Spectrum Access for the Next Wireless Internet

Edward Knightly
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RICE

Spectrum is the Key Enabler

- Pre-1985: ISM used for welders, microwave ovens…
- 1985: FCC allows unlicensed spread spectrum access in ISM bands
- Expected market: cordless phones, baby monitors
- 802.11 specified in 1997 leads to $10 Billion annual in WiFi in 2012

§ 15.247 Operation within the bands 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 MHz.

(a) Operation under the provisions of this section is limited to frequency hopping and direct sequence spread spectrum intentional radiators that comply with the following provisions:

(1) Frequency hopping systems shall have hopping channel carrier frequencies separated by a minimum of 25 kHz or the 20 dB bandwidth of the hopping channel, whichever is greater. The

The Next Frontier

✓ 2.4 GHz and 5 GHz bands
  - We (the research community) mastered and impacted
    - from cross-layer design to application layer
  - Open systems and platforms are a big reason
    - Re-programming COTS WiFi to clean-slate design and WARP

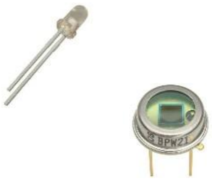
- Vastly diverse spectrum access is the next frontier
  - New bands change everything
  - Clean slate design
  - Use them in new ways (not just "find a band with available air time and good SNR")

Diverse Bands

- UHF TV Bands: 500 MHz to 700 MHz
  - Time to reclaim them and stop calling it "white spaces"

- Millimeter-wave: 30 GHz to 300 GHz
  - It's not just for HDMI cable replacement

- Visible light: 400 THz to 700 THz
  - Modulate every LED



UHF Bands

- Vision: low-cost WiFi-like networking
  - Small cell to km-scale coverage
  - Outdoor tower with indoor service
  - Need sub-GHz for range and coverage
- Where are we now, U.S. and globally?
  - Standards: IEEE 802.11af and 11ac
  - Evolving regulatory models
- Technical and policy challenges ahead

Brief History of UHF Bands

- 1930’s had first television broadcasts
- 1952 FCC dedicates 470 MHz to 890 MHz to UHF TV
- Result: TV revolutionizes culture

1930’s 6 inch screen

1950’s 16 inch RCA

New FCC Spectrum Sharing Rules

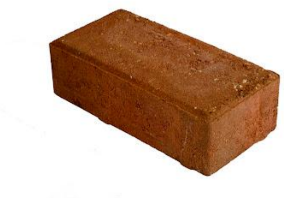
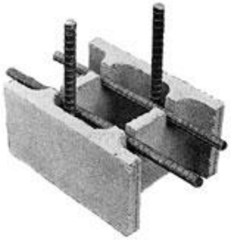
- FCC "Whitespace" Ruling 2010
- Unused 6 MHz UHF DTV channels may be utilized as an "unlicensed" band
  - Strict spectral mask to project adjacent DTV channels
- Database to look up local availability (vs. sensing)
- Most important release of unlicensed spectrum in 25 years

Tech-history question: who is the first researcher to transmit a data packet in UHF bands?

The Promise of “Super WiFi”

- WiFi-like networking in UHF bands
  - New availability due to global transition to DTV
  - Unlicensed spectrum style access
- Signals travel km’s and penetrate trees and walls
- Simplicity and cost advantage of WiFi
- Cost effective rural and urban wireless access

Penetration through Obstacles

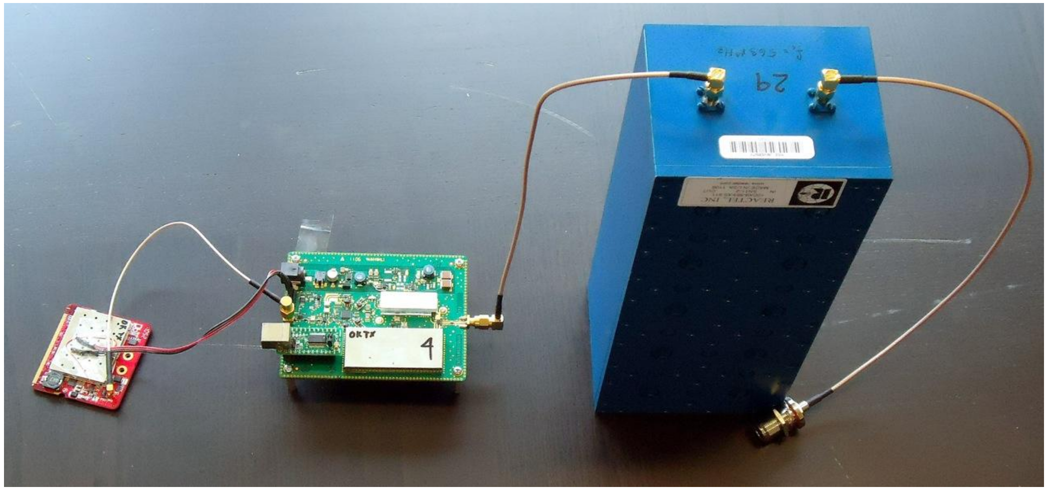
Material/Frequency	500 MHz (UHF)	5 GHz	Difference
	-4.8 dB	-38 dB	33.2 dB
	-9.5 dB	-12.75	3.25 dB
	-23.5	-56.5	33 dB

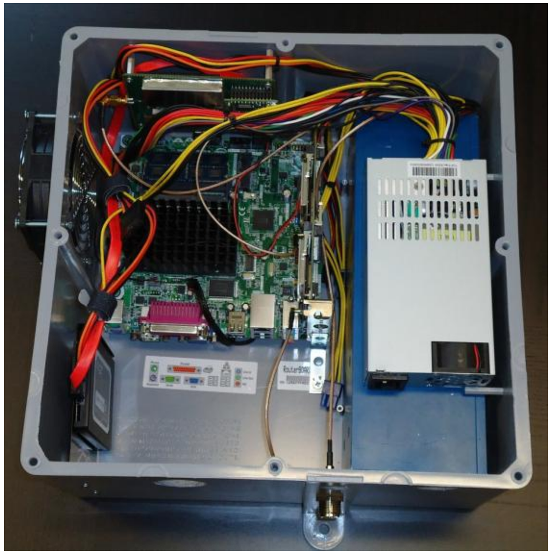
- Frequency and material dependent loss

Super WiFi Trial @ Technology For All

- Network architecture
  - 20 Programmable APs in operation since 2004 with 4,000 users over 3 km^2
- Community engagement
  - Tech training to refurbished PCs

