Multi-Gigabit Wireless Multimedia Communications: Future and Core Technologies*

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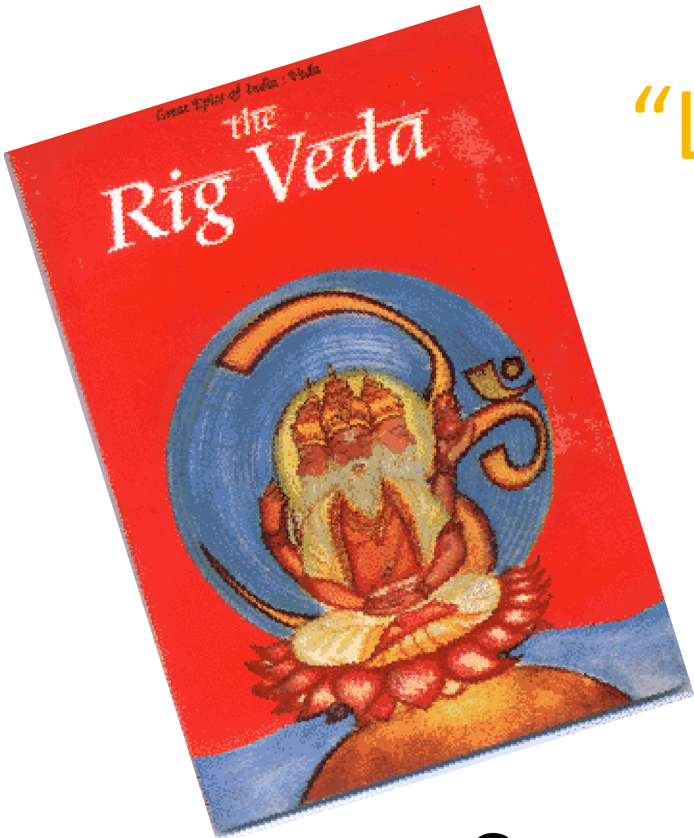
Outline

- The University of British Columbia
- The Forthcoming IEEE Communications Society Election
- Introduction and Motivation
- Current Standardization Activities
- Multi-gigabit Wireless Technical Challenges and Core Technologies
  - 60 GHz Propagation and Antennas
  - CMOS Circuit Design
  - Modulation Schemes
  - LDPC Codes for Error Correction
  - MAC Layer Design
- Conclusions

आ नो भद्राः क्रतवो यन्तु विश्वतः
- ऋगवेद



"Let Noble Thoughts come
to us from all sides"
- Rigveda 1-89-i

Related to Avesta (اوستا):
Sacred texts of Zoroastrianism.

The University of British Columbia

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

The University of British Columbia

- 100 years old in 2008
- A world class university with a spectacular location
- Consistently ranked among world's top 50 universities
  - #34, Times World University Rankings 2008
  - #36, Shanghai Jiaotong University World University Ranking 2008
  - #17, US News World's Best Universities (Engineering and IT, 2009)
- Annual budget of CDN$1,600,000,000
- More than 45,000 students
- 12 faculties and 11 schools, 2 campuses in Vancouver and Kelowna
- World class faculties in medicine, life sciences, law, engineering and management
- One home-grown and one resident Nobel Laureates
  - Michael Smith, Nobel Prize in chemistry, 1993
  - Carl Wieman, Nobel Prize in physics, 2001

Dept. ECE @ UBC

- 56 faculty members, 11 IEEE Fellows
- Two graduate degrees: BASc EE, BASc CE
- Three postgraduate degrees: PhD, MASc, MEng
- Approximately 800 undergrad. students (year 2, 3, 4) and 350 graduate students
- Research groups:
  - Biotechnology
  - **Communications**
  - Control & Robotics
  - Computer & Software Engineering
  - Electric Power & Energy Systems
  - Microsystems & Nanotechnology
  - Signal Processing & Multimedia
  - Very Large Scale Integration Group

