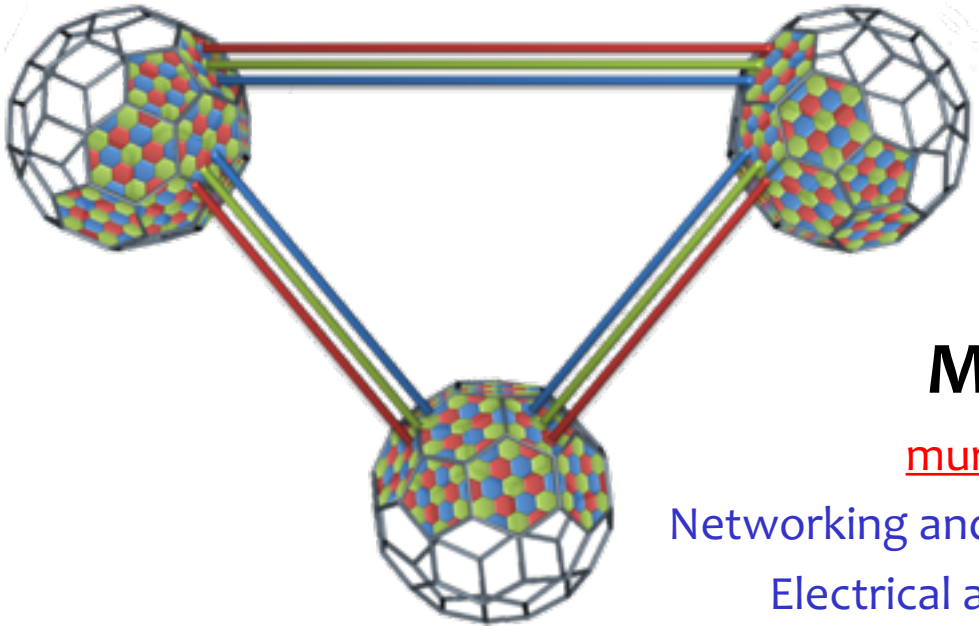
Multi-Element Optical Wireless Modules for Mobile Networking and Lighting



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Project Websites

https://sites.google.com/site/nsfvlc

http://www.ece.ucf.edu/~yuksem/fso-manet.htm

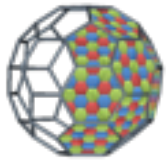
UCF

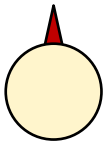
CoNEXT Student Workshop, December 9, 2019

Outline

Part I: Multi-Element FSO (Optical Wireless) Modules

- Motivation
- FSO Modules w/ Electronic Steering
  - Multi-Transceiver FSO Spheres
  - LOS Alignment Protocol
  - FSO Packet Simulations
- FSO Modules w/ Mechanical Steering
  - In-Band LOS Alignment
  - 2D vs. 3D
- Multi-Element VLC
- Future Directions





Part II: Career Advice

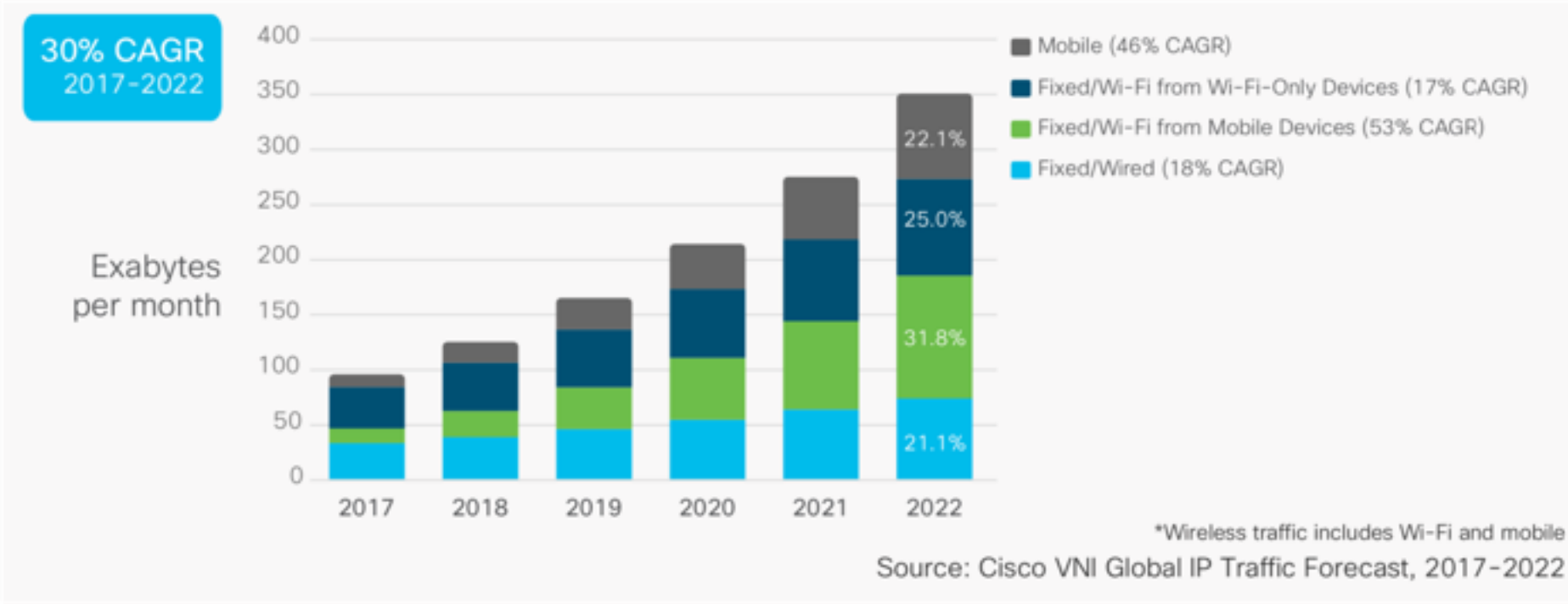
Part I

Multi-Element FSO (Optical Wireless) Modules

Wireless Capacity – NOW!

- Scary trends in mobile wireless demand
  - Grown 4K-fold in 10 years and almost 400M-fold in 15 years.

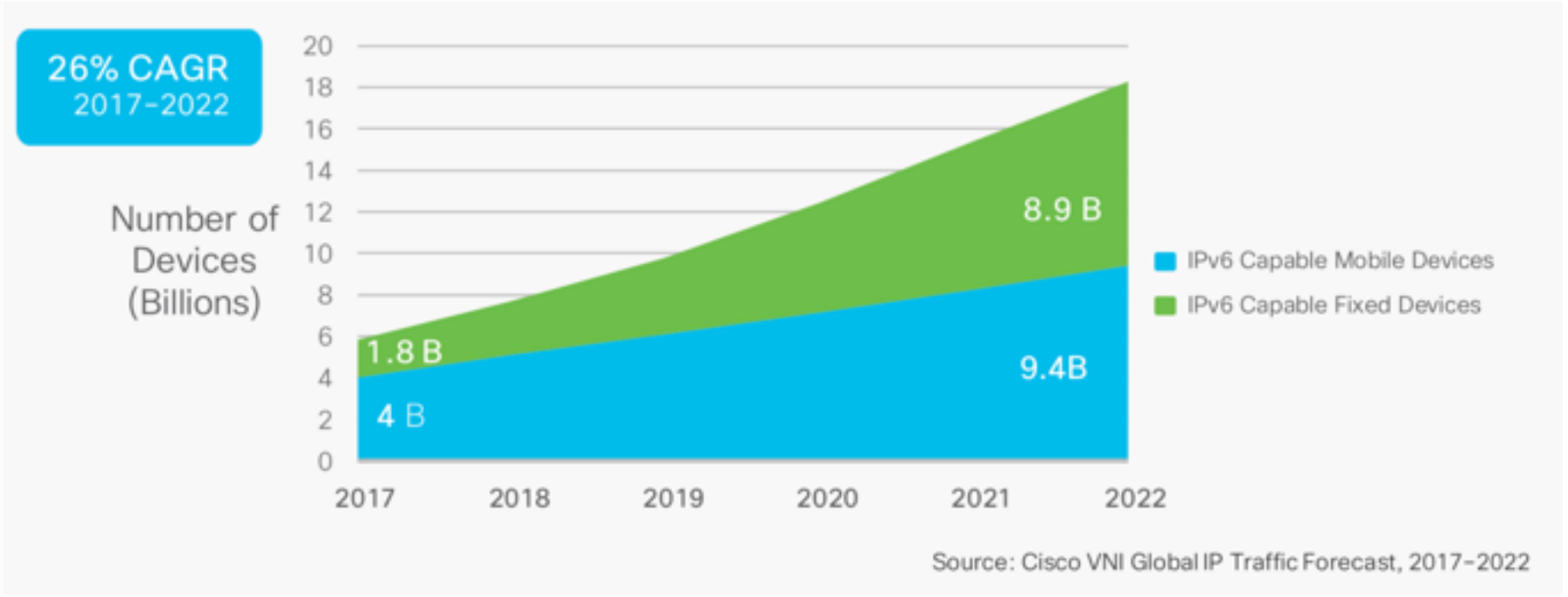
2017-2022 predictions: > 1.5 times increase per year



Cisco VNI Report 2018

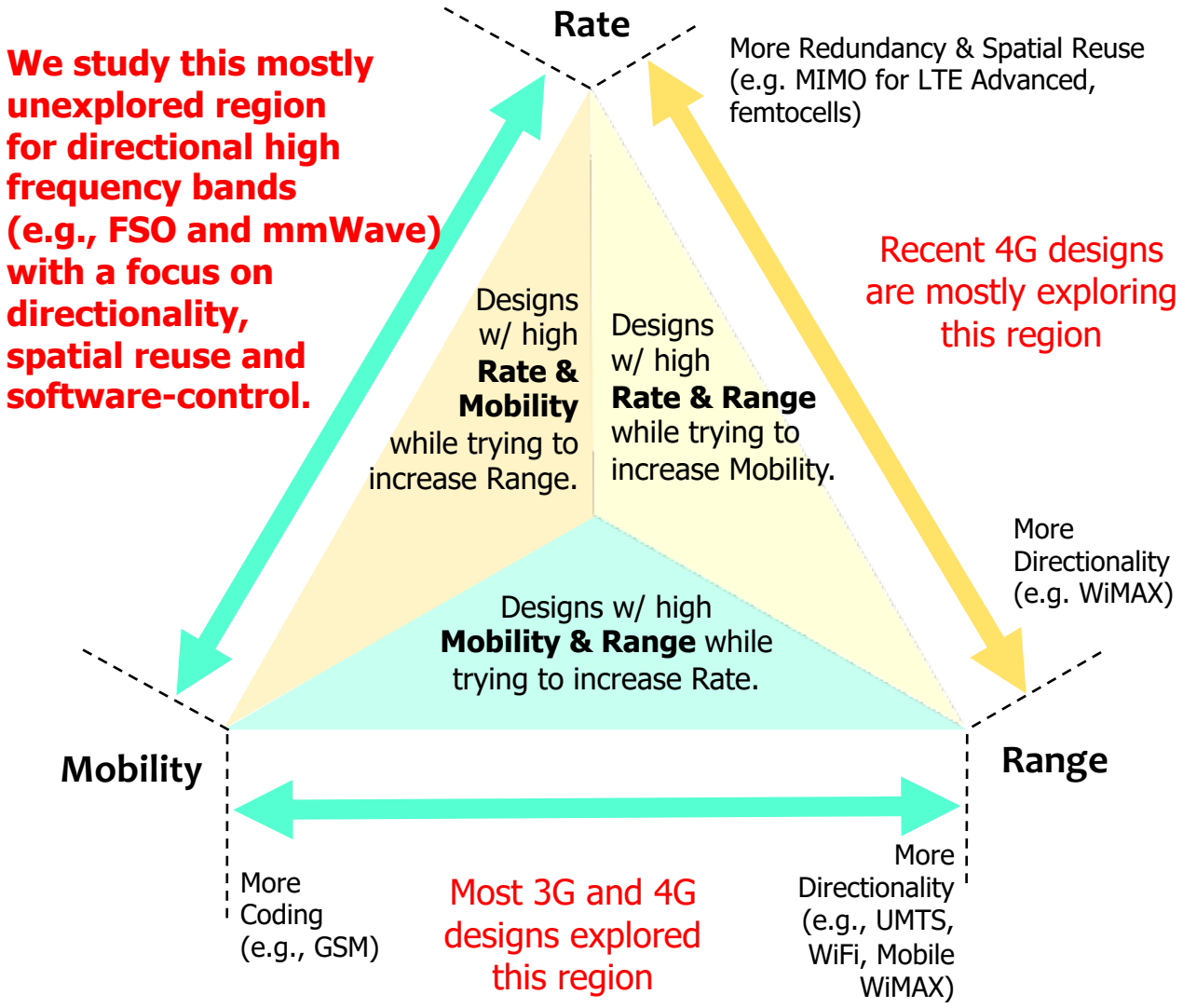
Seems Inescapable by the Internet

- Wireless node count > wireline in 2015!
- Mobile node count will surpass fixed node count too..
- Mobile nodes and M2M will dominate wireless traffic