Rice Super WiFi Research Prototype

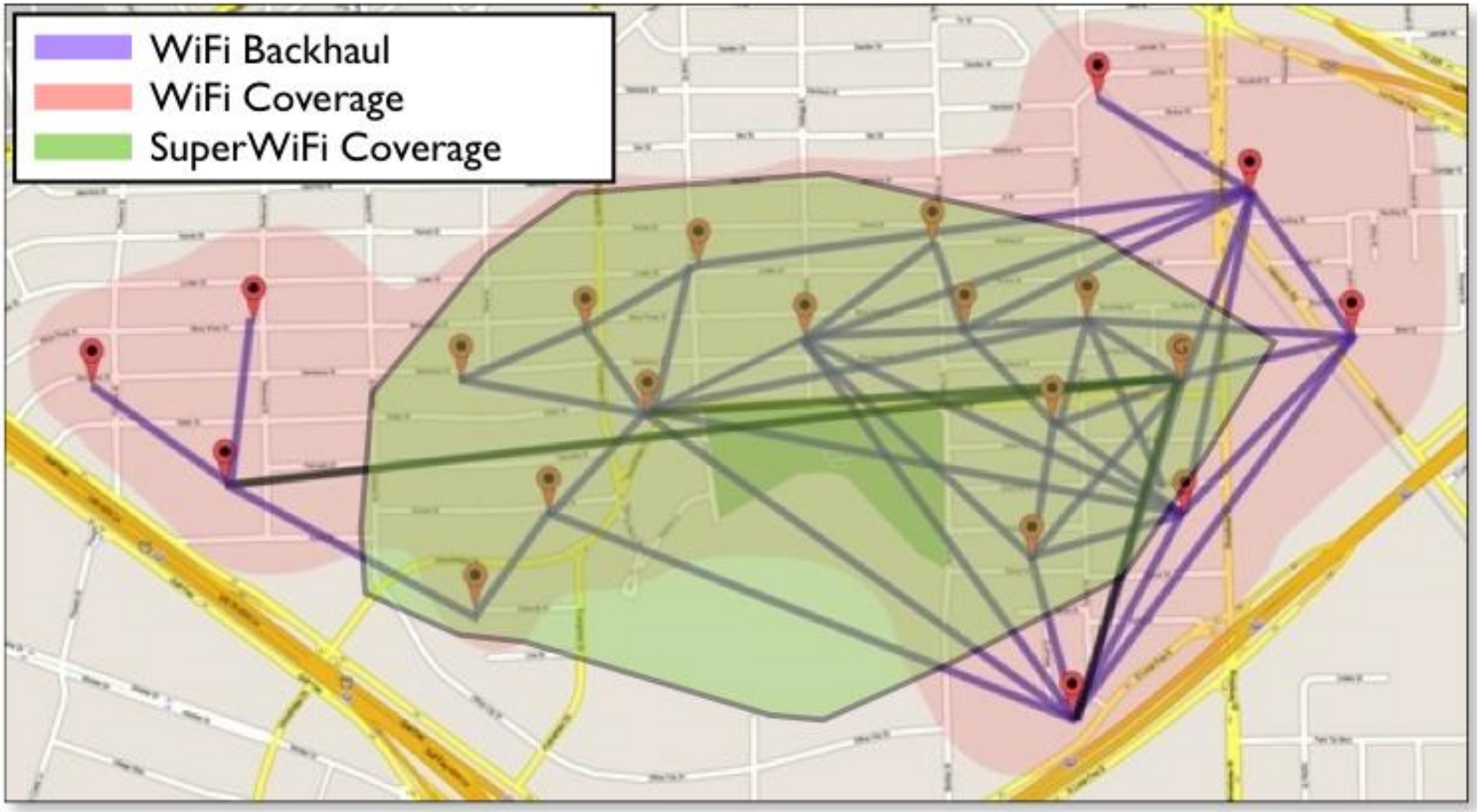




Houston Super WiFi Trial

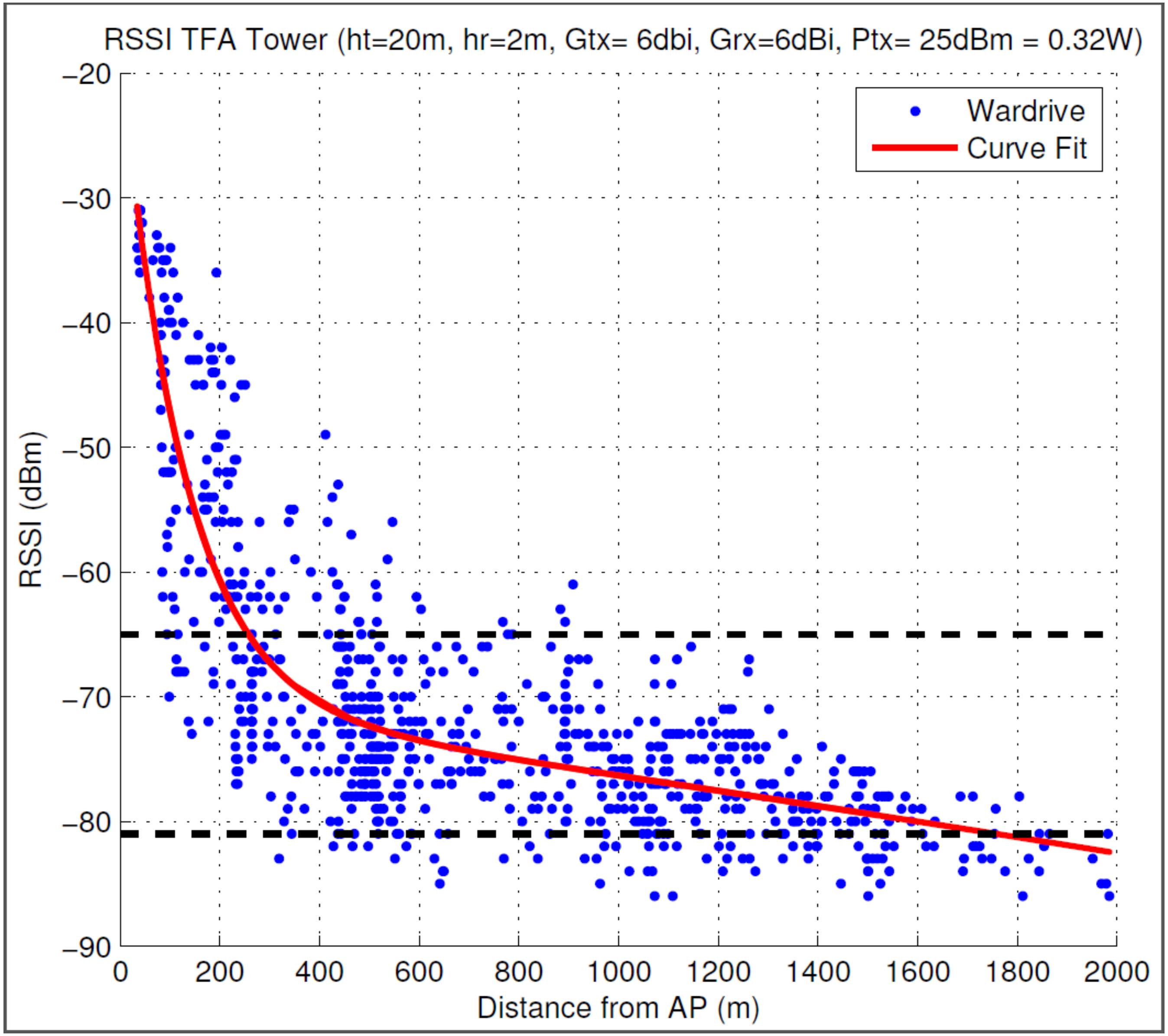
- First residential Super WiFi
  - Tower to home
  - In-home WiFi for commodity devices
  - FCC experimental license (pre-certification)
- Coverage over 2 km
- 10 Mb/sec in 5 MHz

Technology For All Network



- Single Super WiFi node covers > 10 WiFi nodes with superior in-home penetration

TFA Super WiFi War Drive Data



The Press…

size of Rhode Island. Officials say the threat of new wildfires remains high, especially in the western part of the state. **PAGE B2**

TAX THE RICH, POLL SAYS
Most don't want Medicare, Medicaid touched. **PAGE A8**

HARDIN COU
fires Monday in
3,000 acres hav

Houston leads the way in launching 'super WiFi'

First hot spot in U.S. opens Web to disadvantaged

By ERIC BERGER
HOUSTON CHRONICLE

Leticia Aguirre seems an unlikely candidate for the vanguard of wireless Internet technology.

But that's just where the Houston grandmother finds herself today, as quite possibly the nation's first user of "super WiFi" technology at her east Houston home.

"To me the Internet is like a window to travel to places I don't think I'll ever be able to get to," said Aguirre, 48, who works at a nearby restaurant.

She's an early adopter of super WiFi because of a partnership between Rice University, which provided the technology, and Technology For All, a Houston nonprofit that provides free wireless Internet access to low-income households in a three-square-mile area in east Houston.

As its name suggests, super WiFi has created a buzz in the technology community, with providers scrambling to determine how best to use the valuable new WiFi spectrum.

With money from the National Science Foundation, Edward Knightly, a computer

Please see **WIFI,** *Page A4*

INSIDE

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WE RECYCLE

STAR

WEDDING WATCH

TV networks are already toasting the royal nuptials.

STORY ON PAGE D1

NAMES THA

Traditional baby nar are popular again as parents rely on old favorites.

STORY ON P

ERIC KAYNE : FOR THE CHRONICLE

LOOKING AHEAD: Leticia Aguirre of east Houston may be the first person in America to connect to the Internet by "super WiFi," thanks to a partnership between Rice University and Technology For All.

WIFI: New technology able to penetrate through walls

CONTINUED FROM PAGE A1

engineer at Rice, was able to build prototype equipment this winter and create Houston's first super WiFi hot spot a few weeks ago. He believes it is the first such hot spot in the nation.

"This is an early trial," he said. "We're still trying to determine the ideal use for the technology."

Space on spectrum

Super WiFi was made possible in September when the Federal Communications

In Aguirre's Pecan Park neighborhood there are a lot of, well, pecan trees.

"I think the biggest opportunity is the extended range and the penetration through trees and buildings," Knightly said. "It can provide the in-home service that WiFi never could."

Aguirre has tried to use Technology For All's equipment for several years, but could never get a reliable signal.

"I had told them the antenna was not helping, so

travel up to a mile, and penetrate into homes.

A benefit to rural areas

But there are drawbacks as well. The amount of spectrum available between digital TV stations is smaller than the segment reserved for traditional WiFi, so there's limited bandwidth, especially in urban areas with more broadcast TV stations.

That's why Knightly and others believe the technology may see its widest applicability in rural areas.

Next Day…

FCC Federal Communications Commission

How Much UHF Whitespace is There?

- Smithville, Texas
  - Population 4,500
  - 108 MHz total
  - 48 MHz contiguous

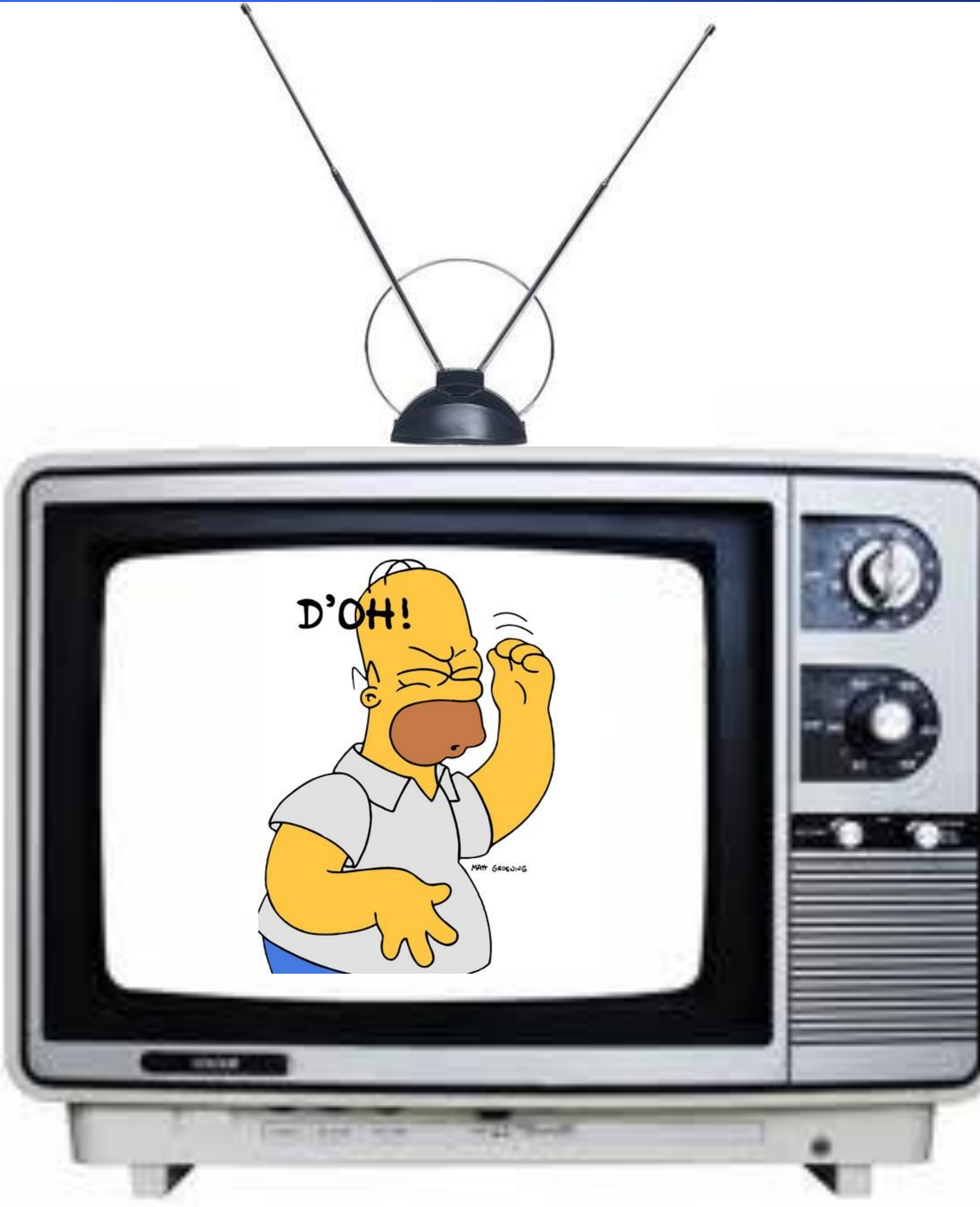
Channel Number	Frequency Range (MHz)
14	470-476
15	476-482
16	482-488
18	494-500
19	500-506
24	530-536
25	536-542
26	542-548
27	548-554
28	554-560
29	560-566
30	566-572
31	572-578
39	620-626
40	626-632
41	632-638
47	668-674
51	692-698