Communications Group @ ECE. of UBC

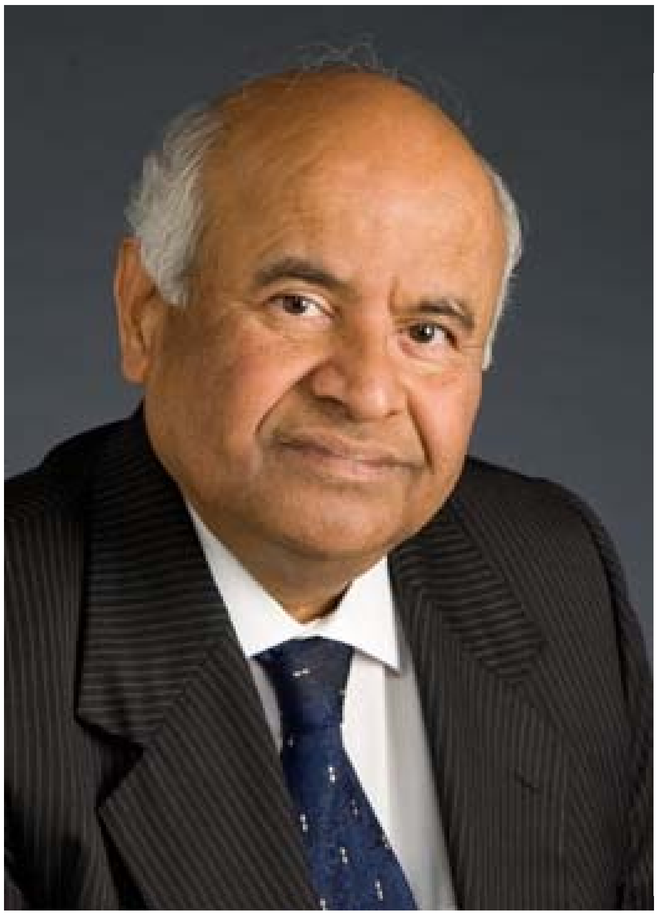
- ***Vijay Bhargava*** – error correcting codes, wireless systems and technologies beyond 3G, cognitive radio
- **Lutz Lampe** – modulation and coding, MIMO systems, CDMA, ultra-wideband (UWB), wireless sensor networks
- **Cyril Leung** – wireless communications, error control coding, modulation techniques, multiple access, security
- ***Victor Leung*** – network protocols and management techniques, wireless networks and mobile systems, vehicular telematics
- **Dave Michelson** - propagation and channel modeling for wireless communications system design, low-profile antennas
- ***Robert Schober*** – detection, space-time coding, cooperative diversity, CDMA, equalization
- **Vincent Wong** – wireless and optical networks, ad hoc, sensor networks

Strong Research Focus on Wireless Systems

Advanced Radio Transmission and Resource Management Techniques for Cooperative Cellular Wireless Networks

- NSERC Strategic Project Grant, $446,000 total, 2009-2012
- Industrial partners: **TELUS Corporation, Sierra Wireless Inc.**
- **V. Bhargava (PI)**, E. Hossain (University of Manitoba)
- Five main objectives:
  - Advanced Transceiver Design for Cooperative Communication
  - Enhanced Channel and Network Coding for Cooperative Communication
  - Relay Selection and Resource Allocation Techniques
  - Medium Access Control (MAC) and QoS Provisioning Framework
  - Inter-cell Cooperation Techniques

Vijay K. Bhargava



Candidate for

IEEE Communications Society President-Elect (2011)

Election to be conducted in Spring 2010

All members and Student members of IEEE Communications Society are eligible to vote.