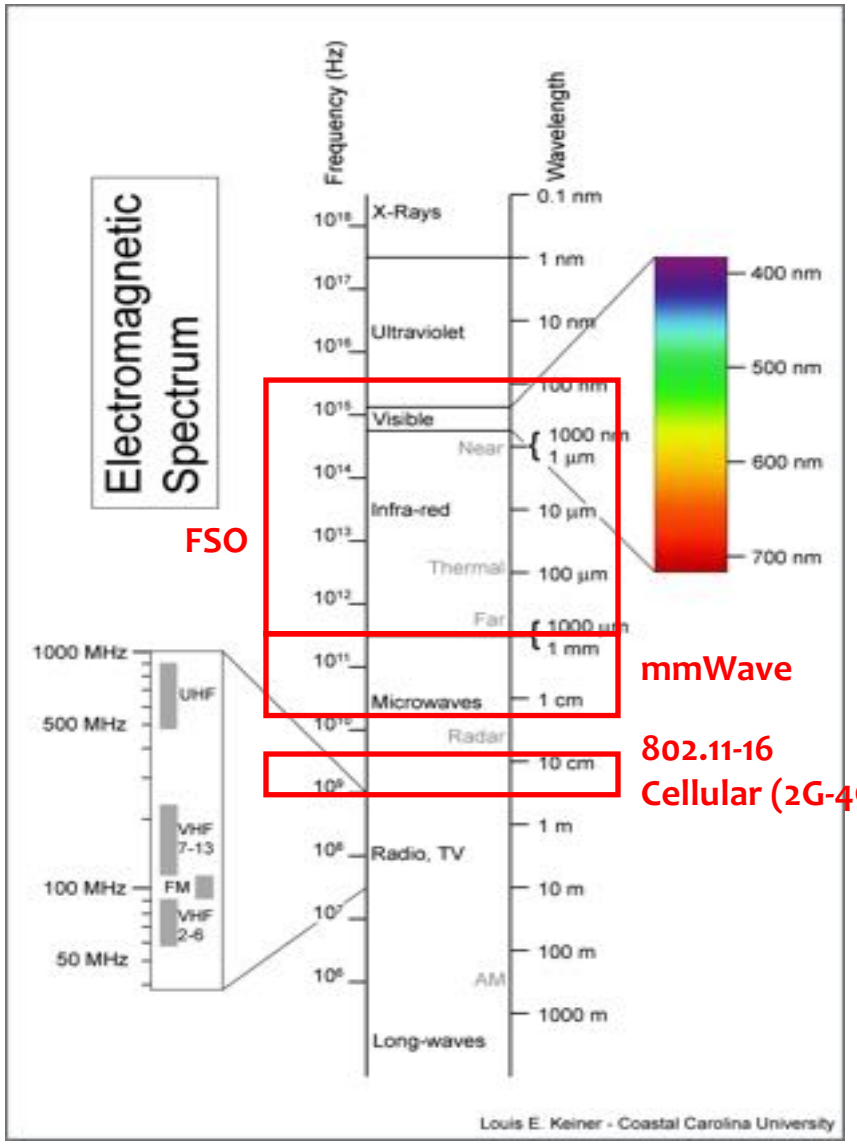


The RF spectrum is getting saturated.. We need alternative communication spectrum resources for opportunistic usage.

Wireless Spectrum Tradeoffs: Rate/Mobility/Range



Wireless Spectrum Tradeoffs (cont'd)



- Mostly unlicensed bandwidth available at higher frequency EM spectrum
  - Higher *rate* even with modest spectral efficiency
  - High *spatial reuse* due to highly directional signal propagation
- But, these EM regions are poorly suited for
  - *range*: small wavelength is absorbed too easily
  - *mobility*: line-of-sight alignment

KEY INSIGHT

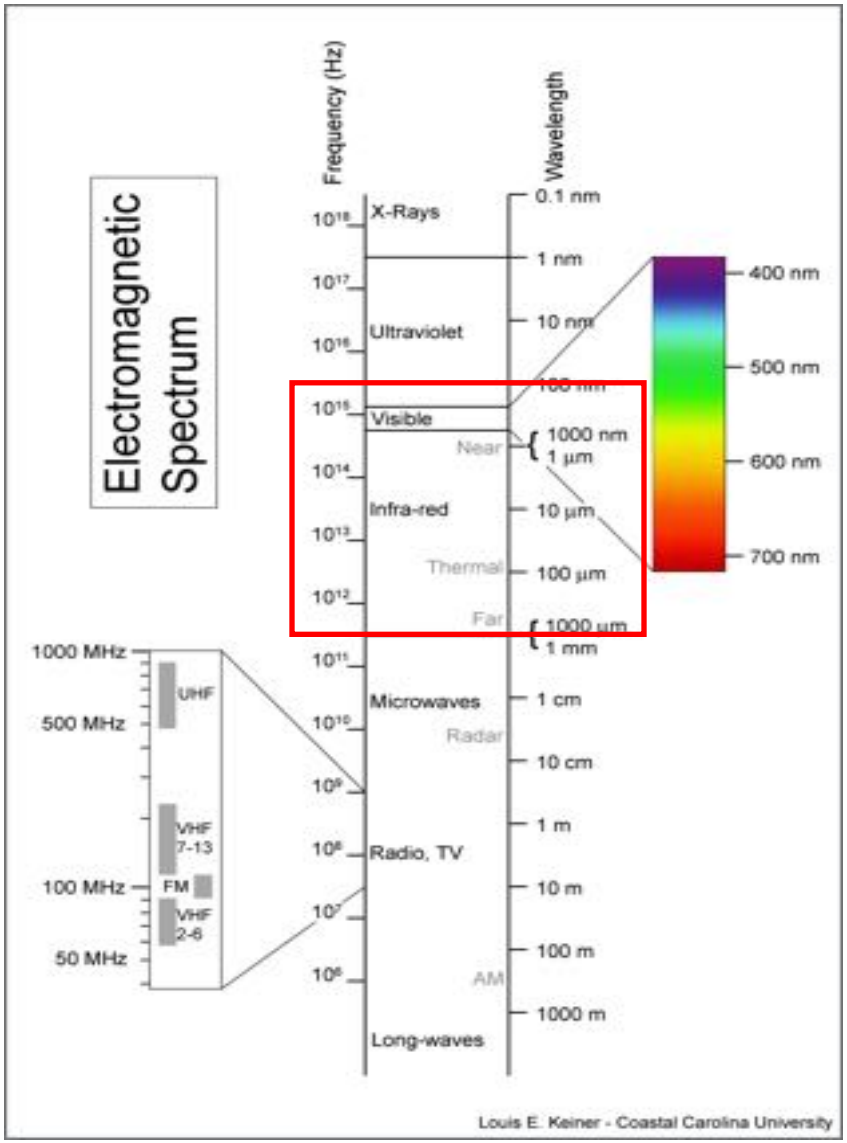
Give up on range goals, focus on *rate* instead!

HOW?

Develop low-cost multi-element designs for opportunistic (ad-hoc) use.

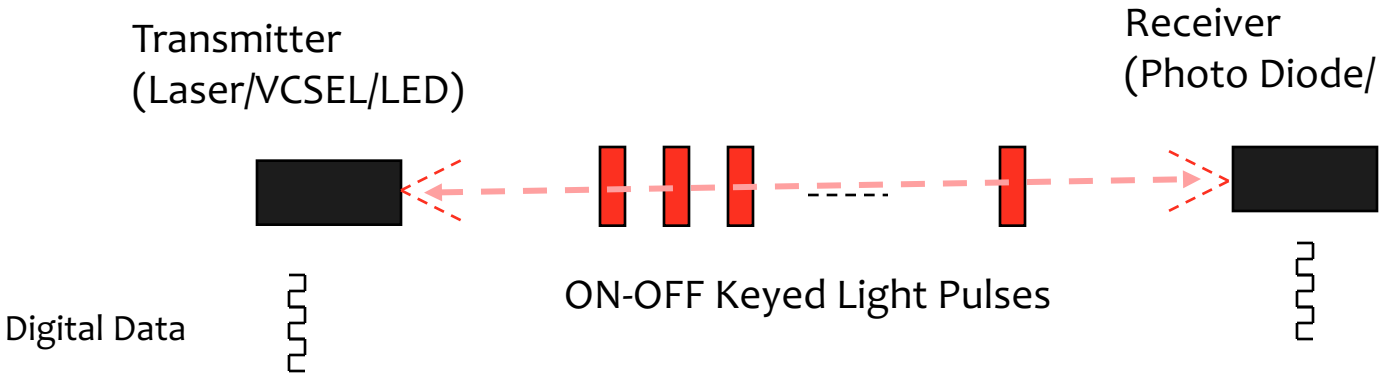
***Handle mobility at higher layers* with limited support from PHY/MAC.**

Free-Space-Optical (FSO): Open spectrum



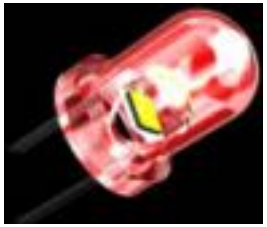
- **<u>Open spectrum</u>:**
  - > 300 GHz
- FSO usage:
  - point-to-point links
  - interconnects
  - indoor infrared/visible communications
- DoD use of FSO:
  - satellite communications
  - air-to-ground, air-to-air, air-to-satellite
- Recent civilian uses:
  - VLC

Optical Wireless: Commodity components



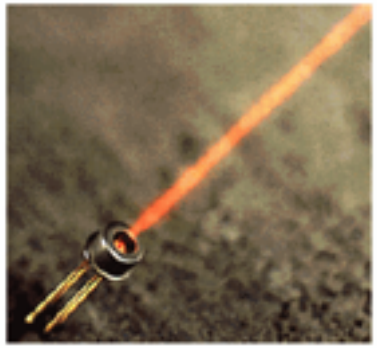
Lasers…

LEDs…



IrDAs…

VCSELs…



Many FSO components are low cost & available for mass production.