- Houston, TX
  - Population 2 Million
  - 0 MHz

Channel Number	Frequency Range (MHz)

What's the Problem? TV!

- For 60 years, 300 MHz of beach front property spectrum remains dedicated to UHF TV
- Less than 10% of the population watches TV via UHF
- Creates an artificial spectrum shortage, raising wireless prices, lower bandwidths



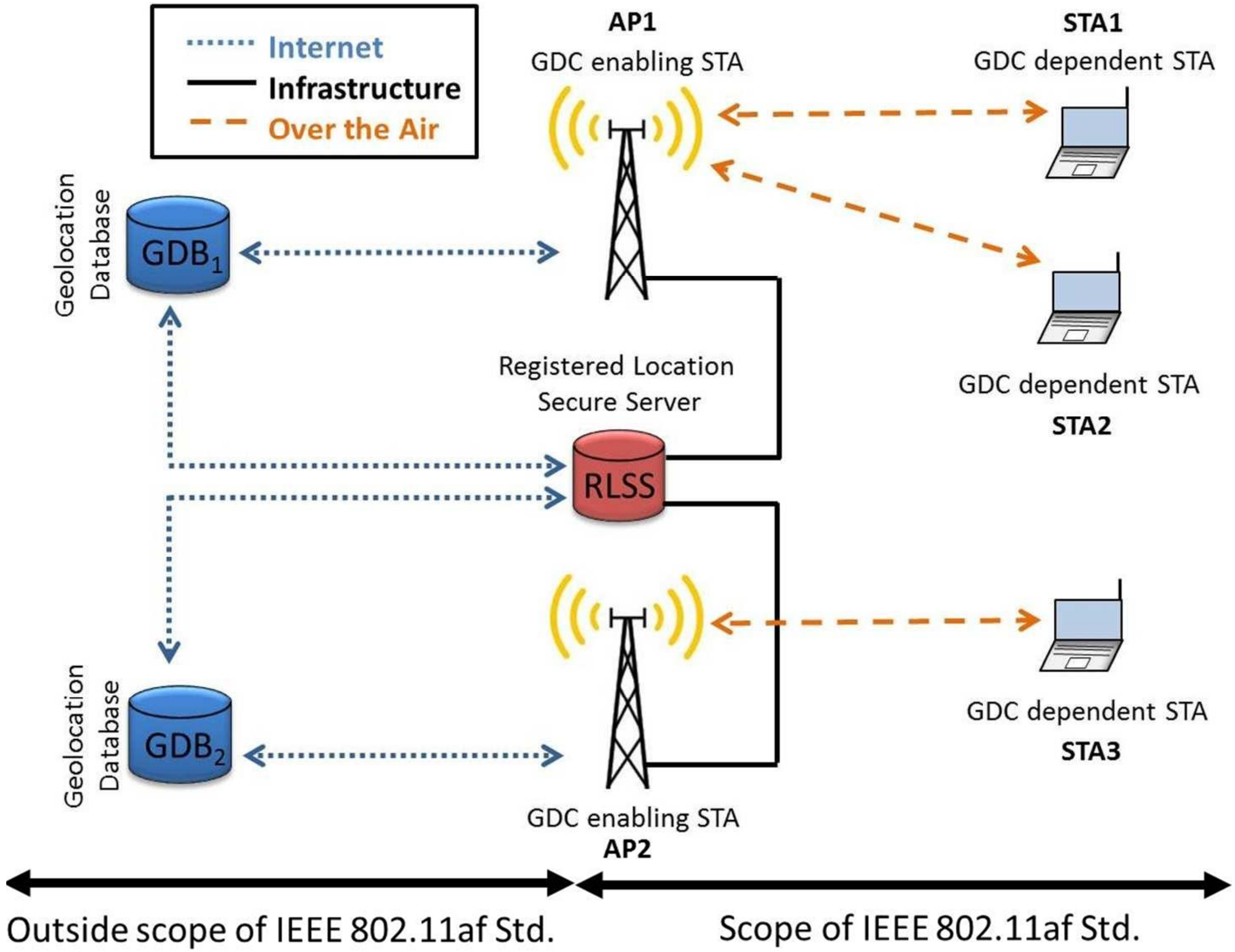
Agenda

- Protocols and standards to make UHF-band wireless networking successful
  - research
- Trials to demonstrate the worth of sub-GHz unlicensed spectrum
  - different issues for different countries
  - impact global spectrum policy
- Path to commoditization to follow cost trend of WiFi

Key Components of IEEE 802.11af

- Geolocation Database (GDC): geographic location and permissible frequencies
  - White Space Map
  - GDC enabling station: AP
  - GDC dependent station: STA
- Registered Location Secure Server (RLSS): Controls a small number of APs
- New control protocols
  - Network Channel Control
- Flexibility for multiple regulatory models
  - Open loop to closed-loop with "kill"

Spectrum Database and IEEE 802.11af



IEEE 802.11af

STANDARDS

IEEE 802.11af: A Standard for TV White Space Spectrum Sharing

Adriana B. Flores, Ryan E. Guerra, and Edward W. Knightly, Rice University

Peter Ecclesine and Santosh Pandey, Cisco Systems

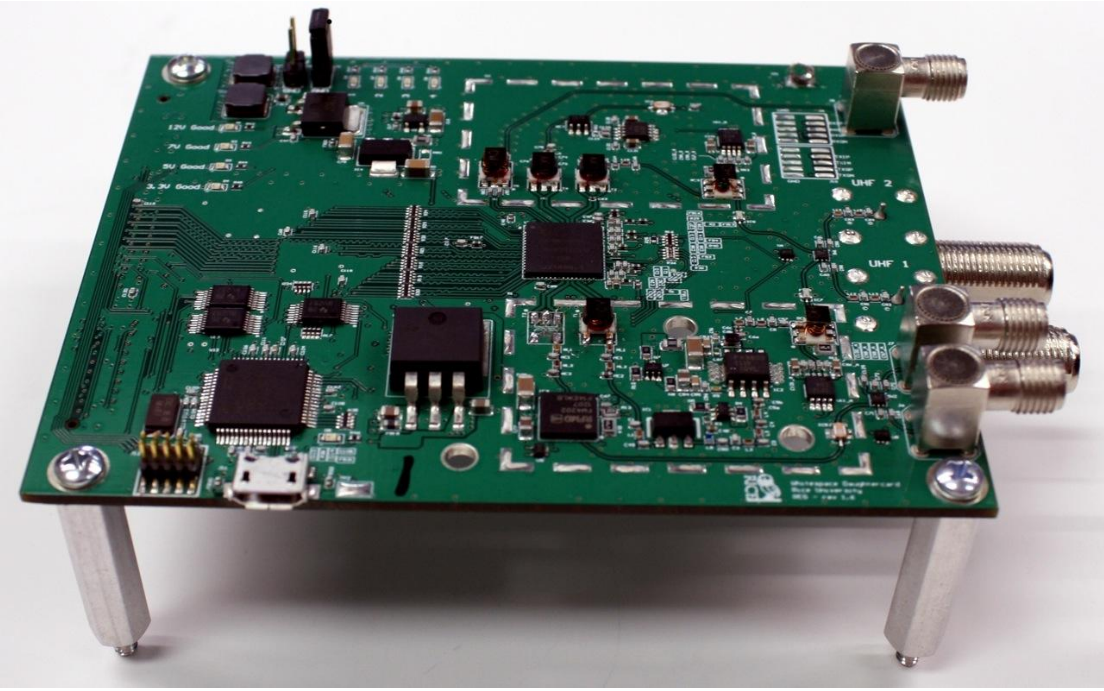
ABSTRACT

Spectrum today is allocated in frequency blocks that serve either licensed or unlicensed services. This static spectrum allocation has limited resources to support the exponential increase in wireless devices. In this article, we present the IEEE 802.11af standard, which

Propagation characteristics of the TVWS band make it a desirable and convenient spectrum for many wireless transmission services [5]. First, because this band resides under the 1 GHz frequency, material obstruction is less harmful than at higher frequencies, allowing non-line-of-sight coverage [6]. The difference in signal attenuation between a variety of materials and