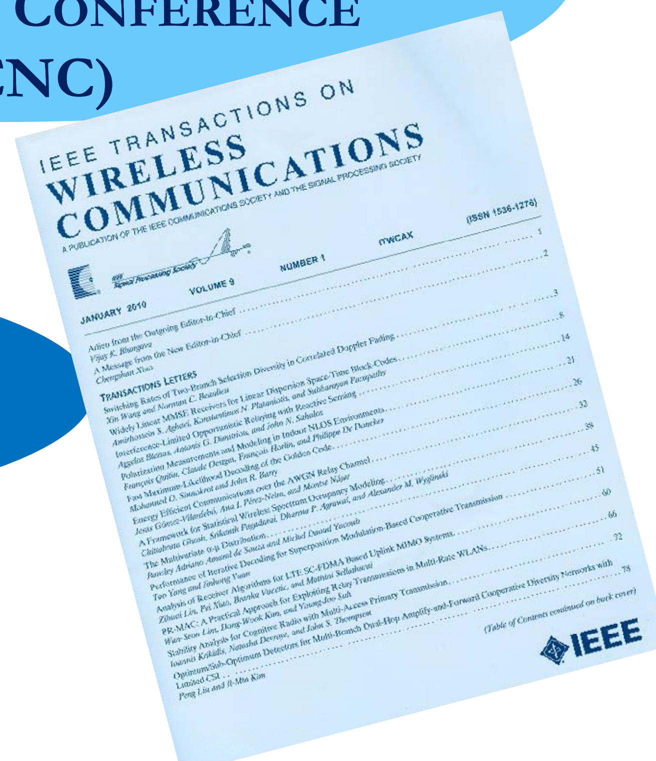
Accomplishments in Previous Positions

For the IEEE Communications Society

❖ A Major New Journal and New Conference

IEEE WIRELESS COMMUNICATIONS AND NETWORKING CONFERENCE (WCNC)

IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS



Accomplishments in Previous Positions

For the IEEE Information Theory Society

- As Society President – Dedication Ceremony in Shannon Park, Gaylord, Michigan (2000)

Claude Elwood Shannon

Father of Information Theory

Electrical engineer, mathematician, and native son of Gaylord. His creation of information theory, the mathematical theory of communication, in the 1940s and 1950s inspired the revolutionary advances in digital communications and information storage that have shaped the modern world.

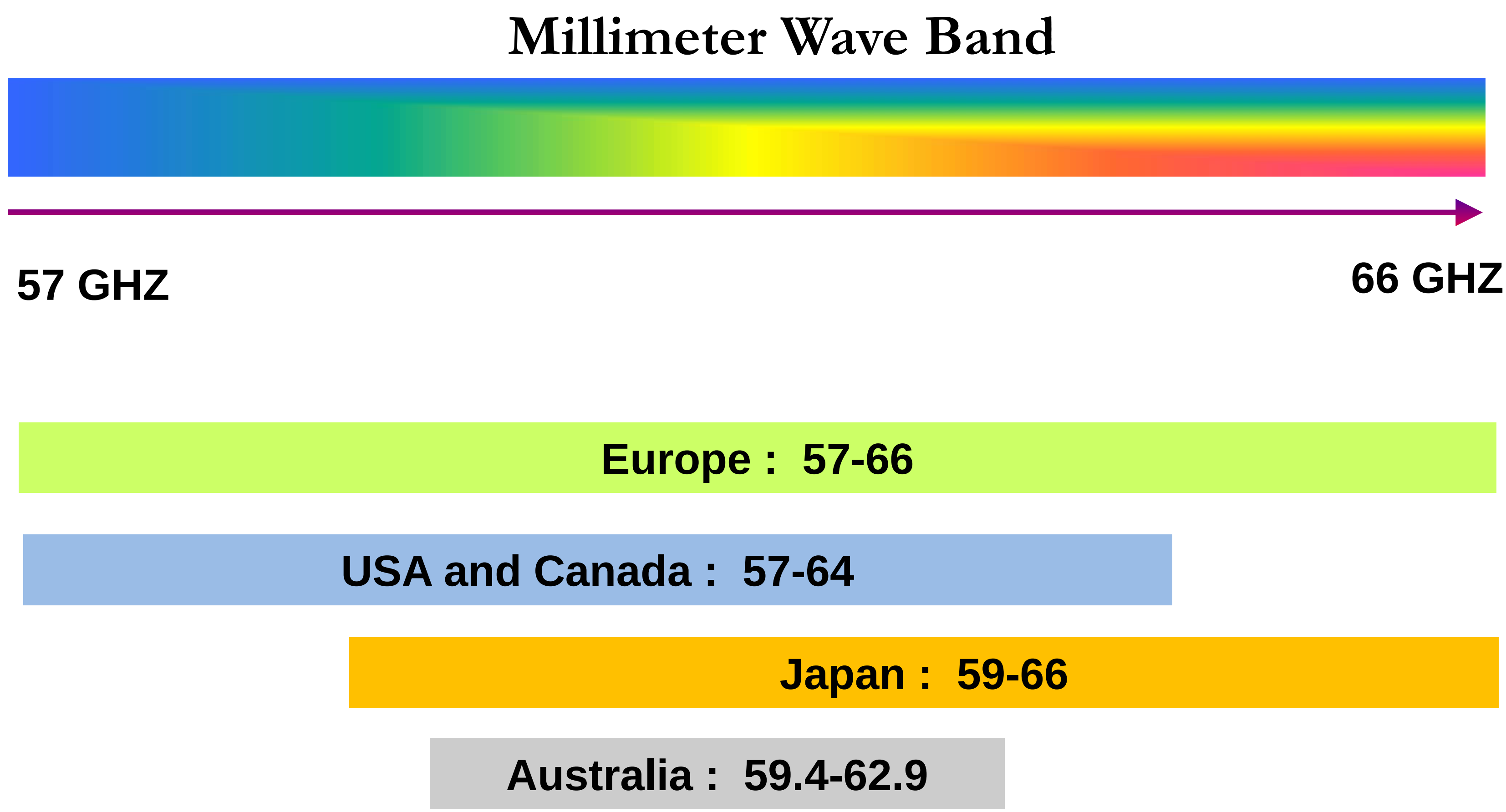
This statue was donated by the Information Theory Society of the Institute of Electrical and Electronics Engineers, whose members follow gratefully in his footsteps.

