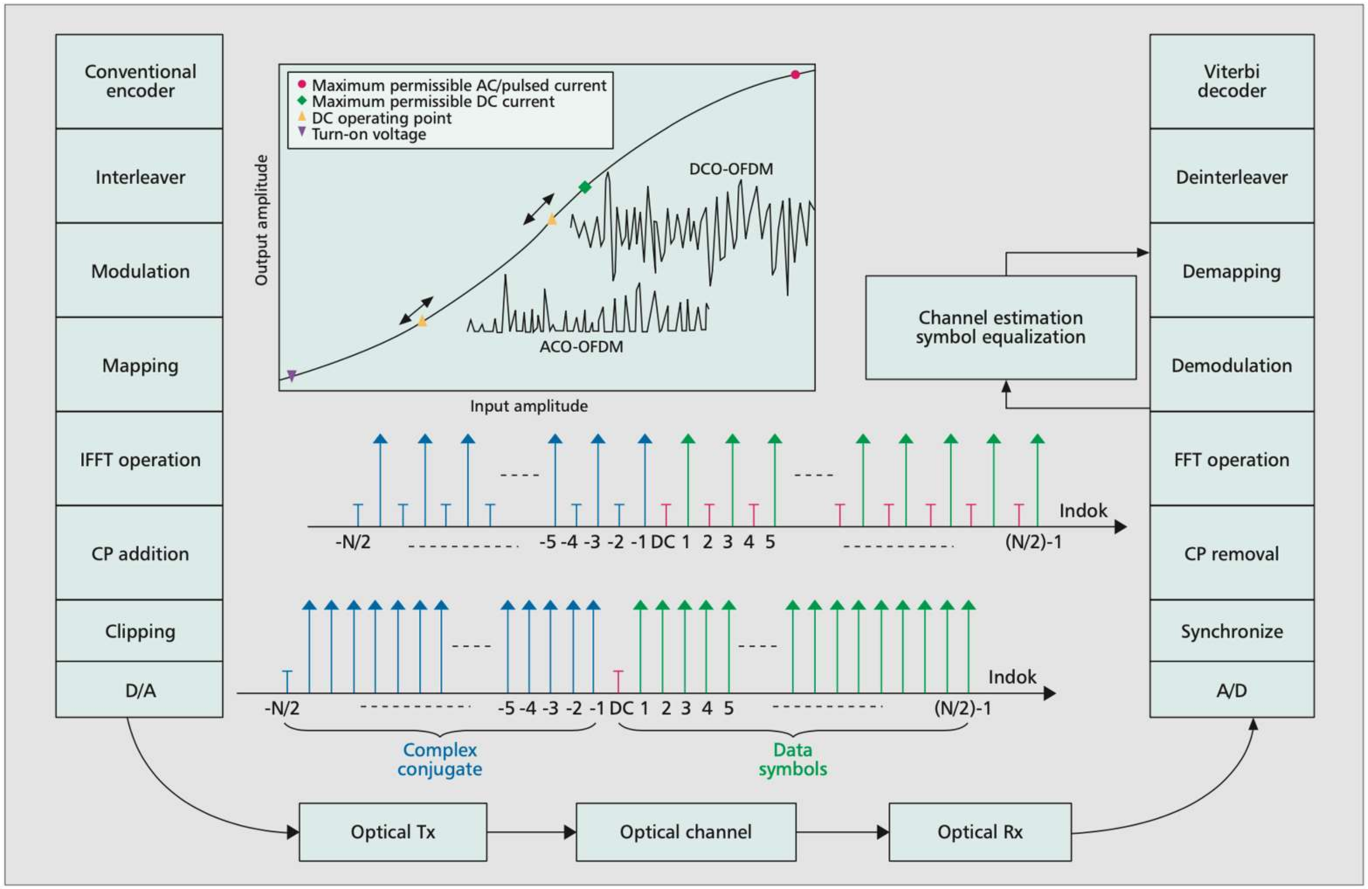


Figure 5. *DCO-OFDM and ACO-OFDM building blocks and LED input-output/voltage-current relationship.*

Uplink

- Wave length division duplexing(WDD) for uplink
  - Requires tracking device
- Time division access
- Color or polarized filter
- RF uplink