IEEE Communications Magazine, October 2013

2nd Generation Prototype



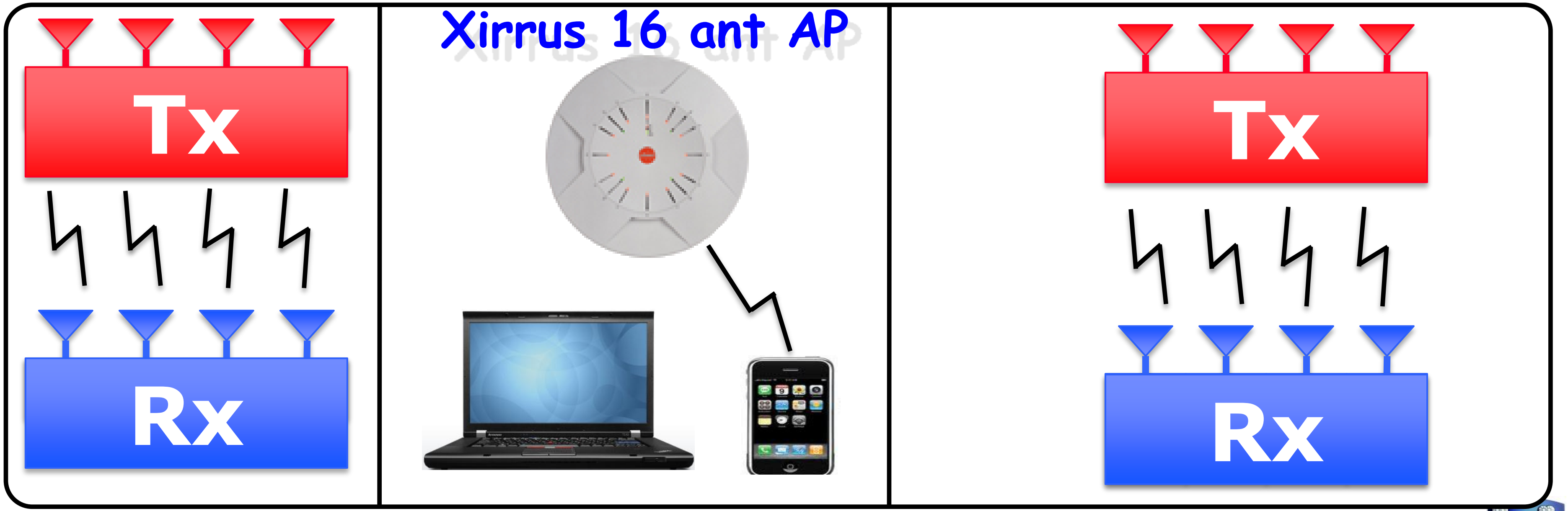
- 1 Watt transmit power 400 – 800 MHz
- 5 to 20 MHz channel width (bonded UHF)
- FPGA baseband capable of 802.11
- Compatible with WARP

Technical Challenges

- Architectural opportunities
  - Network-scale energy management via dynamic ranging
  - Hot spot mitigation via footprint flexibility
  - Mobile architectures for spectrum-aware access
  - New models for spectrum database
- Protocol and network design
  - Interference: the down-side of long range
  - High spectral efficiency: make the most of 6 MHz
  - Many hidden terminals: power and height asymmetry render "carrier sense" ineffective

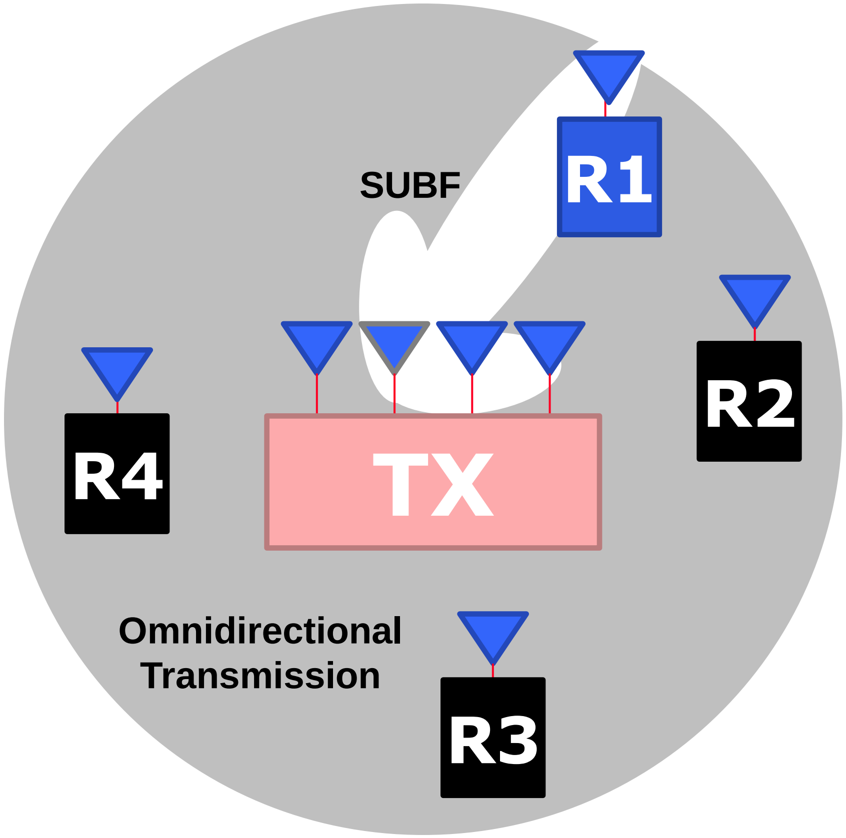
MIMO in IEEE 802.11

- NxM MIMO increases throughput by *min*(N,M)
- Client devices often have M=1 antenna due to cost and space
- Multi-User MIMO allows for APs to leverage antennas belonging to group of nodes



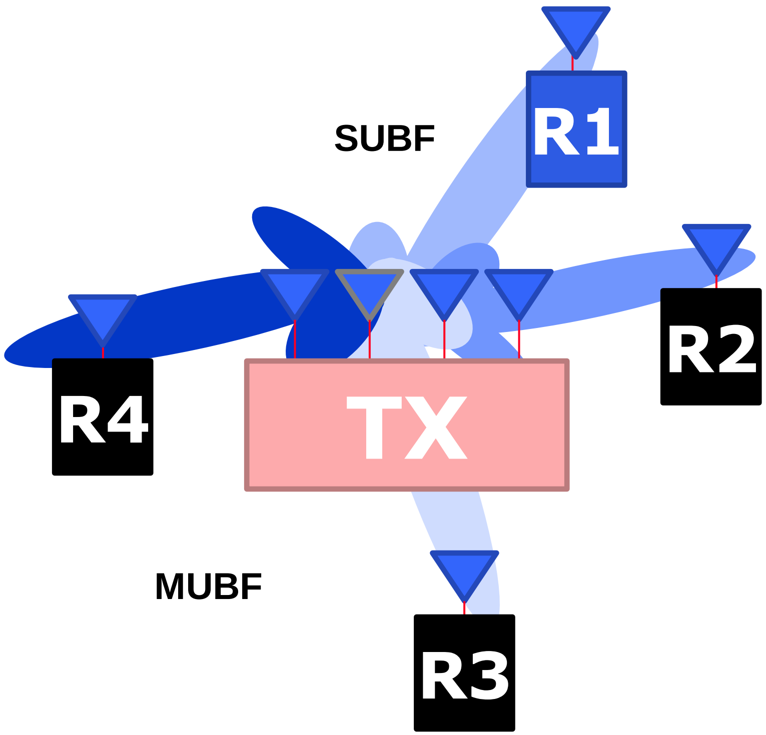
Single-User Beamforming

- Transmitting antenna array focuses energy "toward" receiver
- Exploit Channel State Information at the Transmitter (CSIT)
- Improves client link quality and network spatial reuse
- Analogous to directional antennas with improved energy direction and steering

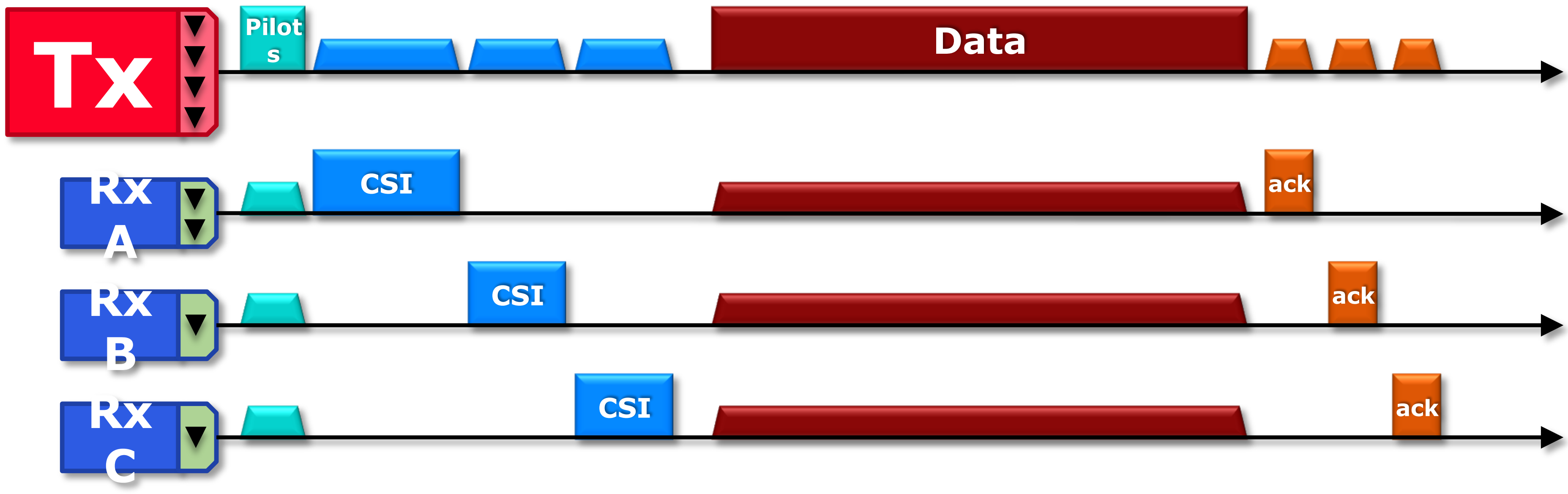


Multi-User Beamforming (MUBF)