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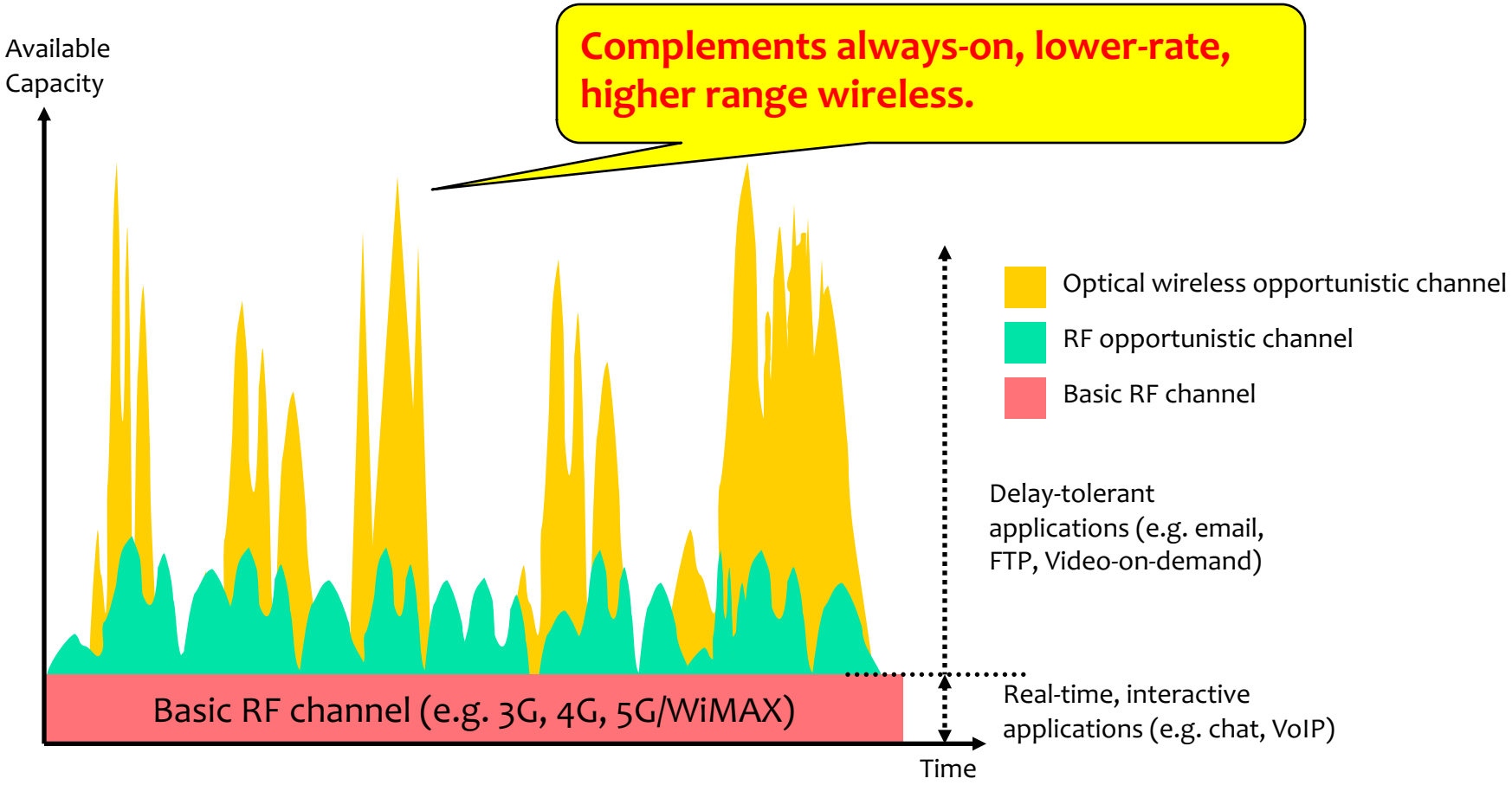
Opportunistic FSO (Optical Wireless) Channel



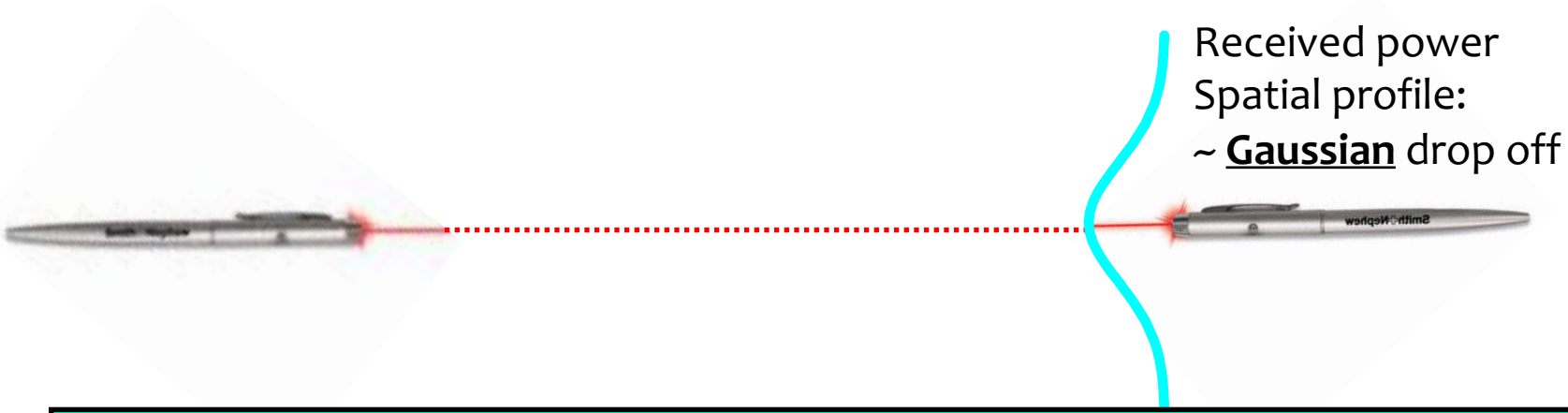
We consider **a specific PHY technology, free-space-optics (FSO),** that could be useful in this context, and its implications on higher-layer protocols.

Optical Wireless: Why?

- **More secure:** Highly directional => low probability of interception
- **Small size and weight:** Dense packaging is possible
- **Very low cost** and **reliable** components
  - <60 cents a piece and <$5 per LED transceiver package + up to 10 years lifetime
- **Very low power** consumption (100 microwatts for 10-100 Mbps!)
  - Even lower power for 1-10 Mbps
  - 4-5 orders of magnitude improvement over RF
- Huge **spatial reuse** => multiple parallel channels for bandwidth increases

FSO Issues/Disadvantages

- Limited range (no waveguide, unlike fiber optics)
- Need line-of-sight (LOS)
  - Any obstruction or poor weather (fog, heavy rain/snow) can increase BER in a bursty manner
- **Bigger issue:** Need tight LOS alignment:
  - LOS alignment must be maintained with mobility or sway!
  - Effects of relative distance and mobility



Can we reap FSO's benefits while solving these issues?

Software-Defined FSO Modules: Spherical Designs

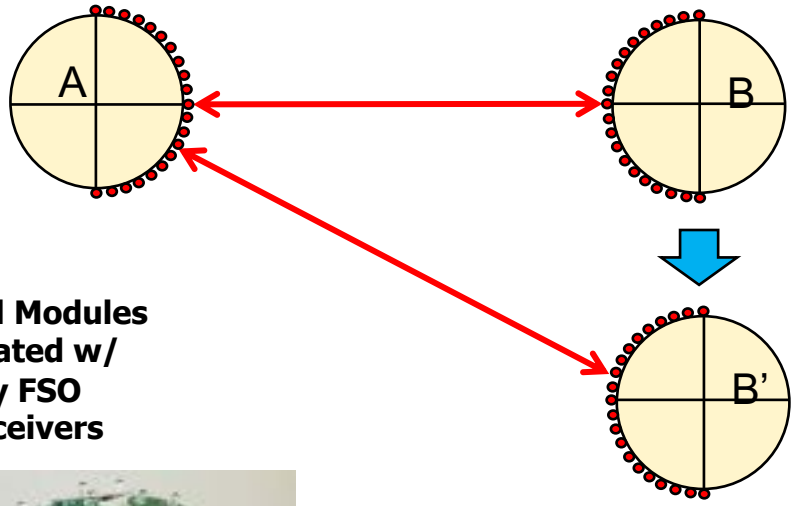
- How to handle mobility under LOS alignment requirement?

Software-Defined Mobile FSO =

Directionality + Angular Diversity + Electronic Steering

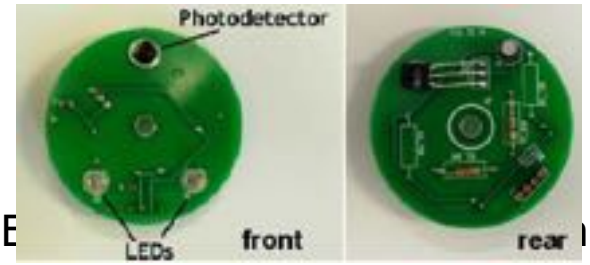
Multi-transceiver spherical FSO designs.

Need a distributed protocol for this!



Bidirectional LOS

Spherical Modules Tessellated w/ Many FSO Transceivers

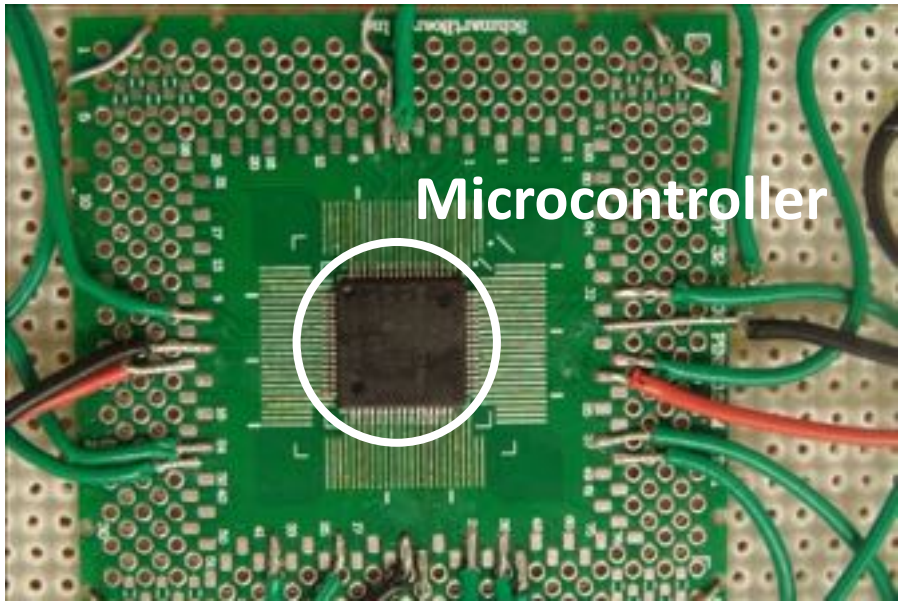


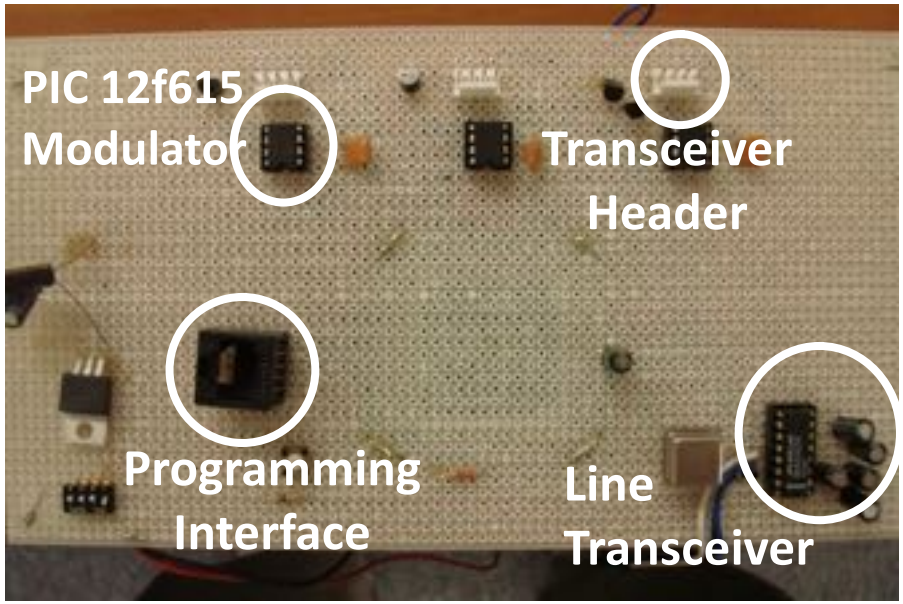
- Multi-element spherical modules
- Angular diversity due to spherical packaging
- Designs conformal to surfaces
- Electronic steering of LOS alignment across many redundant FSO transceiver elements