Dedicated October 6, 2000
Eugene Daub, Sculptor

Introduction & Motivation

- In recent years, there has been increasing demands for reliable, very-high-throughput wireless communications in indoor environments
  - Most of the current wireless local area network (WLAN) and personal area network (WPAN) technologies such as WiFi and bluetooth operate in unlicensed ISM bands which are over-crowded
- 60 GHz mmWave radio is a promising technology for MGbps wireless multimedia communications
  - Vast amount of unlicensed bandwidth
  - Mature CMOS design facilitates low-cost 60 GHz devices

60 GHz Spectrum Allocation



Usage Models for 60-GHz WLAN & WPAN

Examples of Indoor Wireless Multimedia Applications

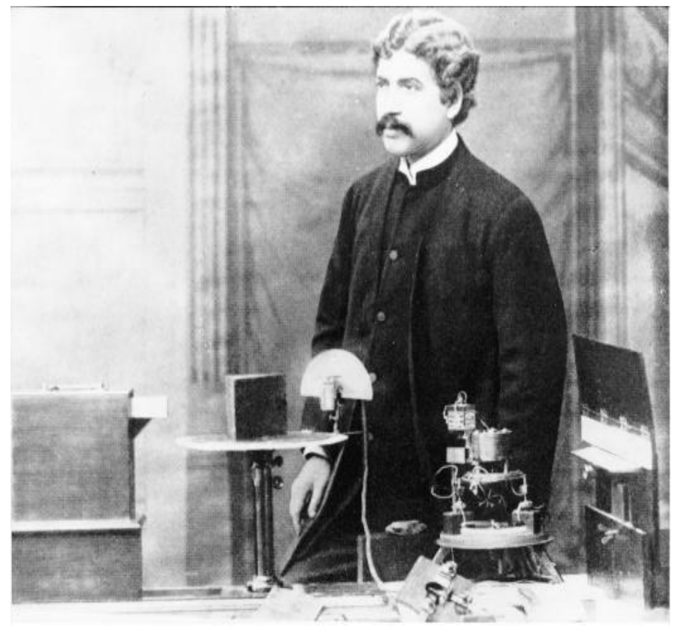
Application	**Rate [Mbps]**
Wireless Burglar Alarm	0.01
Indoor Remote Control	0.01
Wireless Embedded Systems in Cars	0.01
Road Pricing	0.1
Wireless Billing	0.1
Communication Between Home Appliances and Internet	0.1
Wireless Videophone	1.5
Wireless Surveillance Cameras	4-10
Hospital Bedside Application and Patient Monitor	10
Wireless Interactive Design	20-40
Wireless Ad Hoc Communications	0.1-100
High-Quality Video Conference	10-100
Gaming and Trading Terminal	50-100
Wireless IEEE 1394	100-400
Wireless High-Resolution Recording Camera	150-270
Wireless Virtual Reality Devices	450
WLAN Bridge Connecting Giga-Ethernet LANs	100-1000

Standardization for 60 GHz WLAN/WPAN

- **IEEE 802.11 ad**
  - **State-of-the-art PHY/MAC standardization activities o improve WLAN data rate to MGbps**
  - **Dominated by Intel, Broadcom, NEC etc.**
- **WiGig (Wireless Ggabit Alliance, previously known as NGmS)**
  - **60-GHz Industry alliance led by Intel**
  - **Promoters include Intel, Broadcom, NEC, Apple, Dell, Microsoft, Panasonic, LGE, Toshiba, Wilocity, etc.**
- **IEEE 802.15.3c (**First IEEE standard on 60 GHz WPAN**)**
  - Promoted mainly by Japanese companies
- **ECMA TC48**
  - European standardization for 60 GHz WPAN
- **WirelessHD**