- Can employ "Zero-Forcing Beamforming" (ZFBF)
- Transmitter sends multiple streams concurrently to different users
- Improves theoretical system capacity compared to SUBF
- Now standardized in IEEE 802.11ac
- Channel sounding for pre-coding and zero-forcing
- High spectral efficiency



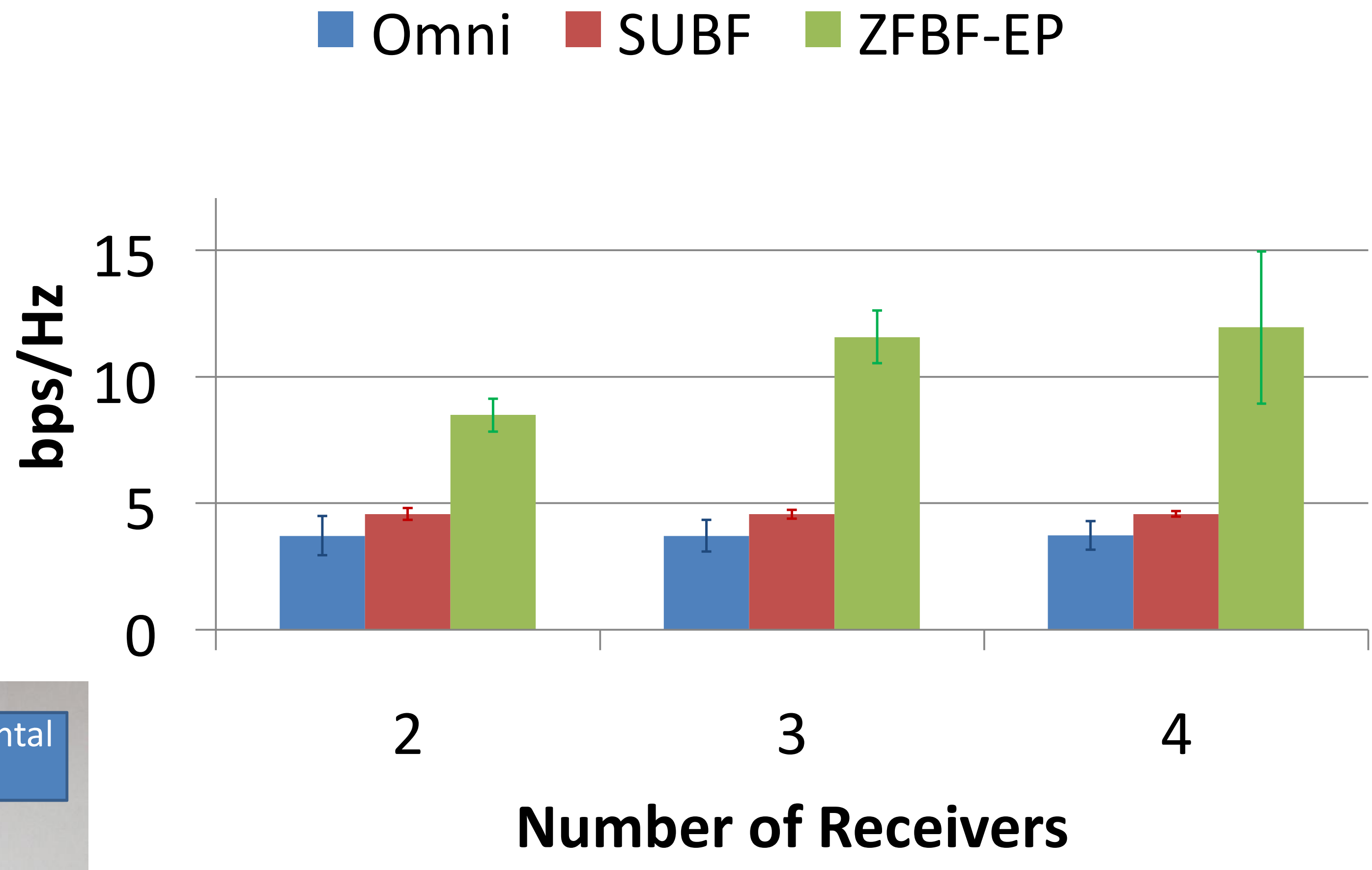
Channel Sounding Timeline for 802.11ac

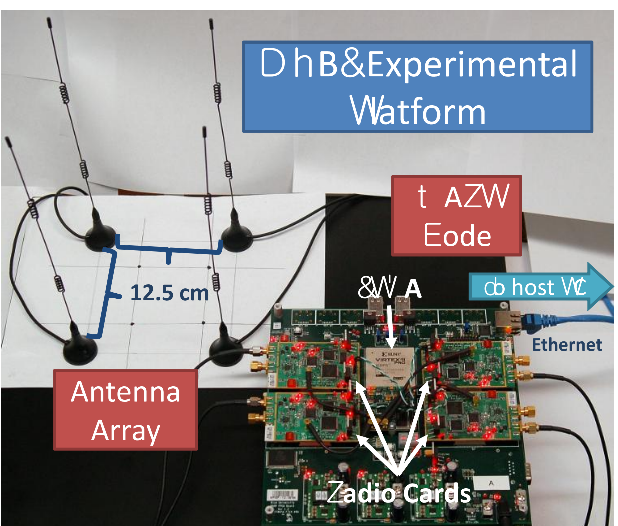


Transmission Procedure

1. Select group and send channel sounding training sequence (Pilot Tones)
2. Receive channel state feedback (CSI) from each receiver serially
3. Construct steering weights and transmit data
4. Acknowledge transmission

Experimental Spectral Efficiency Gains





- 2010 prototype
- World’s first MU-MIMO WLAN

IEEE 802.11ac

STANDARDS

IEEE 802.11ac: From Channelization to Multi-User MIMO

Oscar Bejarano and Edward W. Knightly, Rice University

Minyoung Park, Intel Corporation

ABSTRACT

The IEEE 802.11ac amendment has been proposed to enhance the throughput of IEEE 802.11n beyond gigabit-per-second rates. In this article we present an overview of the most important features proposed in the 802.11ac amendment, including channel bonding mechanisms and multi-user MIMO.

INTRODUCTION

Mobile data traffic is projected to experience an 18-fold increase between 2011 and 2016 due to the growth of mobile subscribers and bandwidth specifications of 802.11n have been kept for 802.11ac (e.g., static and dynamic channel bonding and simultaneous data streams), these have been enhanced to allow support for wider channels as well as more data streams, among others.

The two main features that allow 802.11ac to achieve gigabit transmission rates are:
- Static and dynamic channel bonding
- Multi-user multiple-input multiple-output (MU-MIMO)

To enable these two features, substantial modifications are required at the PHY. For the most part, at the MAC level, the proposed changes are needed to guarantee compatibility with the modified PHY. More specifically, key

Sub-GHz MUBF Challenges

- Limited multipath outdoors
  - Necessitates greater client separation distances
  - Careful consideration of user grouping algorithm
- Interference management
  - Multiple cells and out-of-network devices
- Overhead amortization
  - Ensure throughput benefit outweighs overhead to sound channels
- Antenna array size
  - BF requires minimum $\lambda/2$ separation distance
  - @ 500 MHz, $\lambda=0.5$m ➔ large physical array size

Next Trial: Latin America

- More spectrum availability (fewer TV channels)
- Spectrum sharing rules under development
- National broadband plans for underserved