3-Transceiver Prototype

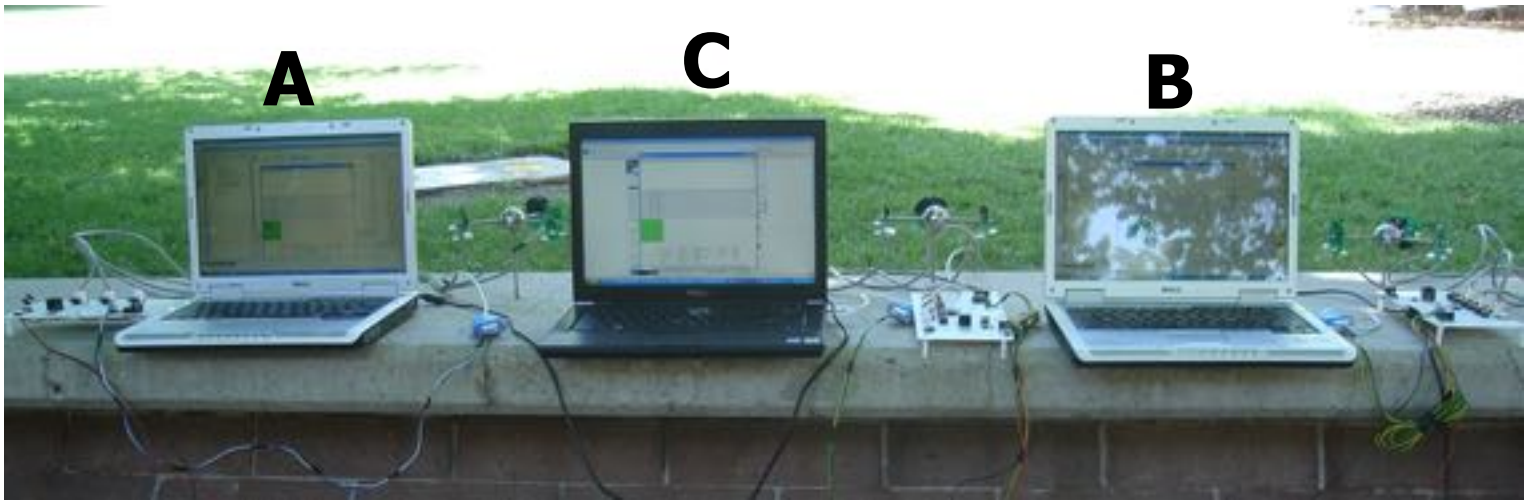
Circular 3 Transceiver Design

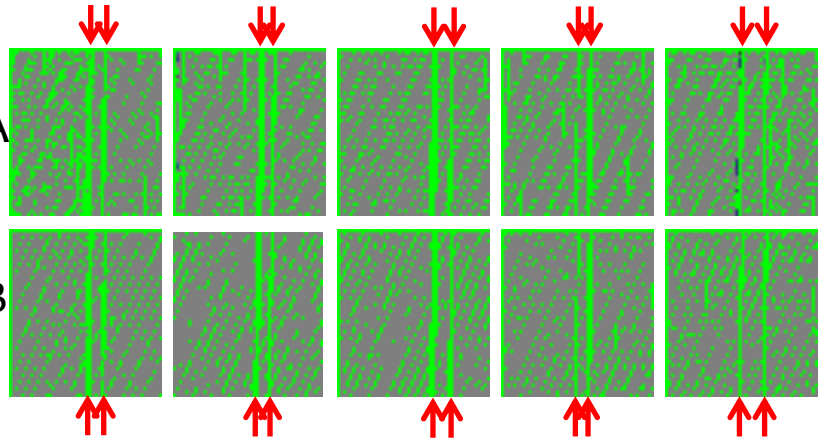
The design consists of 3 FSO transceivers connected to a circuit board with a microcontroller.

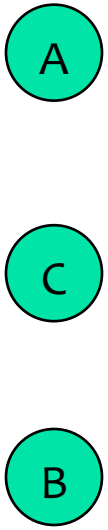




FSO Prototype: Mobility Experiment



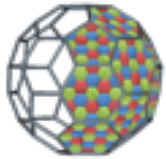




~19Kb/s ~20m frame size 50B

alignment timer 500ms

Ad Hoc Networks 2013



Worth It?

OK. It works..
But, does it really worth the effort?

Can we really scale wireless capacity via these multi-transceiver FSO modules?

What are the limits?

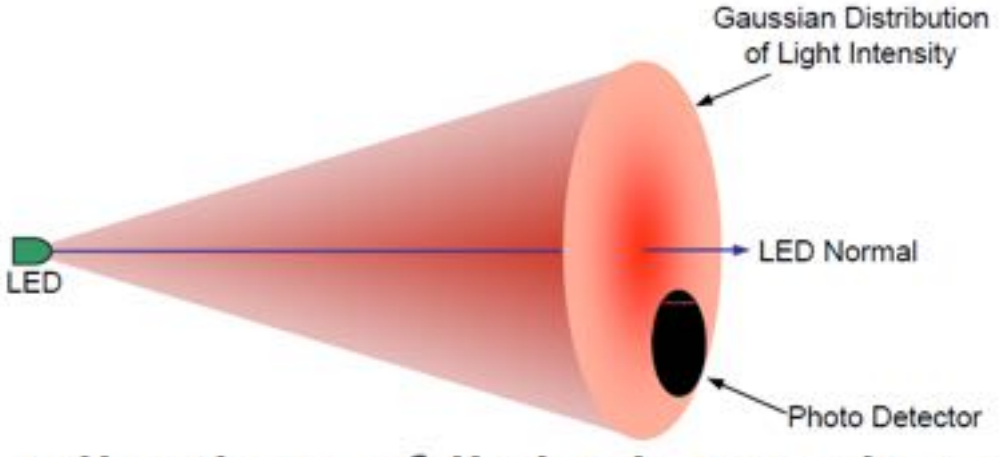
How to tune the LOS alignment protocol?

How about power consumption of all these transceivers?

...

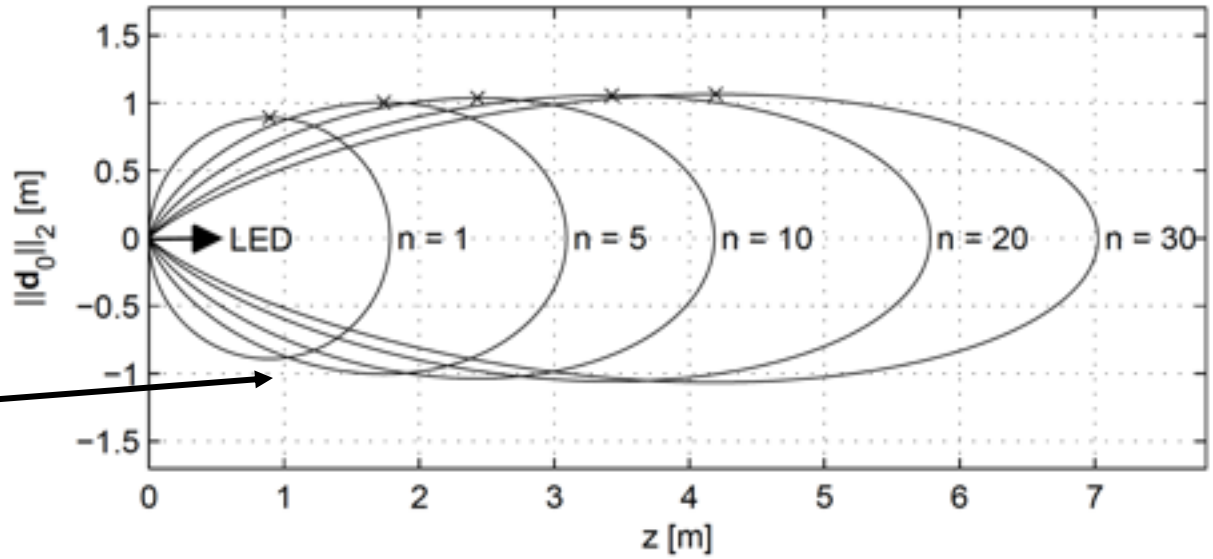
FSO Packet Simulations: Propagation & Interference

- FSO Propagation
  - Geometric Attenuation
    - divergence angle
    - receiver's surface
  - Atmospheric Attenuation
    - visibility



$$P_{mk} = \frac{n+1}{2\pi}\cos^{n}(\phi_{mk})$$

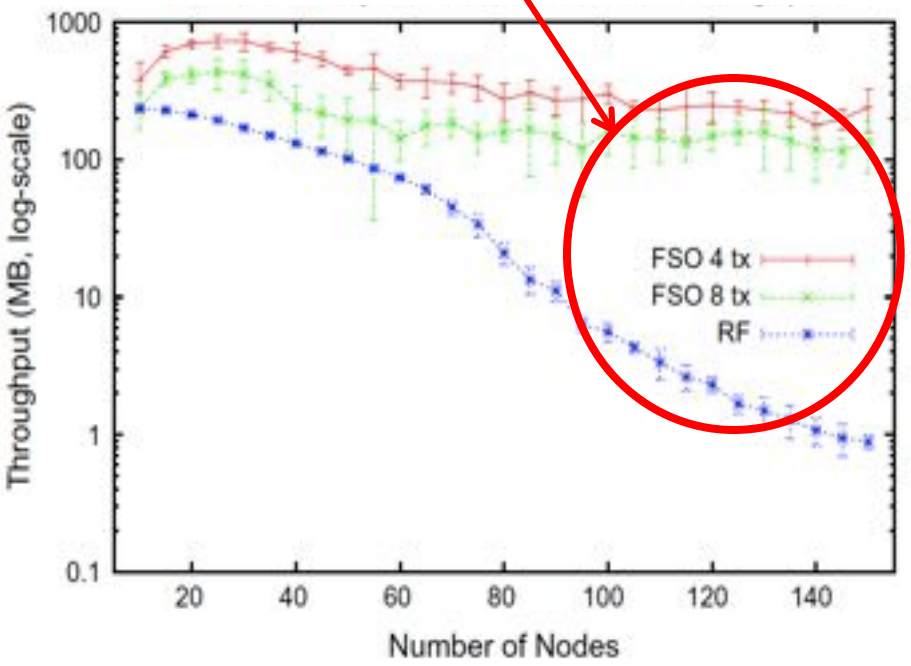
Lambertian law

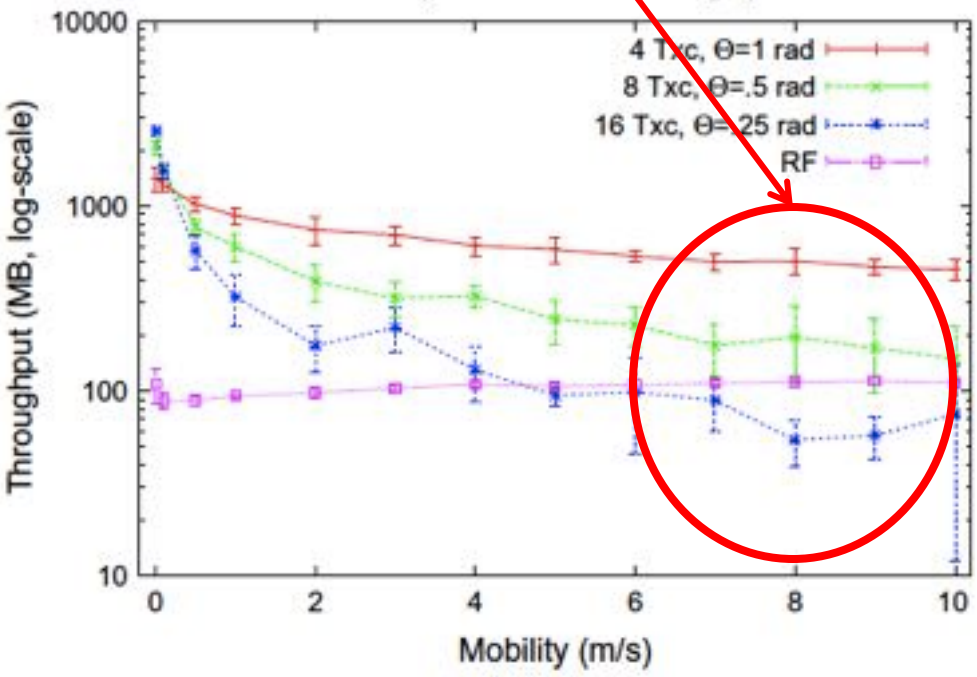


TCP Throughput over FSO Modules

Spatial reuse exploited: > 100-fold improvement in dense networks

For high mobility, need to increase/tune search frequency or use buffering at layers 2 or 3.