Localization with Visible Light

- Motivated by lack of GPS indoors
- Alterative to RF, Ultra wideband, ultrasonic,
  - Require additional hardware
  - There are certain RF technologies but not widely available

Localization with Visible Light

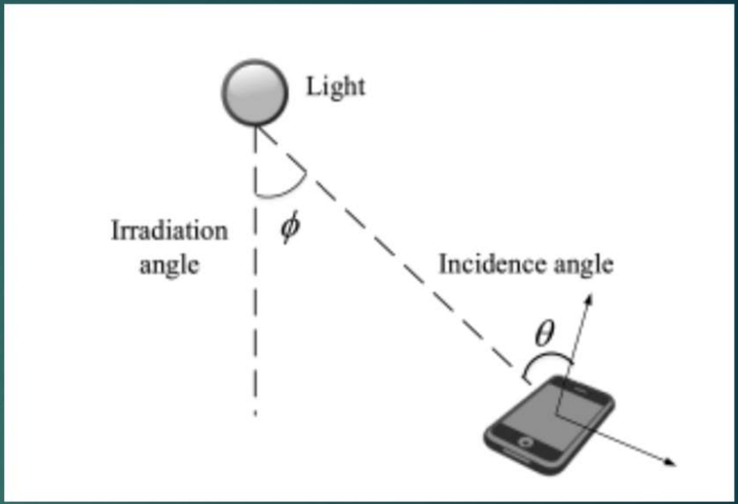
- Light Sensor based(Photodiode)
  - Needs to separate light signal from other signals
  - Energy efficient
  - High sampling rate
- Camera based
  - Can do Angle of Arrival
  - Multipath isn't as much of issue
  - Current devices have cameras(smartphones)
  - High power usage
  - Low sampling rate

Pros and Cons of indoor localization based on light

- Advantages
  - Existing Infrastructure
  - Rather precise
  - Low additional energy costs
  - Immune from interference from other rooms
- Disadvantages
  - Generally requires direct line of sight
  - May not work well in daytime(or anytime with lights not in system)

Trilaterization with Received signal strength(RSS)

- Uses angle of arrival to judge location
- Pr is received energy
- τ/T is the constant parameters of LED
- d is distance
- C is power of transmission



$$P_r = C.\sin\left({}^{\tau\pi}/_{T}\right).\frac{\cos\theta.\cos\emptyset}{d^2},$$

Other methods of trilaterization

- Time of Arrival and Time Difference of Arrival
  - Needs synchronized sensors
  - Expensive clocks due to high speed of light
- Optical angle of arrival
  - Expensive to compute
  - Needs camera
  - Can’t encode much data(small sample rate)

Approaches based on encoding

- Fingerprinting
  - Known information about the setting
  - Find most likely place where light condition exists
  - Done with prior measurements and see probability of each place
- LED sending identity location
  - Like RFID tag but utilizing light based transmission
    - Non-standardized

Evaluation

- Density = Number of lights/Area
- Performance index = Density*Accuracy
- Height not included due to lack of reporting on height in most papers
- Doesn’t include
  - barriers
  - daylight or other light sources
  - effect of some LEDs on signal of others
  - Movement or orientation of receiver

Results of localization tests

- RSS trilateration able to get around 5 cm accuracy(.2 PI)
  - 46 cm with reflections
- Fingerprinting within 30 cm(.01 PI)
- Seems that fingerprinting is good enough to use, though requires a lot of setup
- Trilateration may have fewer uses
  - Requires camera

Additional challenges

- Low camera sampling rate
  - Rolling shutter for quick sampling suggested
  - Don’t know how AOA would work with the different parts
  - Probably to make camera act like photosensor
- Daylight conditions
  - Suggested low light conditions(human eye cannot perceive)
  - Experimental 1.3 meter range
    - Dense clustering needed

Vehicular Application (Liu, C. et al., 2011)

Needs to support:

- Single point vehicle to vehicle communication
- Vehicle to access point communication
- Evolution to vehicular networks (development of a MAC protocol)
- Communicate and disseminate information about forward collision warning, signal violations…

What the paper claims:

- Yes, it is possible to build robust hardware that facilitate VLC using off-the-shelf components.
- Computer simulations also indicate that VLC can also support ad-hoc network formation and simple protocol implementation