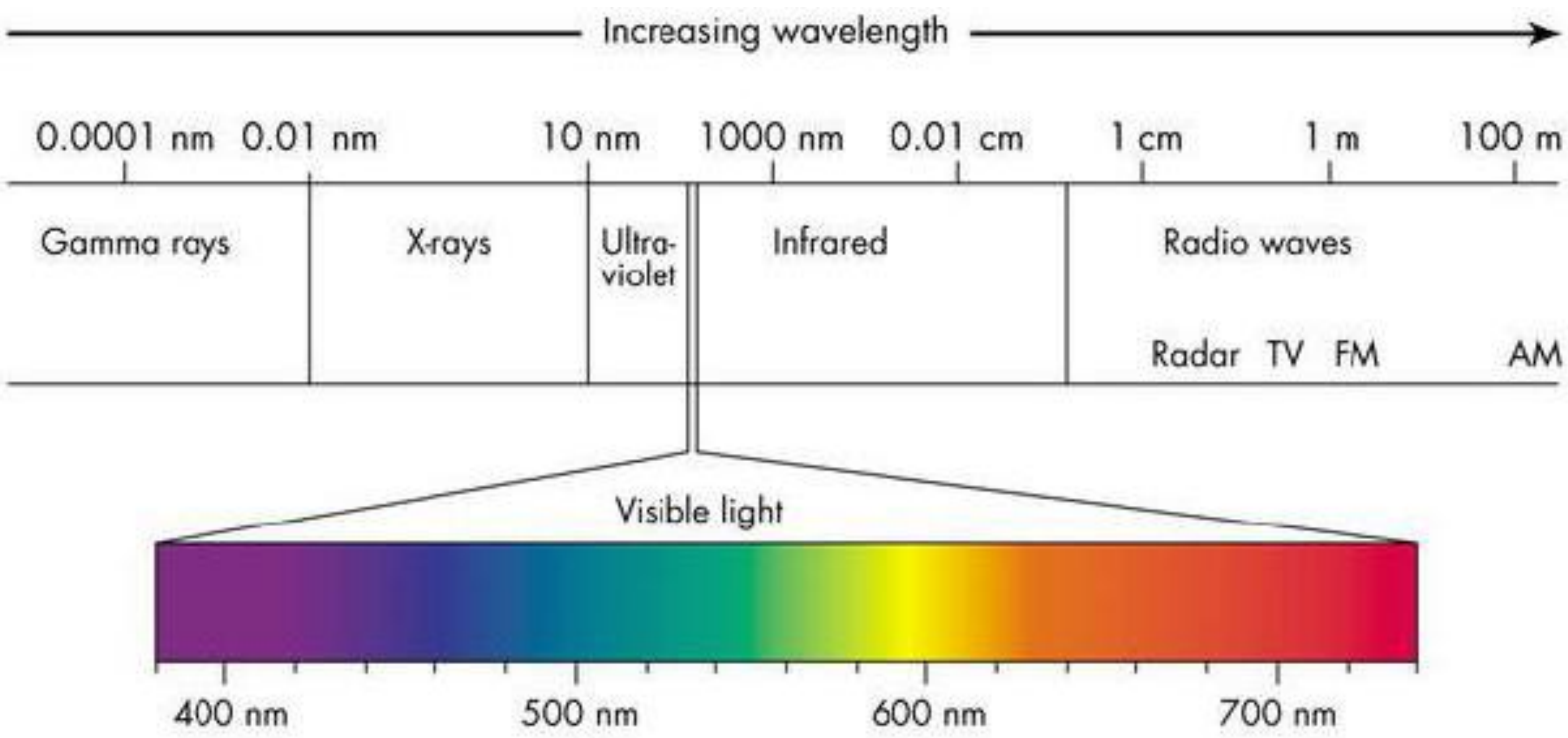
Missing Element: Wireless Connectivity

- National imperative:

  “servicios de conectividad y de telecomunicaciones a bajo costo, de calidad, incluyendo infraestructura, contenidos, sistemas y servicios de información, con el objeto de alcanzar el desarrollo económico y social con equidad basados en el acceso universal de nuestros ciudadanos”

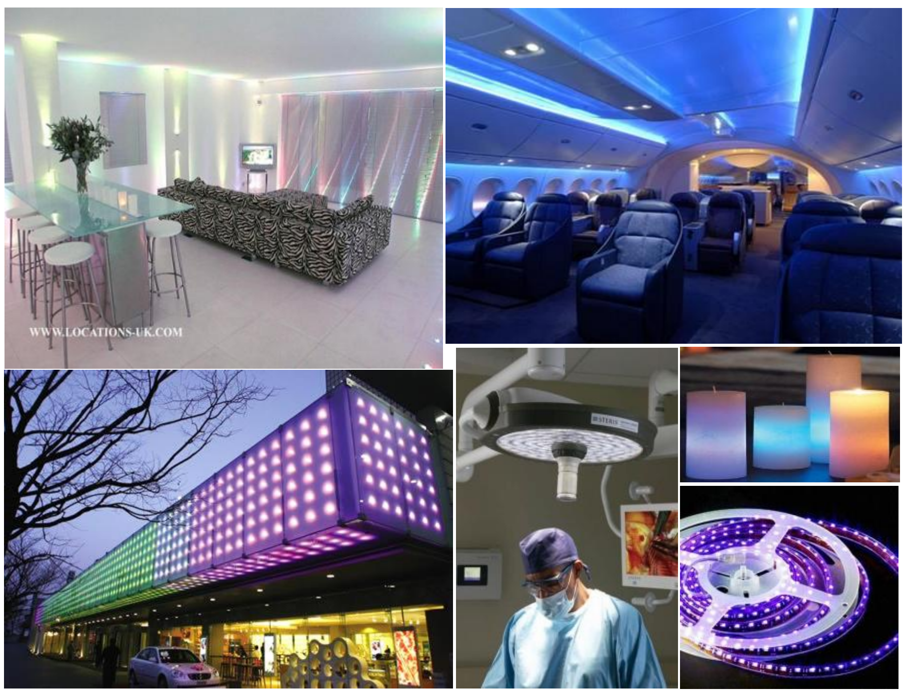
Visible Light

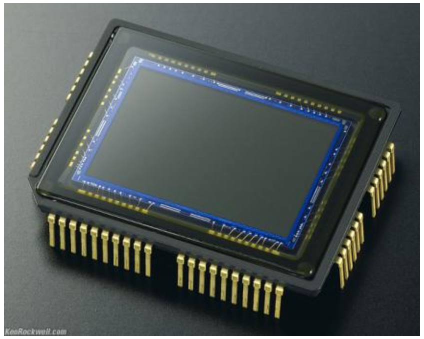
- Spectral range:
  - 400 to 800 THz (400 to 725 nm wavelength)



Visible Light Communication

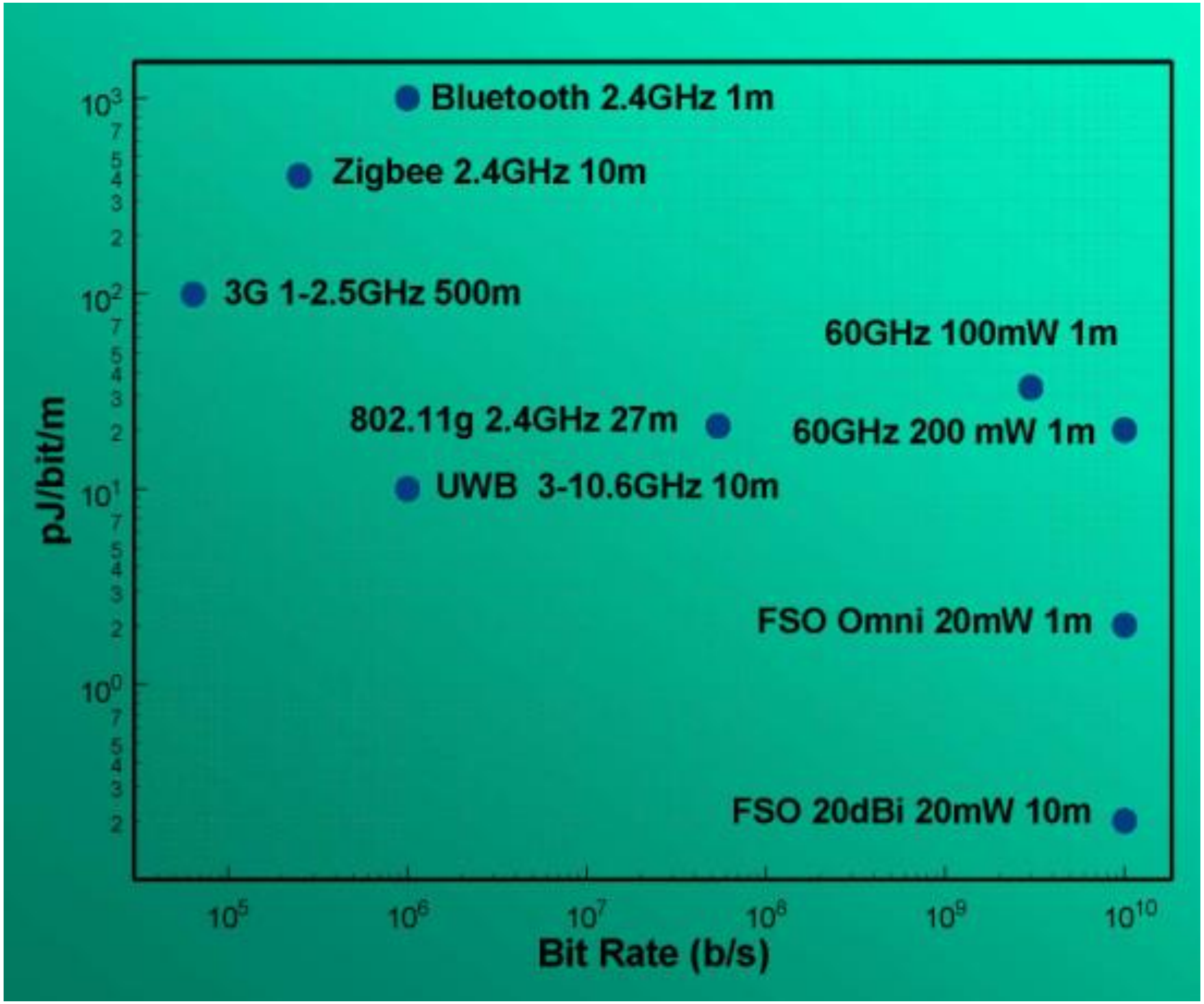
- LED <u>transmitter</u>
  - modulating signals at high frequency at lighting source
- Photodiode or image sensor <u>receiver</u>
- Diverse application scenarios