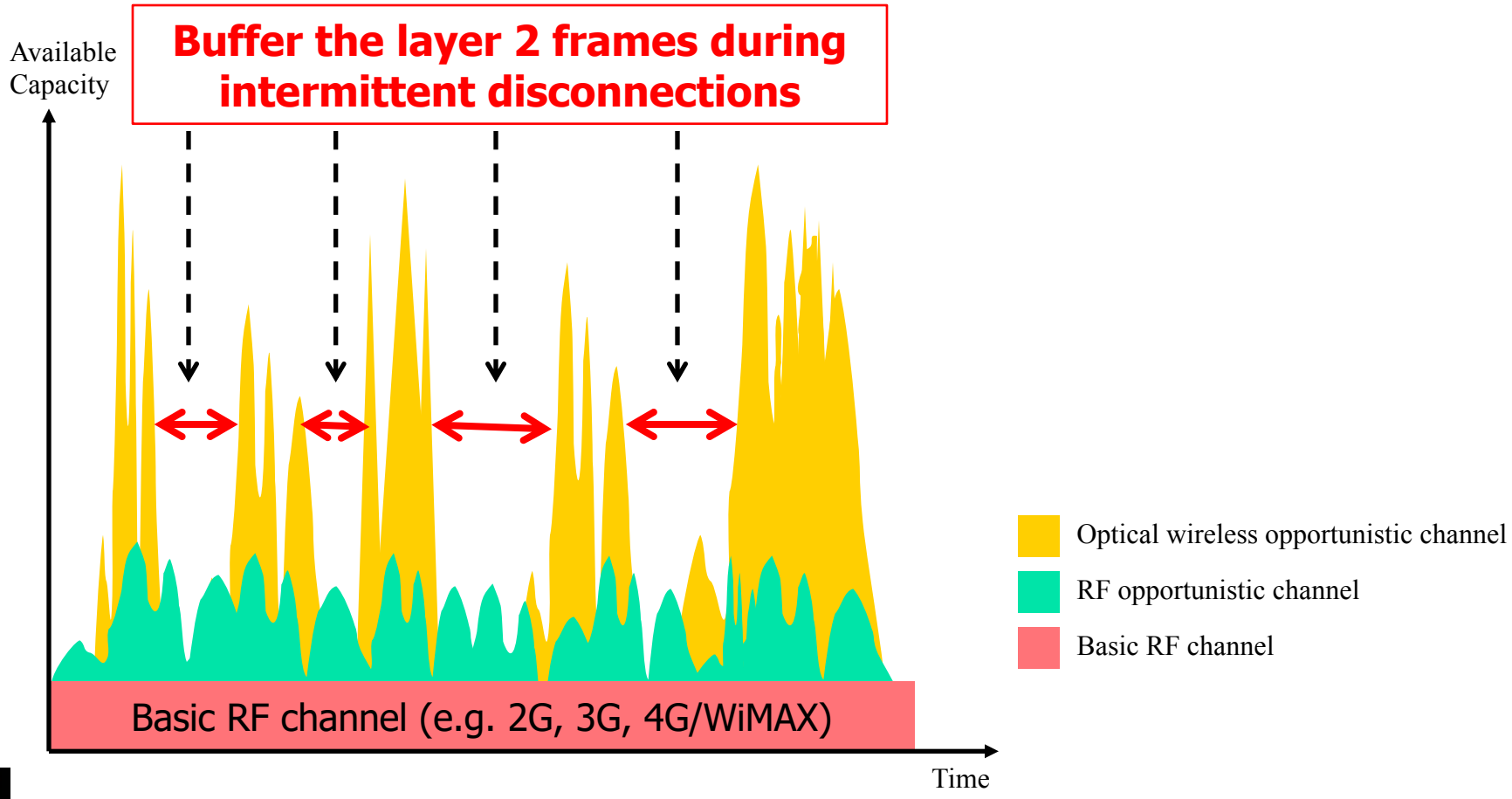




Ad Hoc Networks 2014

FSO Modules: Buffering

- End-to-end transport like TCP is extremely sensitive to intermittency ➔ Need to smoothen the opportunistic FSO channel.

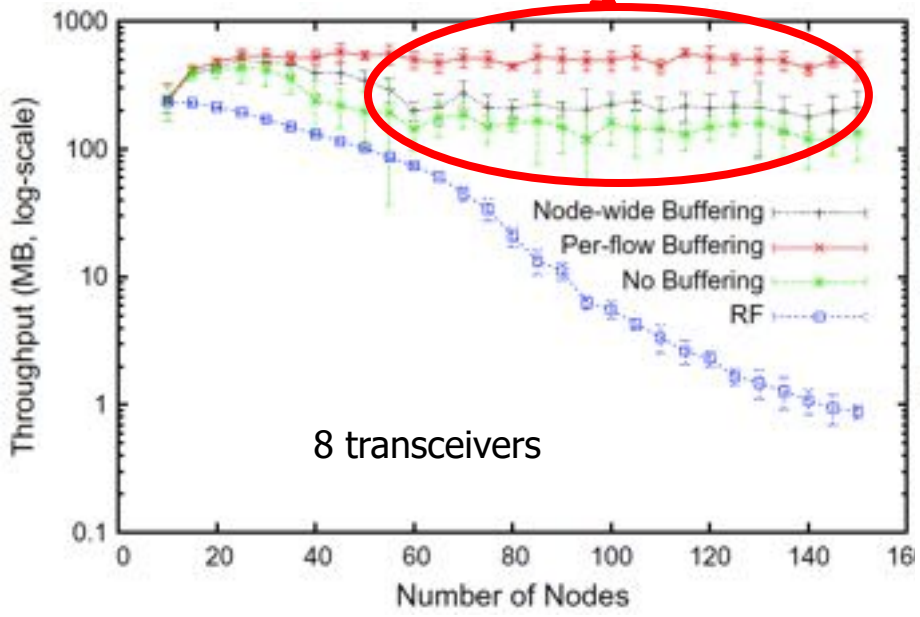


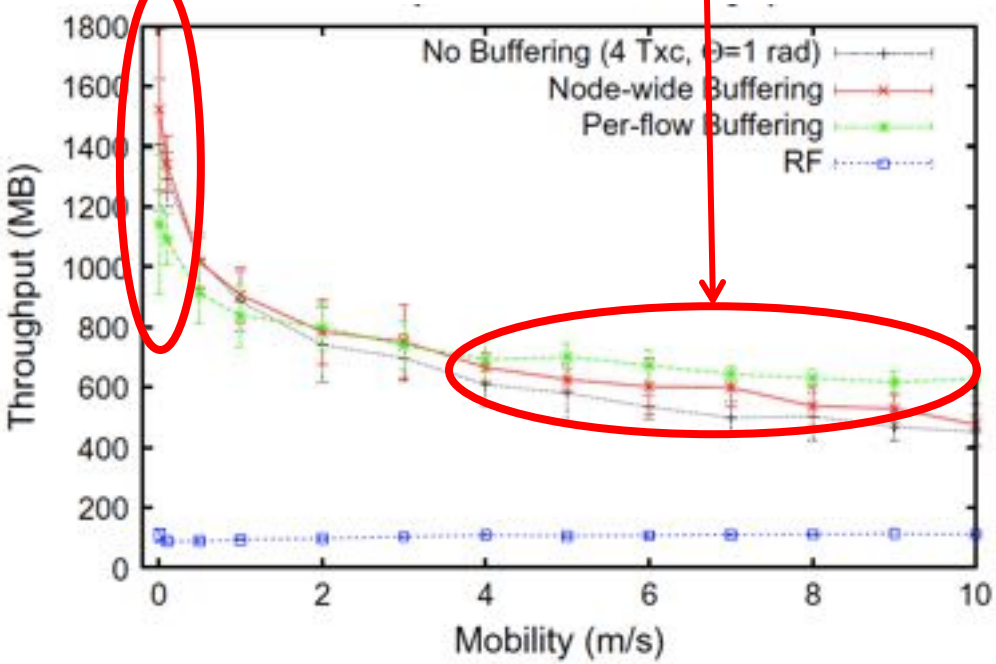
FSO Modules: Buffering

Cross-layer buffering makes FSO almost independent of network size!

But, interacts with TCP congestion control at low mobility!

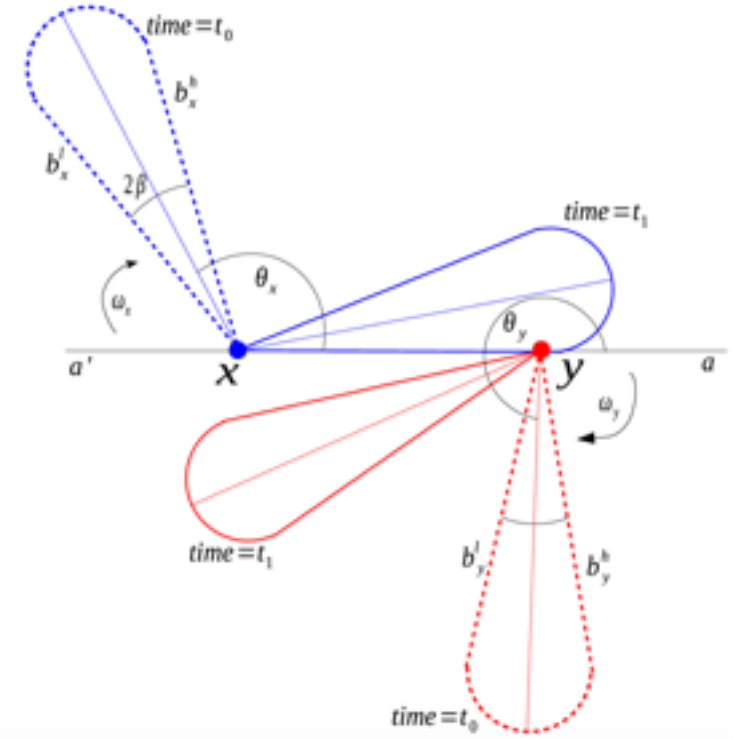
Buffering helps significantly at high mobility.