Receiver and Transmitter

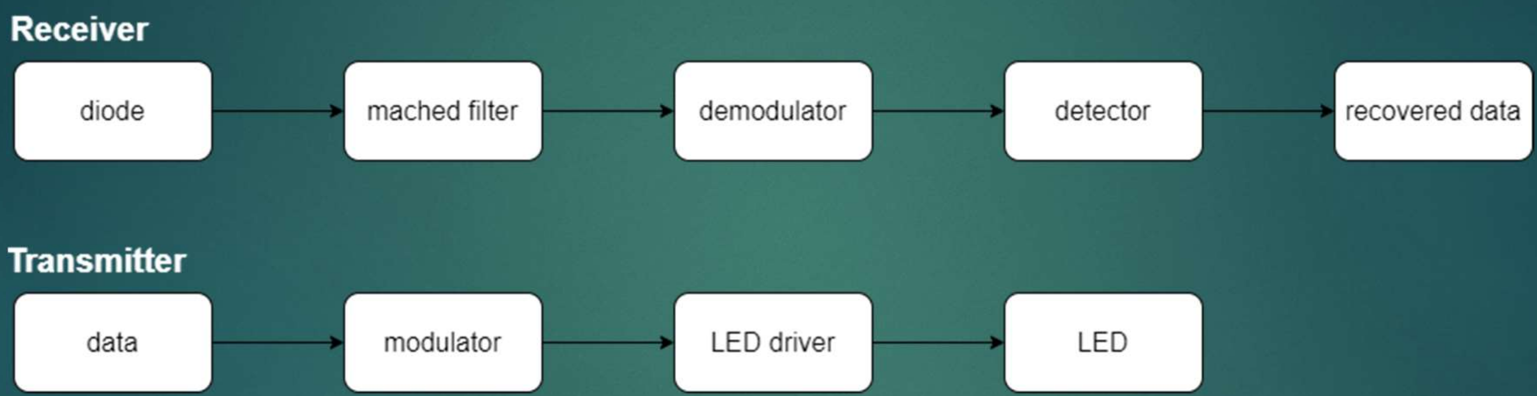
Transmitter:

- WLEDs (seems to be the consensus, can provide lighting as well as facilitate communication)
- Pulse modulated at very high frequency (undetectable to human eye)

Receiver:

- Photodiodes
- Can saturate (bad), need physical enclosure to limit field of vision.
- Also requires matched filter in order to amplify SNR

Schematic

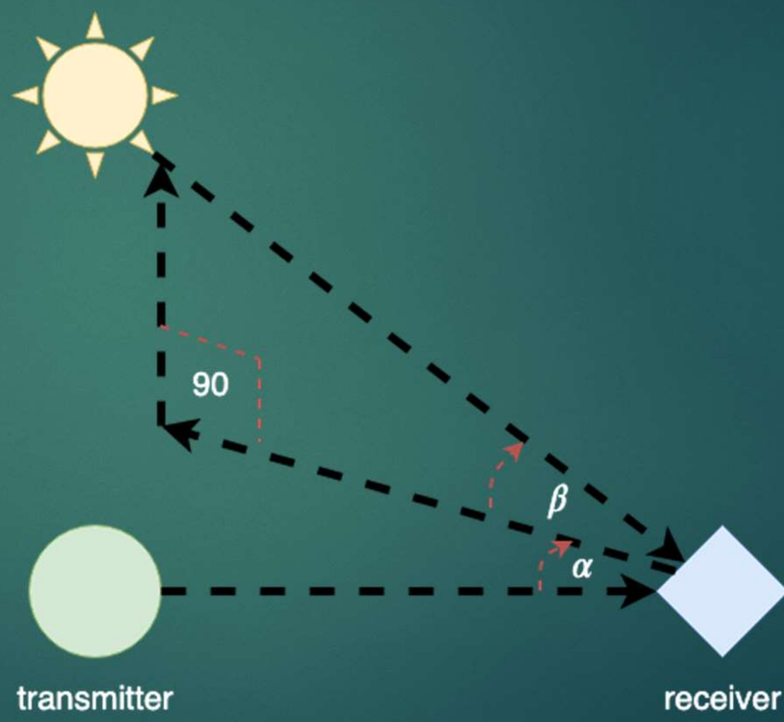

Receiver
diode
mached filter
demodulator
detector
recovered data
Transmitter
data
modulator
LED driver
LED