60 GHz mm-Wave Radio: History

- Origin of 60 GHz radio can be traced back to the work of J. C. Bose in 1890's.
  - In 1897, J.C. Bose described to the Royal Institution in London his research carried out in Calcutta at millimeter wavelengths.
  - Used waveguides, horn antennas, dielectric lenses, polarizers and semiconductors at frequencies as high as 60GHz
  - Much of his original equipment still in existence at the Bose Institute in Calcutta
- Initially, 60GHz band designated for military purposes in US
- Opened by Federal Communications Commission (FCC) for commercial use in 1990's



60 GHz mm-Wave Radio: Advantages

- High transmit power allowed compared to existing WPAN and WLAN standards due to low interference
- The signal is usually confined within a room due to high material absorption
- Higher throughput can be achieved through frequency reuse
- Higher transmit power and larger bandwidth allow use of simple modulation schemes
- The antenna area is small due to smaller wavelengths
  - More antennas can be accommodated in a small area

60 GHz mm-Wave Radio: Challenges

- Low transmission range
  - Friis* free space path loss equation shows that, for equal antenna gains, the path loss is proportional to square of the carrier frequency
  - High material absorption
  - Deep shadowing
- Performance of CMOS circuits is limited at such a high frequency
- Baseband analog bottleneck needs to be avoided at the receiver
  - The interface circuits are required to convert the signal with high resolution and operate at over twice the Nyquist rate
  - Thus, the device complexity could be quite high for 60 GHz devices

* Harald T. Friis (1883-1976)

60 GHz mm-Wave Radio: Beamforming

- Omni-directional antennas are inefficient
- Multi-antenna beam-forming techniques need to be studied
- Antenna array is a feasible solution at 60 GHz due to small antenna dimension
- Antenna arrays could be used to generate narrow directional beam with high gain, thus increasing the transmission range
- Beam-forming also reduces multi-path fading problem

60 GHz mm-Wave Radio: CMOS Circuit Design

- Historically, the cost of the 60GHz devices, implemented using compound semiconductors*, has been very expensive
- SiGe versus CMOS debate will continue
- When will we see high speed front ends with acceptable price?
- Bulk CMOS process at 130nm for 60 GHz RF building blocks has been demonstrated
- A fully integrated CMOS solution can drastically reduce costs

* Exotic but not main stream technologies

60 GHz mm-Wave Radio: CMOS Circuit Design

- With technology advancement 65nm CMOS process to further improve speed and potentially lower power consumption of the devices is possible
- As size is reduced, speed increases but other drawbacks may limit gain
- 32nm CMOS has been demonstrated but we may “hit the wall” around 20-10nm
- CMOS driven by digital technology $\Rightarrow$ analog front end and move to digital
- Improved CMOS circuit design requires
  - Accurate device models capable of predicting the wideband performance of the transistors
  - Rigorous characterization and testing methodology for predictable design
  - Optimized layout of CMOS transistor for maximum frequency of operation

子曰：三人行必有我师焉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60 GHz mm-Wave Radio: Modulation Schemes

- Modulation schemes tolerant to limited performance of CMOS circuits need to be studied
  - Must have low peak-to-average power ratio
  - Must be insensitive to phase noise
  - Spectral efficiency is not a crucial issue due to the availability of vast bandwidth
  - Minimum shift keying (MSK) is a promising candidate for modulation

60 GHz mm-Wave Radio: Analog Signal Processing

- More analog pre-processing will reduce the burden in the baseband digital processing*
  - Synchronization and equalization can be carried out partly in analog domain
  - Simplified requirements on the Analog-to-Digital Convertors (ADC)
  - Synchronization and equalization parameter errors are estimated in the digital domain and corrected in analog domain

*Digitally assisted analog signal processing or mixed signal processing $\Longrightarrow$ System-on-a-chip

60 GHz mm-Wave Radio: LDPC for Error Correction

- State-of-art standards such as WiFi (IEEE 802.11 n), WiMax (IEEE 802.16e) and ETSI DVB-T2/C2/S2 all adopted LDPC codes
- The major challenge for 60 GHz systems is to design low-complexity and high-throughput decoders
- Rate compatibility is a necessity for code design
- To achieve a good tradeoff between complexity and performance, it would be of interest to explore LDPC codes based on circulant matrices using combinatorial optimization techniques