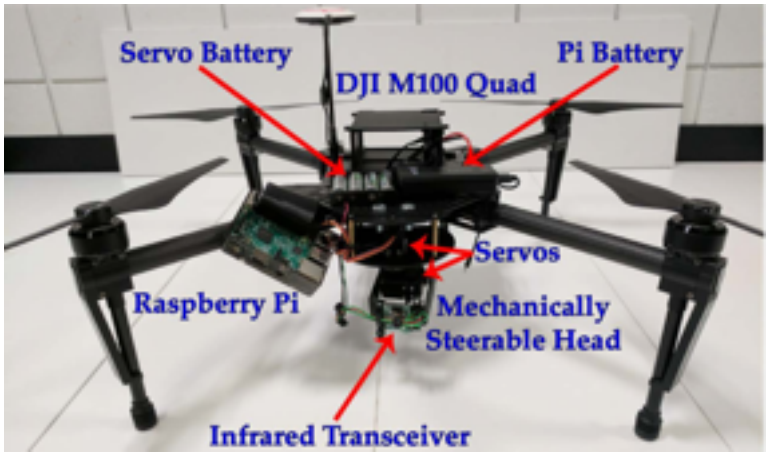


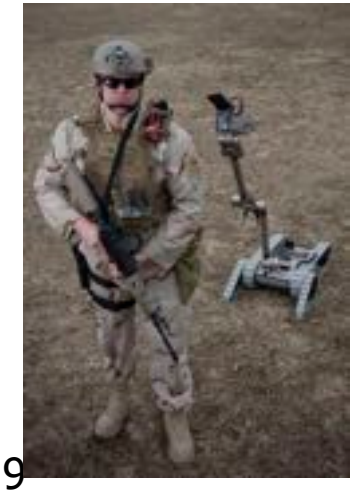


FSO Modules: Mechanical Steering

- Assumptions:
  - One transceiver on mechanically steerable head
  - Equipped with Inertial Measurement Unit
  - In-band: No radio or out-of-band channel
  - No GPS



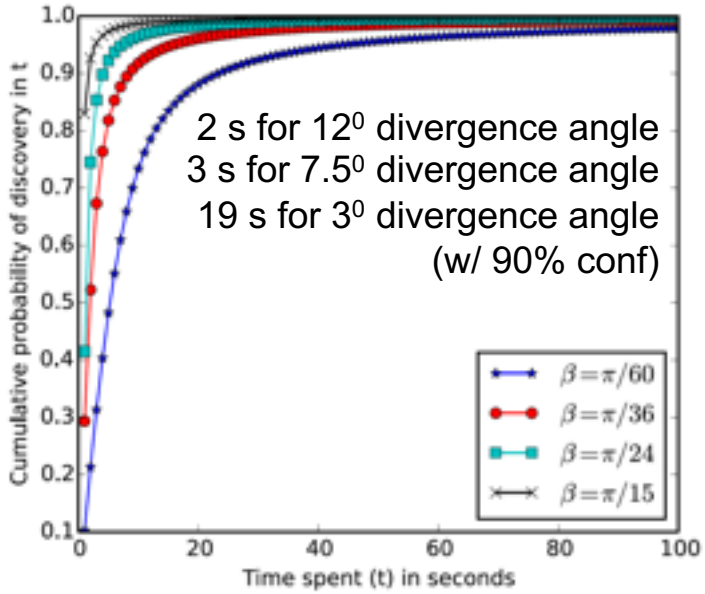




- Can we **discover** and **maintain** the FSO link in
  - 2D: PackBots, UGVs, ships
  - 3D: UAVs, Google Balloons, FB solar drones

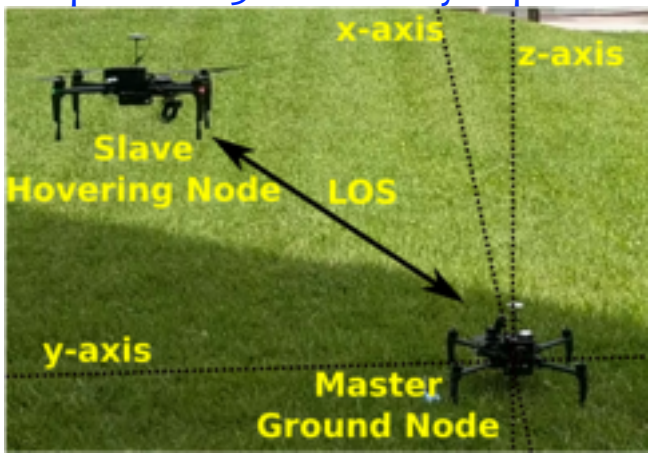
(Sort of) In-Band LOS Discovery

- 2D: Randomized rotation



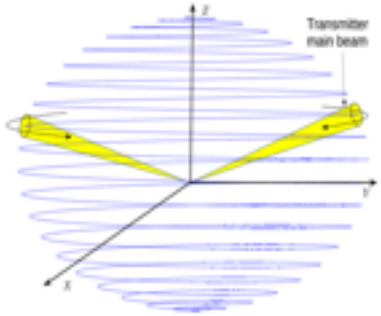
2 s for 12^0 divergence angle
3 s for 7.5^0 divergence angle
19 s for 3^0 divergence angle
(w/ 90% conf)

Snapshot of 3D discovery experiments



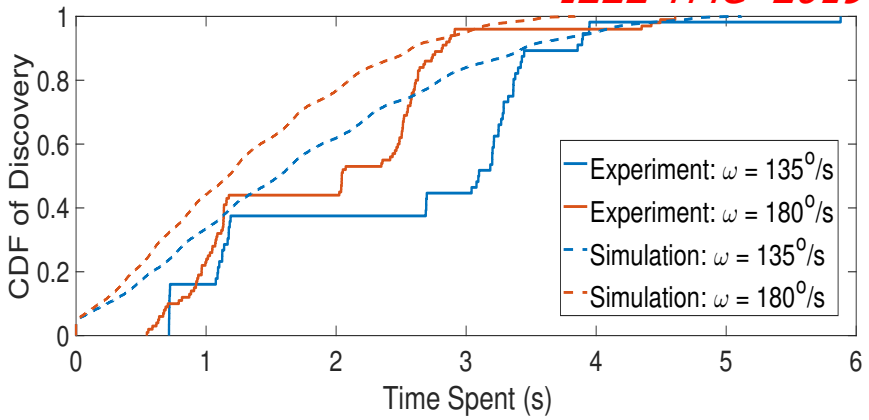
IEEE MILCOM 2016
Ad Hoc Nets 2019
(patent pending)

- 3D: Synch w/ RF at the start, then, rotate over a helix:



0.2 s for 12^0 divergence angle
0.4 s for 7.5^0 divergence angle
0.9 s for 5^0 divergence angle
2.5 s for 3^0 divergence angle
(w/ 90% conf)

IEEE MILCOM 2016
IEEE TMC 2019



Discovery within a few seconds:
No GPS, only initial synchronization via a beacon

3D: Still evaluating a totally in-band solution

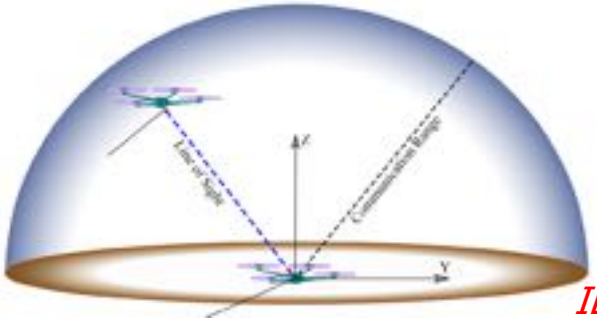
In-Band LOS Link Maintenance in 3D

- Key Idea: Use the link itself to exchange at every t_x

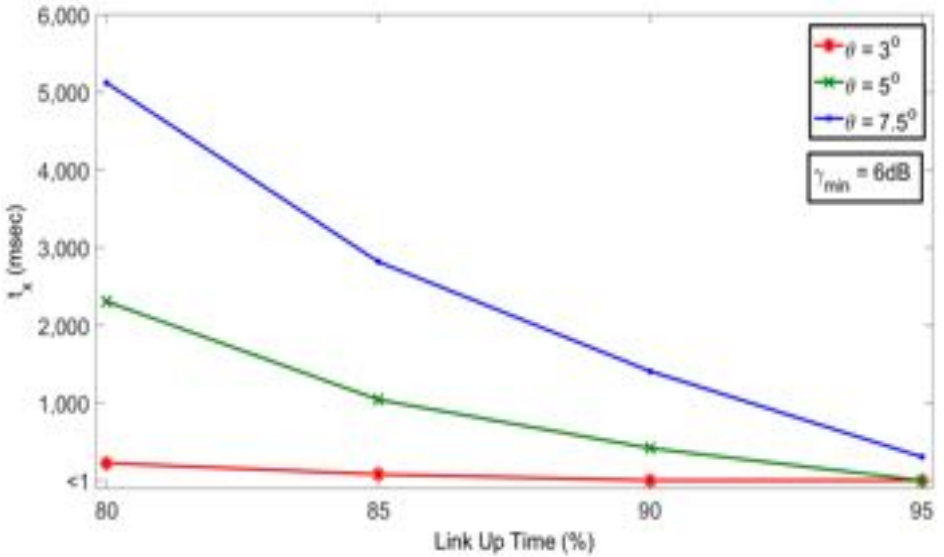
<Direction, Speed, Orientation of the head>

- Then, each node can autonomously determine
  - Angular Velocity of head
  - Direction of Rotation

	Laser at Long Range	LED at Short Range
Speed	25 m/s	5 m/s
Range	2.5km	100m
θ	2, 2.25, 2.5 mrad	3°, 5°, 7.5°



IEEE TMC 2017
IEEE MILCOM 2016
IEEE ICC OWC 2016
ACM MOBICOM HotWireless 2015
IEEE WCNC 2014



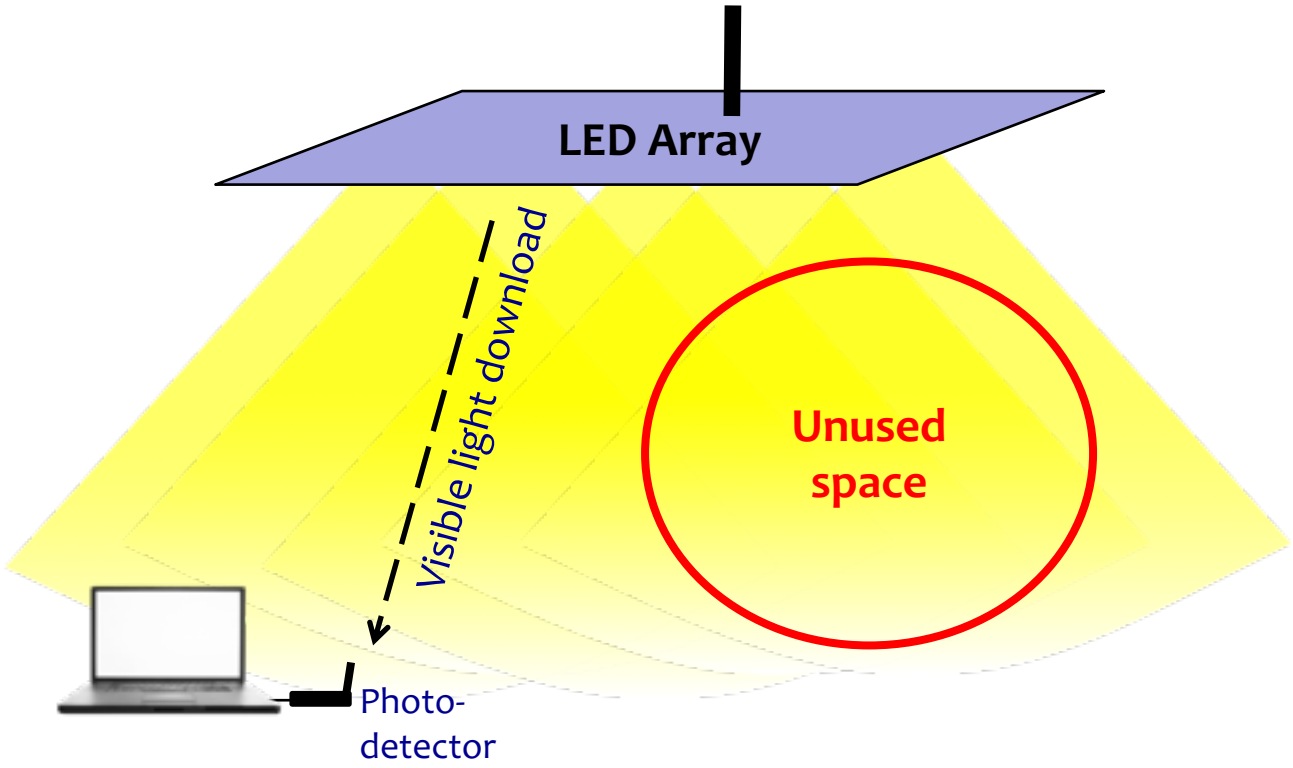
Smaller tolerance to deviation → Smaller t_x

Visible Light Communication

- **Transmission: How to use a visible light source which, in addition to illumination, can transmit information using the same light signal?**
- **Reception: How to detect the received data-carrying light signal and decode the information?**
- **Goals:**
  - High Communication Range
  - High Data Rate
  - Robust Reception in Mobile Settings
  - Uniform Illumination
  - Low Power Consumption

} The focus of our work

Why Multi-Element/Stream VLC?