Experimental Setup

- Each experiment repeated 30x, then the results were averaged. (Liu et al., 2011)
- Split into 2 major subsections:
  - Feasibility of transmitter-to-receiver communication tested under various conditions (day, night…)
    - This was a physical test with real hardware
  - Feasibility of the ad-hoc network formation and performance.
    - This was simulated using some of the results found from the first part plus some general assumptions about road conditions and traffic
    - Used 30 vehicles in a simulated multi-lane highway

Point to point VLC communication

- Diurnal (Daylight)



Diurnal Testing – Setup

- Main source of noise assumed to be direct sunlight
- Since receiver is mounted horizontally on the roof of the vehicle, the only interference from sunlight would occur during dusk and dawn, when the angle of elevation is quite low.
- Thus the testing limited data capture to when the elevation angle was between 10º and 45º
- Measured packet delivery ratio

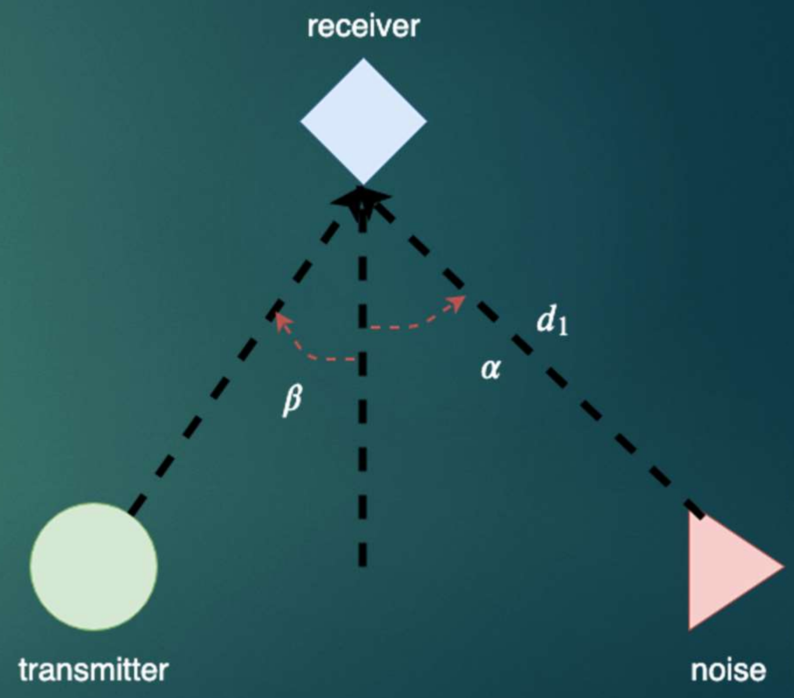
$$PDR = \frac{Succesfully\ delivered\ packets}{Total\ packets}$$

Diurnal Testing – Results

- Within ~100m between the receiver and transmitter, the error rate was **exactly** zero
- Beyond 100m, the error rate was virtually 100%
- This suggested high resiliency to sunlight as a form of noise
- (GAPS in knowledge)
- Note that the LED transmitter used was built from 120 x 120mW individual LEDs

Night-time testing – Setup

- Main driving assumption here was that noise during night-time mainly caused by external halogen and LED light sources.
- Same metric (PDR) measured and averaged.
- Did not consider other transmitter to be sources of noise.