And It's Green…

- Low energy per bit per meter compared to RF



Source: PSU VLC Workshop, 2010

New Standards: IEEE 802.15.7

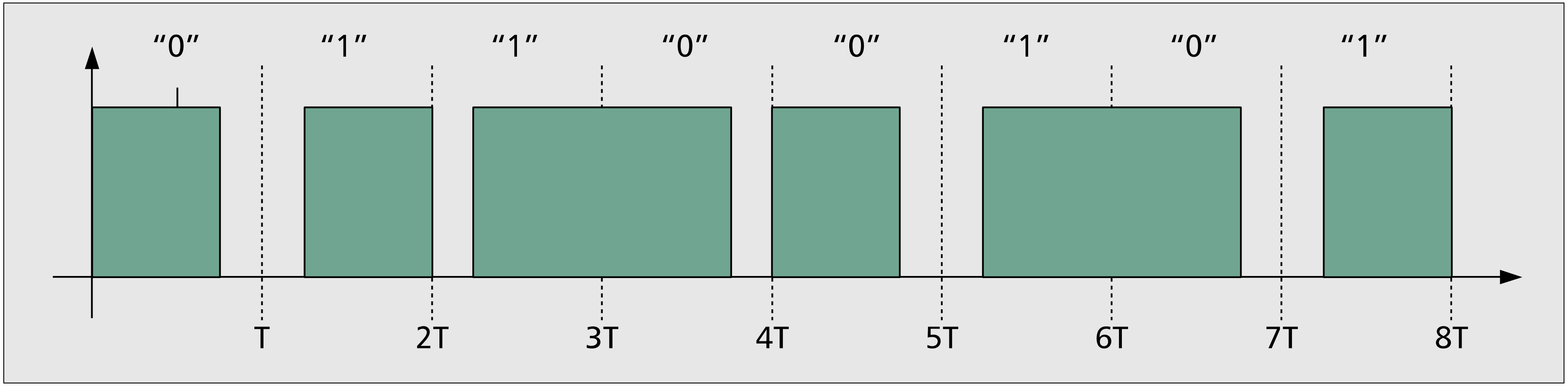
- Up to 100 Mb/sec

- How to go fast?
  - Multiple optical sources (MIMO)
  - Multiple frequencies (colors)
  - Advanced modulation CSK (color shift keying)
  - On-Off Keying (OOK) where "off" = "less bright"

  Can emit constant-brightness "white"

Modulation and Coding

- 2-VPPM: Variable Position Pulse Modulation
- A generalization of Manchester coding
- 75% pulse width for increased average intensity level



Color Shift Keying (CSK)

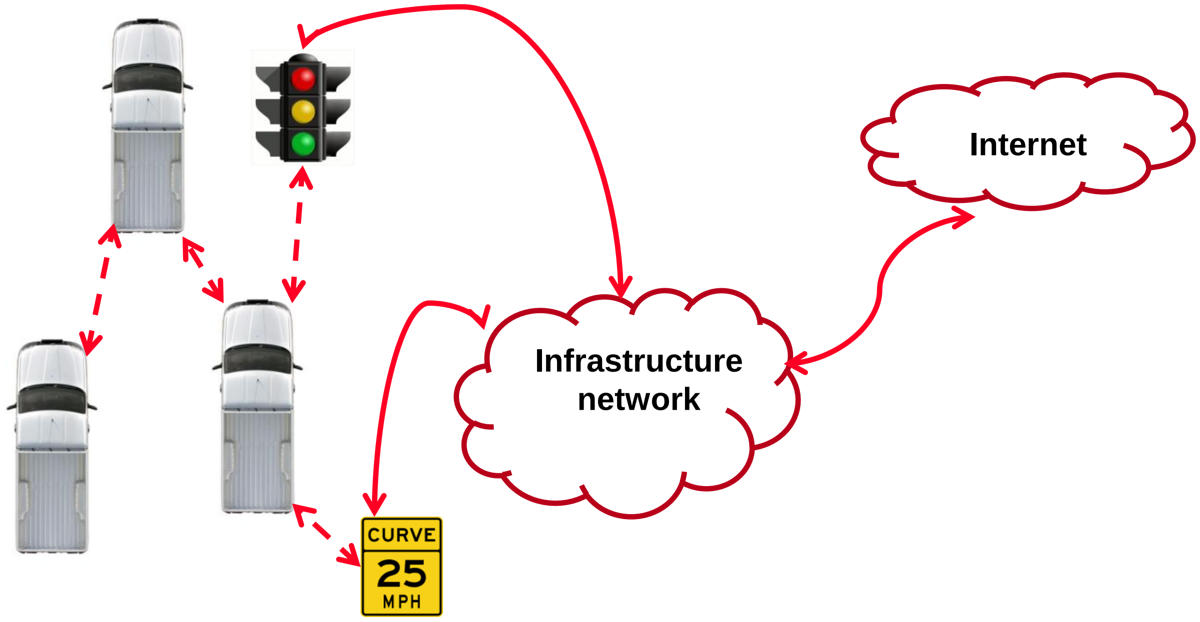
- White light via simultaneously exciting red, green and blue LEDs
- 4-CSK (two bits per symbol)
  - Source wave-length keyed to 1 of 4 possible wavelengths (colors) per bit pair combination
- IEEE 802.15.7 breaks the spectrum into 7 color bands
- Design codes so that the resulting color is guaranteed to be white

Applications: Vehicular VLC (V^2LC)

- Applications: vehicle safety and internet access
- Requirements: stringent reachability and latency
- Infrastructure support: vehicle and infrastructure lighting (traffic lights, street lights)
- Modulation not noticeable by people

C. Liu, B. Sadeghi, and E. Knightly, "Enabling Vehicular Visible Light Communication (V^2LC) Networks," in *Proceedings of ACM VANET 2011*.

V^2LC Network Architecture and Services



- Multihop inter-vehicle forwarding
- Limited neighbor broadcasting
- Infrastructure-to-vehicle one-hop broadcasting
- Vehicle-to-infrastructure one-hop anycasting
- Vehicle-to/from-infrastructure unicasting

Vehicular Safety Demonstration

- Tail light: transmit speed, location, heading, break status, turn signal status, etc.
- Warn nearby drivers

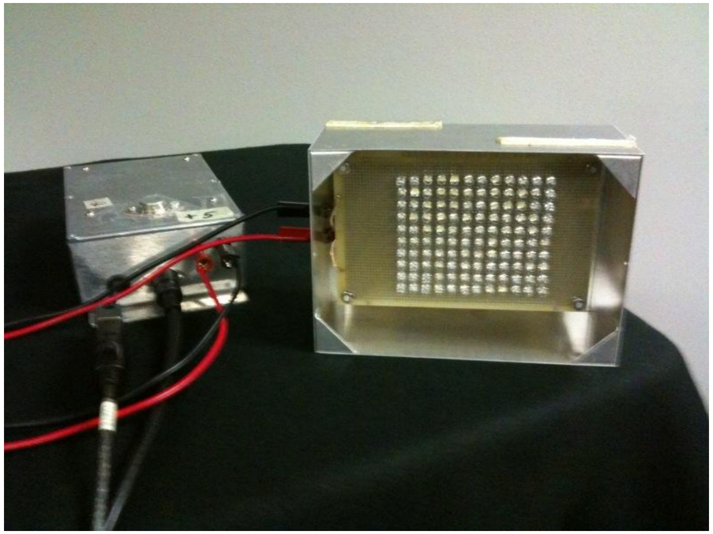
- Tx: Unmodified tail light LED

- Rx: single photodiode

- No perceptible flicker

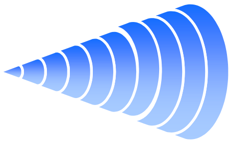
Intel and National Taiwan University demo at ACM *MobiSys 2013* and *IEEE Communications Magazine* December 2013

Intel-Rice Prototype and Experiments



The Communication Medium

- War drive experiments: binary field of view
  - Within a few centimeters, loss goes from 0% to 100%
  - Typical angle: 12^o
  - Typical range: 100 meters



- Multipath experiments: only short-range reflection
  - The reflected signal is received only in close range (< 1.5 m)
  - No hindrance to full duplex at > 1.5 m
  - Rare reflections at stop lights

Receiver & transmitter
at 100 cm separation

Will VLC Work in the Daytime?

Sunlight spectrum

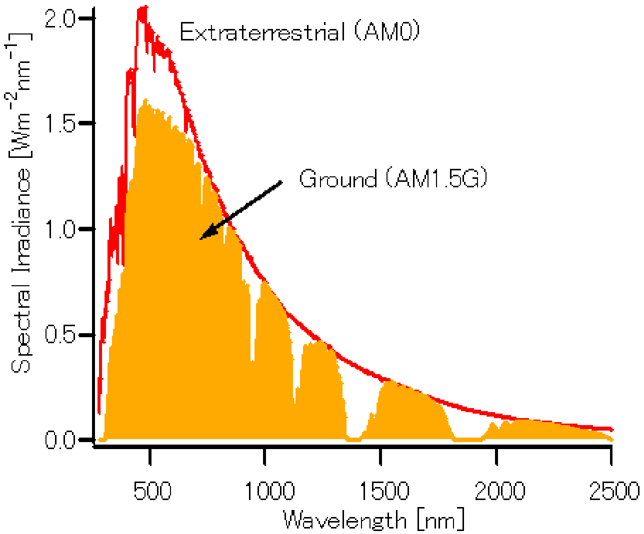
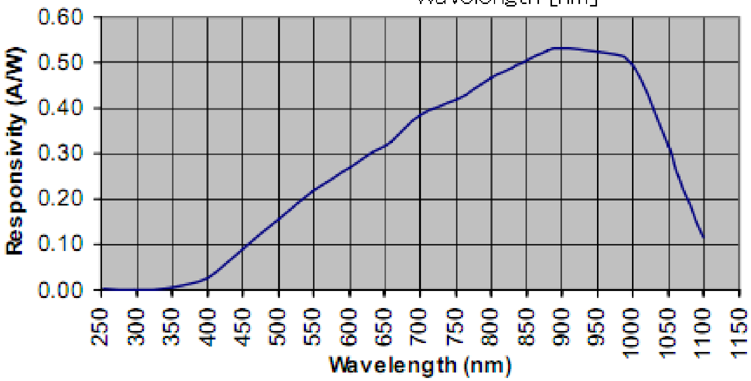
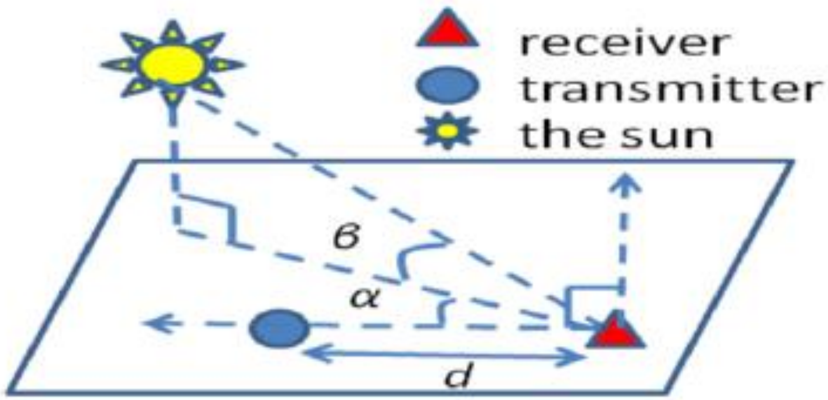