Single data stream
PHY solution
Large divergence – for smooth lighting

Multiple data streams
Narrow divergence – for higher spatial reuse
Spherical structures – to retain smooth lighting

ACM MOBICOM VLCS 2015

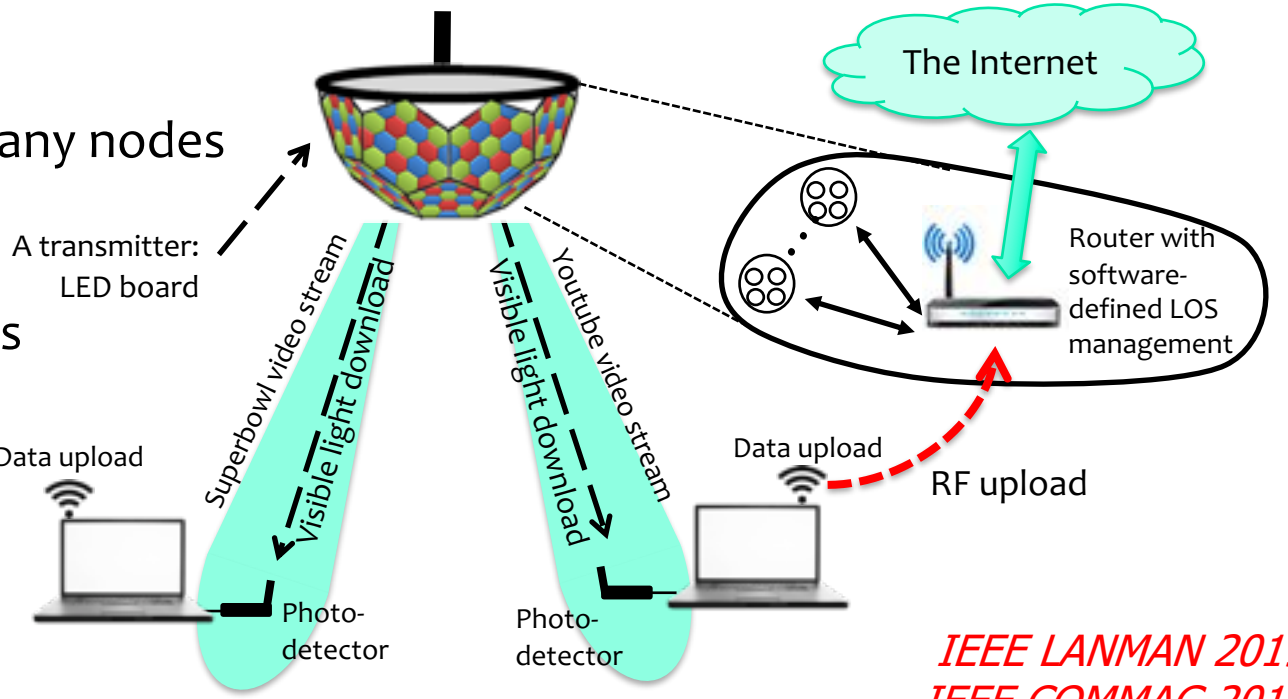
The Architecture

Idea: Replace bulbs with many-LED structures that have a router in them.

- Main components
  - The Bulb
  - RF/FSO LOS management protocol

Applications in:

- Internet of Things: Many nodes in a small area
- Indoor localization
- RF-sensitive platforms such as hospitals, aircrafts



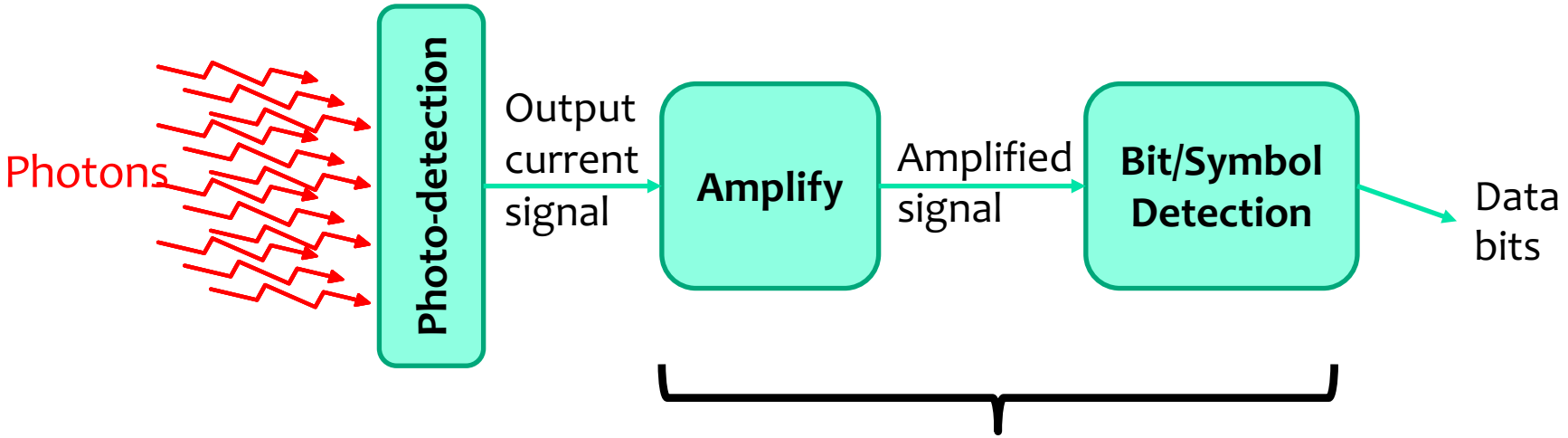
IEEE LANMAN 2019
IEEE COMMAG 2018
IEEE JSAC 2018

VLC Receivers for Mobiles

- Existing VLC solutions use receivers with large FOV but a small aperture area.
- Small aperture area allows high speed reception.
- But, can easily be blocked by a finger!

- How can we increase the reception aperture area while keeping the reception rate high?

VLC Receiver Design



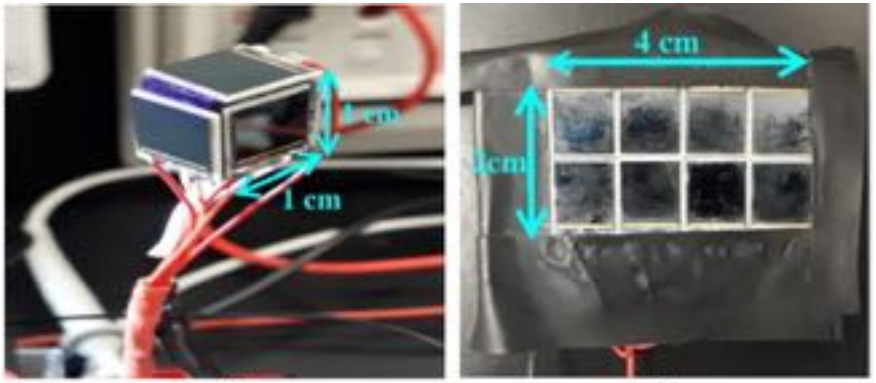
We re-worked this part while increasing the photo-detection aperture area.

VLC Receiver Design: Photo-detection

- Each APD
  - Has 1cm^2 aperture area
  - Costs $50 per piece
- 5-8 APDs
- Can be arranged conformal to the surface of the mobile device

IMPORTANT CHARACTERISTICS OF FDS1010

Specifications	
Wavelength Range, λ	$350 - 1100$nm
Peak Responsivity, $max[\mathcal{R}(\lambda)]$	0.725A/W
Active Area per PD, A	100mm^2
Rise/Fall Time, t_r/t_f ($V_B = 18V$)	18ns
Dark Current ($V_B = 18V$)	80μA
Capacitance, C_J ($V_B = 18V$)	169.2pF
Maximum Tolerable Reversed Biased, $V_{B,max}$	25V
Maximum Output Photocurrent, I_o	10mA
Maximum Optical Input Power, $P_{i,max}$	10mW

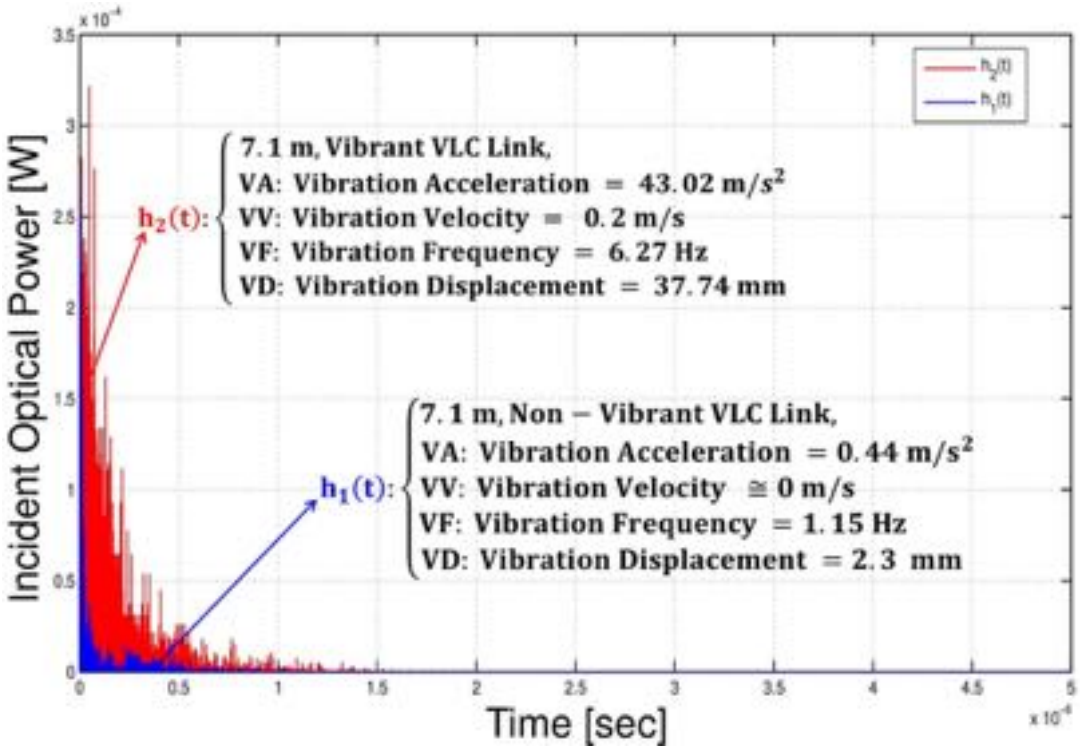


(a) (b)

Delay Spread from Vibration

- Vibration characterizations:
  - speed of 0.2 m/s
  - acceleration of 43.02 m/s^2
  - displacement of 37.74 mm
  - and frequency of 6.27 Hz
- Max delay spread in vibrant VLC link ≈ 312 ns
  - ~10 times reflection in the room

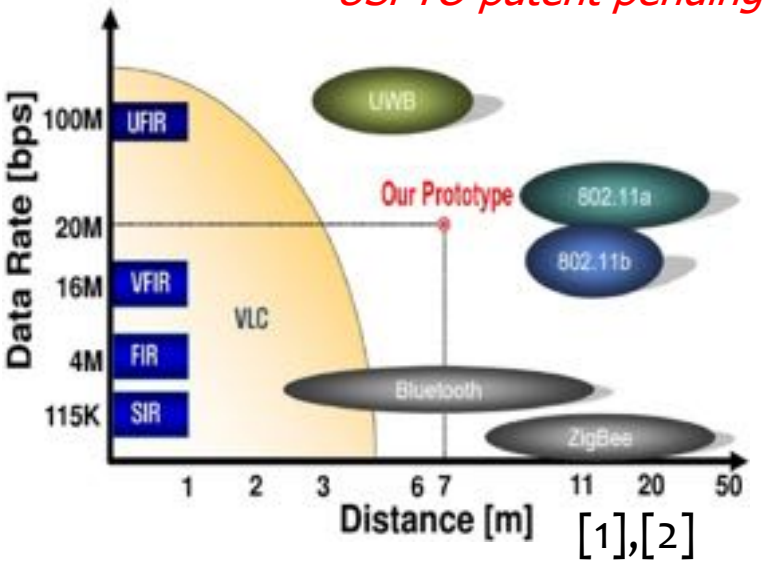
Red: Vibrant VLC link
Blue: Non-Vibrant VLC link