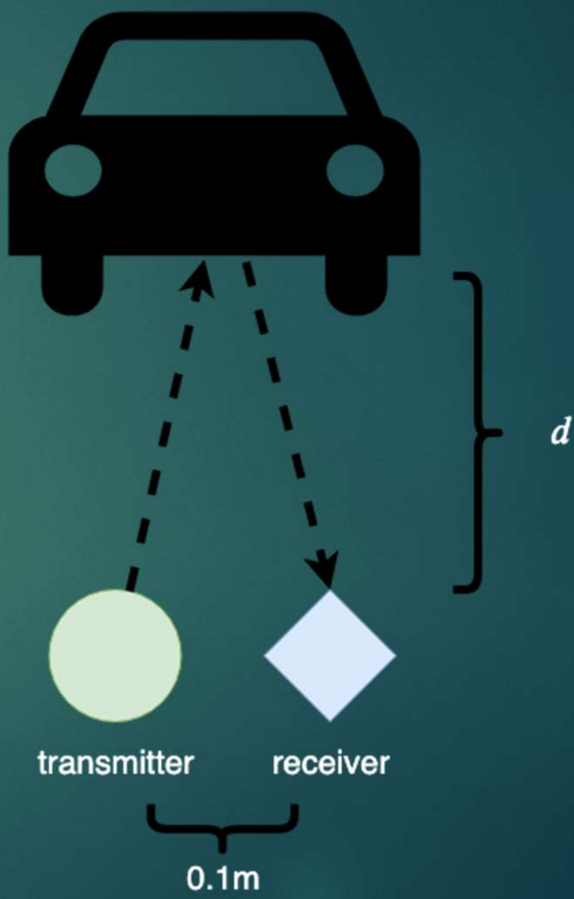


Night-time testing – Results

- Had similar results to diurnal testing
- Receiver displayed very strong resiliency to external noise
- LED sources of noise does not impact PDR whatsoever, no matter how close the noise source is to the receiver.
- Noise sources from halogen lamps cause PDR to drop to 0 when distance (d_1) between noise source and receiver <100m

Testing full-duplex communication

- Determine the minimum allowable inter-vehicular gap that facilitates error-free full duplex communication
- Sources of interference assumed to be multipath propagation from other transmitters



Results

- As long as vehicles maintain a minimum 1.5m distance between each other, communication should be 100% reliable
- Any closer than 1.5m and the reflection off the vehicle body would contribute too much multipath interference and cause SNR to drop
- Again we see a clear, definitive cutoff for 100% reliability and 100% failure rate.

What these results mean

- Although not asserted by the paper, it seems very optimistic that PDR would be 100% without fail under all conditions
- We don't know how long the transmissions were (shorter packets less likely to fail) or whether or not 30x is sufficient
- Although major sources of noise were identified and tested, this was done in a static environment. Results might be more akin to urban environment if done so with consideration for reflections from pavement, buildings (especially at night)
- This is a good first exploration

Ad-hoc networking using VLC

- Computer Simulated
- 30 vehicles, operating on a virtual 3 lane road, under various configurations of different traffic densities
- Uses the ALOHA protocol, with 100kbps data rate as demonstrated in the prototype
- Success metric defined as the percentage of all vehicles that can be reached by a single initiating source node

Vehicle-to-Vehicle Broadcast

- Head of the vehicle cluster needs to be able to broadcast message to the rear in the event such as discovering an accident.
- 100% reachability if vehicles maintain front-rear spacing of less than 66m, beyond that results fluctuate
- Packet delay also increases with inter-vehicular spacing
- Packet collision rate relatively consistent across all distances, shows minor peak at 40m

Infrastructure to vehicle broadcast (one hop)

- For inter-vehicular spacing greater than 22m, we get 100% reachability from an infrastructure node to any vehicle on the lane
- Less than 22m distance, we start seeing effects of vehicles blocking each other across lanes, which lowers the reachability.

Unicasting between vehicle and infrastructure

- Vehicles form an ad-hoc network to bridge gap between infrastructure and any reachable node
- In this experiment, vehicles in the lane farthest from infrastructure nodes try to continuously contact gateway by piggybacking onto the ad-hoc vehicular network
- Throughput measured as fraction of data rate 100kb/s
- Results show that denser traffic lead to higher throughput, but net throughput < 1 due to inefficiencies of the routing protocol

General comments about Ad-hoc networking feasibility

- The paper again makes optimistic claims about the feasibility of building an ad-hoc network that supports high throughput.
- Generating results based on simulation is a good start, but some key aspects of the simulation may have been left out or needs to be further explored.
- Direction of traffic were assumed to be same for all vehicles, but what if direction of travel was different? Could interference from oncoming traffic headlights affect reliability? What about weather conditions? Would the simulated distances change under cloudy skies vs rain vs sun?
- All in all, it does cover fundamental concerns and questions for actually attempting to build a vehicular network using VLC.

Conclusion

- Infrastructure seems to already be present to facilitate this
- Existing modulation schemes applicable
- Demonstrates ability to support networked communications
- With bandwidth quickly running out over existing RF frequencies, development and exploration of VLC may be necessary.
- Promising results thus far

Works Cited

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