Photo-diode response



Visible (white) light spectrum, 390—750 nm

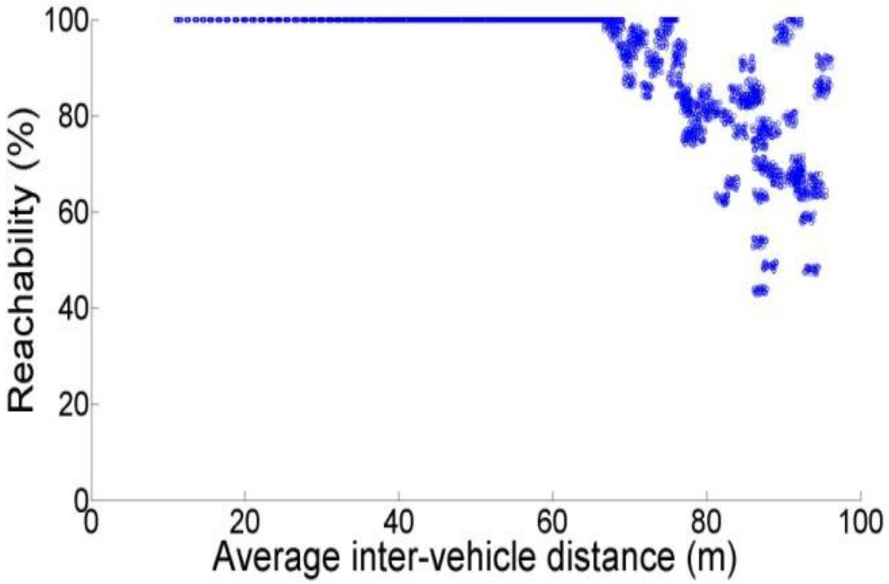
Experiment: Robustness to Wideband Noise



- Limits: photodiode saturation in direct sunlight
  - Sun must be direct and < 12 degrees from horizon AND
  - Data source must be > 100 meters away
- Opportunities
  - Other potential data paths (complete outage rare?)
  - Better receiver can "capture"

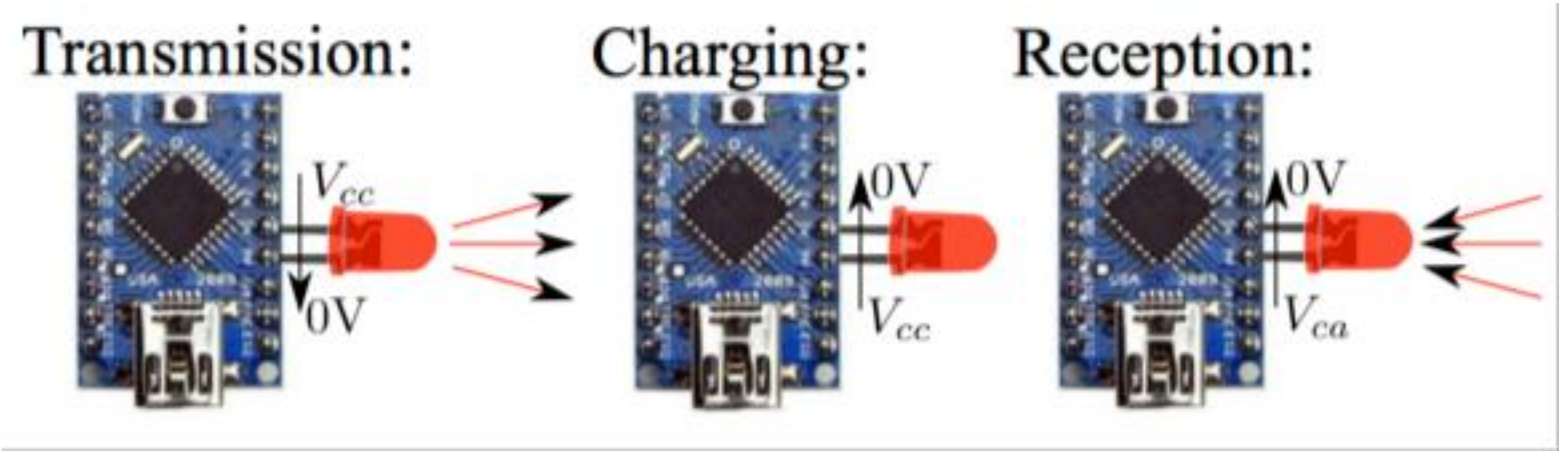
Safety and v2v Broadcasting

- Experiment: safety communications under various traffic density
- Links have limited range and angles.
- When can vehicles reliably warn each other about upcoming hazards?



LEDs as Receivers!?

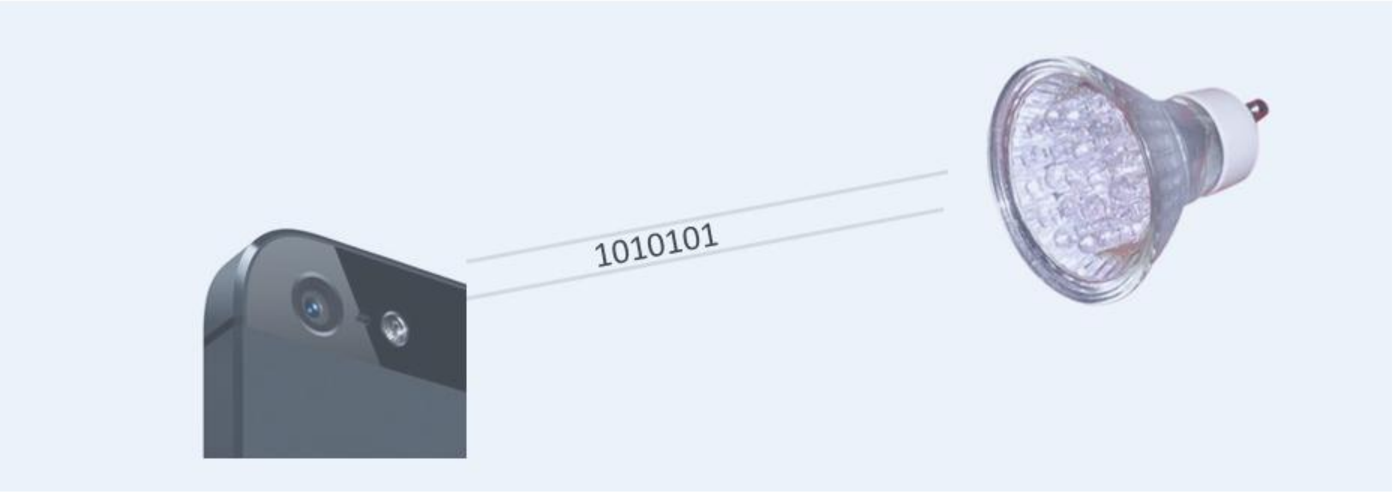
- Low-complexity design
- Applications from microcontrollers to toys
- On-Off keying for transmitter
- Receiver: operate LED in reverse bias
  - Capacitor discharges faster when received light creates photocurrent

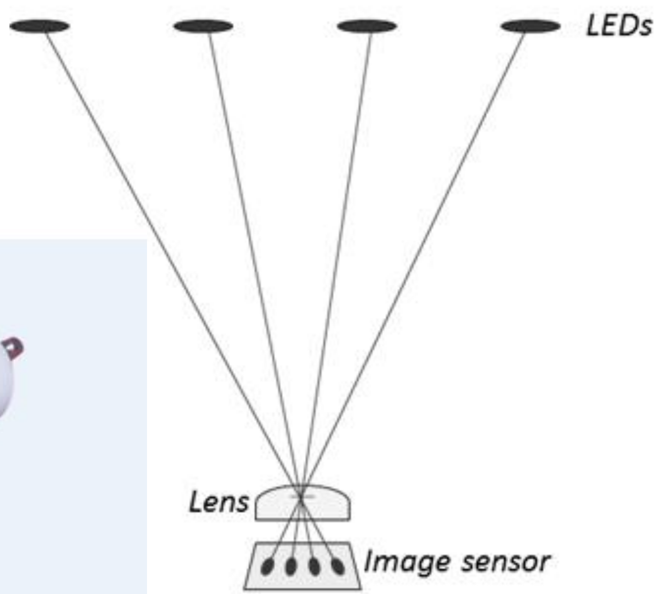


Source:. Giustiniano et al., best paper winner, IFIP Wireless Days 2012

Cameras as Receivers

- Leverage ubiquity of cameras on communication devices
- Receiver array vs. single photodiode
- Spatial separation/resolution for massive MIMO





Source: Rick Roberts, Intel Labs

VLC Challenges

- High mobility
  - Maintain connectivity
  - Maintain real-time performance
  - Dynamic and smart selection of transmit lights

- Protocol design from the ground up
  - Vehicular emergency services, LAN, microcontrolled devices

- Prototypes and experiments with new services and real-world operating conditions

- PHY advances for robust, low-cost, high-performance links

Summary

- Opportunities for truly diverse spectrum access
  - Wavelengths from meter to nanometer
  - Frequencies from 100’s of MHz to 100’s of THz
- Research and trials critical
  - New models of spectrum sharing
  - New application scenarios and proof-of-concept demos
  - Exploit flexible and evolving IEEE 802 standards
- Steer the FCC, markets and policy

http://networks.rice.edu