VLC System Performance

IEEE ICC 2019
USPTO patent pending

- Max Range $\approx 7\ m$
- Max BW $\approx 20 - 26\ MHz$



[1],[2]

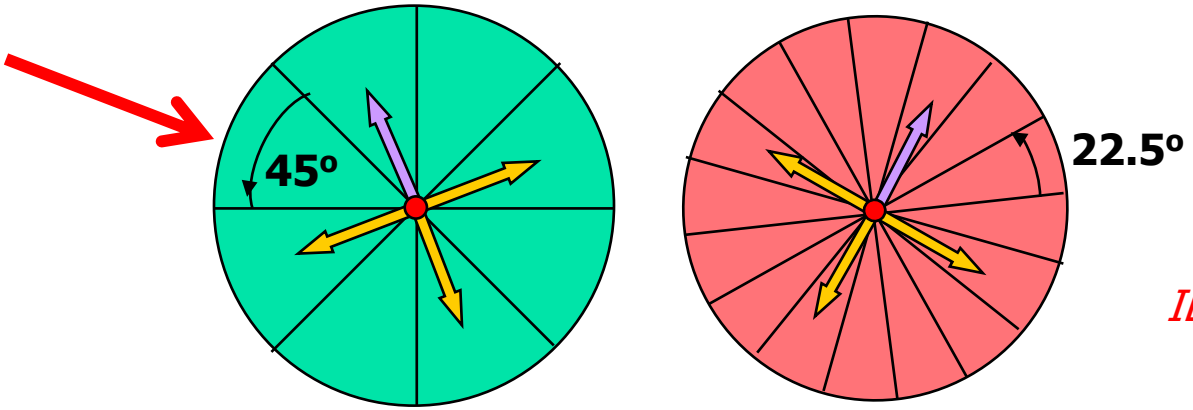
	R	BW	FOV	Packet Loss Rate
Our Prototype	7.1 m	20 MHz	360°	10^{-6}
Pure LiFi-X [23]	1.8 m	42 MHz	60°	$\approx 3.4 \times 10^{-5}$
[21]	2.4 m	10 KHz	10°	10^{-2}
[20]	50 m	50 KHz	75°	3.2×10^{-4}
Thorlabs [24]	0.45 m	12 MHz	150°	$\approx 10^{-4}$

[1] E. T. Won, D. Shin, D. Jung, Y. Oh, T. Bae, H.-C. Kwon, C. Cho, J. Son, D. O'Brien, T.-G. Kang, and T. Matsumura, IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs): Visible Light Communication: Tutorial, 2018.

[2] S. Rajagopal, R. D. Roberts , and S. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," IEEE Communications Magazine, vol. 50, no. 3, pp. 72–82, March 2012.

FSO Modules at Higher Layers

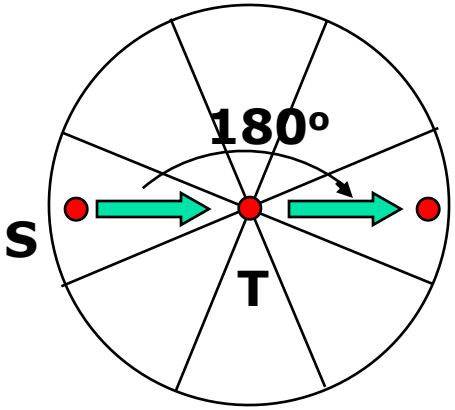
- Local sense of direction: Angle-of-arrival detection possible!



LOCALIZATION

IEEE/OSA JLT 2015
IEEE VTC 2015
WINET 2012
IEEE GLOBECOM OWC 2010

- Local sense of direction: Directional forwarding is possible!



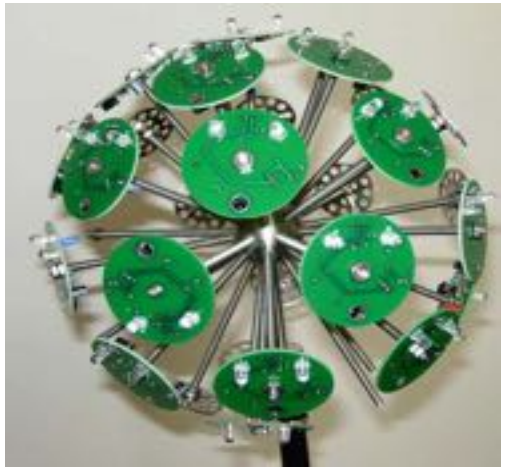
ROUTING

IEEE/KICS JCN 2016
HotP2P 2011
WINET 2010
P2P 2009
IEEE/ACM ToN 2009

UCF

Future Directions

- Carry the concept to **high-speed miniaturized** modules
- Hardware issues
  - feedback from transmitter
  - dense packaging of many components
  - scalable controller
  - optimal designs for illumination and communication



Future Directions

- Software issues
  - Alignment is precious, treat it carefully
    - Need cognitive techniques to manage LOS alignment when hundreds of transceivers per module exist
  - High-speed (1+ Gbps) data rates
    - Buffering may not work, try joint designs with layers 3 & 4
    - Auto-tuning of the LOS alignment protocol
- Hybrid electronic + mechanical steering
- VLC+WiFi
  - LOS alignment
  - LED partitioning

Part II

Career Advice!

Ideal Ph.D.

- Significant and clear impact
  - The big picture and motivation always in mind
    - What is your hypothesis?
    - Why should someone care about your work?
    - **Task: Prepare a poster of your thesis work**
  - Strong publication record with depth and breadth
    - What are the major conferences and journals for your area? How do they rank?
    - What are your ongoing deadlines?
    - **Task: Have a publication plan**

Ideal Ph.D.

- High job prospects
  - Alignment with trends and hot problems
    - What are the top 5 research problems in your area?
    - What are the top 5 fundable themes in your area?
    - **Tasks: Find and read NSF solicitations in your area. Subscribe to IEEE and/or ACM.**
  - Being connected to others
    - Who are the top researchers in your area -- both in academia and industry?
    - Who are your peers working on a very similar problem?
    - **Task: Engage in your community**

Ideal Ph.D. (cont'd)

- Strong recommendations by colleagues and your advisor
  - Engaging service activities
    - Have you volunteered at a workshop or conference?
    - Have you written quality reviews?
    - Were you reliable in your service commitments?
    - **Task: Ask for reviewing a paper and do a great job at it.**
  - Solid TA work and coursework
    - Would the professor you TAed for write a stellar recommendation for you?
    - Did you go beyond expected in your course work?
    - **Task: Plan (i.e., talk to appropriate people) to TA a course before you graduate and do a great job at it.**
    - **Goal: Impress a professor (other than your advisor) by doing an excellent job at his/her course.**
  - Personable, enjoyable, and a charm to work with!
    - Are your coworkers and colleagues avoiding you?
    - Have you truly helped a colleague of yours in his/her work?
    - Have you contributed to establishing a warm culture in your workplace?
    - **Task: Identify (and execute) a collaboration with a colleague in your lab and do a great job at it.**

Ideal Ph.D. (cont'd)

- Experience in defining and selling new ideas
  - Clearly defines new important problems and comes up with ideas to solve them
    - BS: Proficiency
      MS: Mastery in a given problem
      PhD: Defines new problems of value
    - Have you come up with ideas your advisor could not think of?
    - Do you always agree with your advisor?
    - Do you have hunch or strong opinion on the top problems in your area?
    - Are your ideas incremental or non-incremental (revolutionary/transformative)?
    - **Task: Identify a new problem in your thesis, write a paper on it, and convince your advisor to publish it.**

Ideal Ph.D. (cont'd)

- Experience in defining and selling new ideas (cont'd)
  - Have experience in proposal writing
    - Have you thoroughly read solicitations related to your work? Do you know what a "solicitation" is?
    - Have your advisor involved you in writing a proposal?
    - Have you tried convincing someone why they should give money for your research?
    - What is the dollar value of the problems you are trying to solve?
    - **Task: Identify a new research direction building on your thesis and convince one of your lab mates and your advisor that it is worthy of writing a proposal.**

Passion

- Ph.D.: 5+ years!
- Why are you doing this? Where do you want to arrive?
  - Permanent residence in the USA
  - Impress someone
  - Show how good your original country is
  - …
- Doctor of Philosophy
  - Required for academia.
  - "love of wisdom" -- Wikipedia
  - "PhD students are often motivated to pursue the PhD by scientific and humanistic curiosity, the desire to contribute to the academic community, service to others, or personal development." -- Wikipedia
- Doing Ph.D. without passion is pain for everybody!
- It is your work, you must own it.

After Ph.D.

- <20% lands a faculty position in the USA
- Others go to industry or academia in other countries
- Industry
  - Type 1: Research lab
  - Type 2: Engineer – mostly software
  - Quality of your doctoral research matters in industry too
  - Summer internships help
  - Well defined tasks; have a boss; less job safety; strict schedule
- Academia
  - Publication quality and quantity
  - Fundability of your topic area
  - Presentability
  - Personality
  - You define the tasks; minimal boss; more job safety; flex schedule

Funding

- NSF, DoD, NIST
- A typical NSF proposal
  - 1-page summary, 15-page heavy document, references (very hard to do without Bibtex)
  - Many other additional paperwork: budget, bio, current & pending, facilities, collaborators
  - The total package is 30+ pages
- Criteria
  - Intellectual Merit: transformative, high-risk high-reward, bold vision with several top quality ideas
  - Broader Impact: real use cases, educational
- 4 reviews from panelists, in-person discussion
- Turnaround time: 6 months
- Funding rate: 5-15% → It is a privilege to have funding!

Presenting Yourself

- Webpage
  - Make sure it looks good
  - Post your papers, research videos, etc.
- Google Scholar
- Elevator speech
- Conferences
  - Meet with your peers, don't just attend
  - Ask questions, don't just sit and listen
- Cover letter
- Research Statement
  - What is your research about? Why should others care?
  - Why is it fundable?
  - What are future directions you are planning to take?

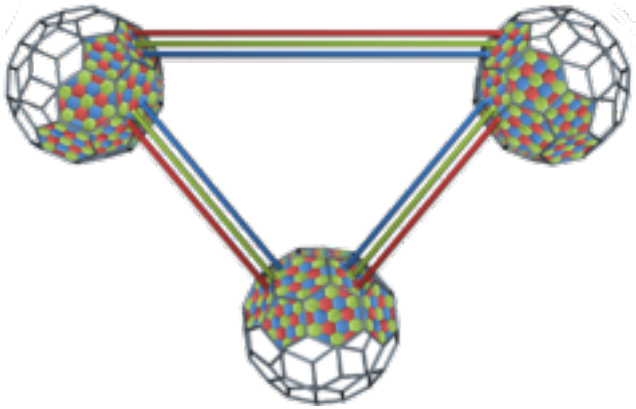
Publications

- Pubs are the baseline products of a researcher
  - "publish or perish"
  - 1 conference paper per semester
  - 1 journal paper per three semesters
- Quantity vs. Quality
  - Must show you can publish at top venues
  - h-index, citation count
- Depth and Breadth
  - Dead without depth, edge with breadth
  - Must have at least one top quality journal paper

Publications

- Strategies:
  - Start early – Have a paper published in your first year.
  - Every hour of your work should be meant for a paper
  - Maintain a publication plan for the next 12 months – writing takes a long time, plan well ahead
  - The only parameter you can control: Writing better and more papers!
  - Do summer internships and collaborate with labmates for breadth

THE END



Questions?

- Sponsors