Example of Structured Short-Length LDPC Codes (IEEE 802.15.3c)

(576,288), Code rate: 1/2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	-	-	-	4	-	-	-	-	-	2	-	-	5	-	-	-	-	10	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	9	-	-	-	-	5	5	-	-	-	10	-	-	-	-	-	-	8	-	-	-	-	-	-	-	-	-	-	-	-
3	-	11	-	-	-	15	-	-	-	-	-	8	-	-	-	6	-	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	10	-	-	2	-	-	13	-	-	-	-	10	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	-	2	-	-	-	4	-	-	-	-	-	2	-	-	5	-	-	-	-	10	-	-	7	-	-	-	5	-	-	-	-	-
6	-	-	-	9	5	-	-	-	-	5	-	-	-	10	-	-	8	-	-	-	-	-	-	16	-	2	-	-	-	-	-	-
7	-	-	11	-	-	-	15	-	8	-	-	-	6	-	-	-	-	-	17	-	-	6	-	-	7	-	-	-	-	-	-	-
8	10	-	-	-	-	-	-	2	-	-	13	-	-	-	-	10	-	5	-	-	0	-	-	-	-	-	-	8	-	-	-	-
9	-	-	2	-	-	-	4	-	2	-	-	-	-	-	-	5	10	-	-	-	-	-	-	7	-	-	-	-	-	-	-	-
10	9	-	-	-	-	5	-	-	-	-	5	-	-	-	10	-	-	8	-	-	16	-	-	-	-	-	-	-	-	-	-	-
11	-	-	-	11	-	-	-	15	-	8	-	-	-	6	-	-	-	-	-	17	-	-	6	-	-	-	-	-	-	-	-	-
12	-	10	-	-	2	-	-	-	-	-	-	13	10	-	-	-	-	-	5	-	-	0	-	-	-	-	-	-	-	-	-	-
13	-	-	-	2	-	-	-	4	-	2	-	-	5	-	-	-	-	10	-	-	7	-	-	-	5	-	-	-	-	-	-	12
14	-	9	-	-	-	-	5	-	-	-	-	5	-	-	-	10	-	-	8	-	-	16	-	-	-	-	-	2	-	16	-	-
15	11	-	-	-	15	-	-	-	-	-	8	-	-	-	6	-	17	-	-	-	-	-	-	6	-	-	7	-	-	-	10	-
16	-	-	10	-	-	2	-	-	13	-	-	-	-	10	-	-	-	-	-	5	-	-	0	-	-	8	-	-	16	-	-	-

(576,432), Code rate: 3/4

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	-	9	-	4	-	-	5	12	-	16	-	5	-	2	-	10	5	-	-	-	-	10	8	-	7	-	-	-	-	-	-
2	-	11	-	10	-	15	2	-	-	16	-	10	-	13	-	8	-	-	10	6	5	17	-	-	6	-	-	-	-	-	-	-
3	-	2	-	9	5	4	-	-	-	12	-	16	-	5	-	2	-	10	5	-	8	-	-	10	-	-	7	16	-	2	-	-
4	10	-	11	-	-	-	15	2	10	-	16	-	8	-	13	-	6	-	-	10	-	5	17	-	0	6	-	-	7	-	-	-
5	9	-	2	-	-	5	4	-	16	-	12	-	2	-	5	-	-	-	10	5	10	8	-	-	16	-	-	7	-	-	-	-
6	-	10	-	11	2	-	-	15	-	10	-	16	-	8	-	13	10	6	-	-	-	-	5	17	-	0	6	-	-	-	-	-
7	-	9	-	2	-	-	5	4	-	16	-	12	-	2	-	5	5	-	-	10	-	10	8	-	7	16	-	-	5	-	-	2
8	11	-	10	-	15	2	-	-	16	-	10	-	13	-	8	-	-	10	6	-	17	-	-	5	-	-	0	6	-	8	7	-

(576,504), Code rate: 7/8

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	2	11	9	10	4	15	2	5	12	16	16	10	5	13	2	8	10	5	10	6	5	17	10	8	6	7	16	0	2	-	-	-
2	10	2	11	9	5	4	15	2	10	12	16	16	8	5	13	2	6	10	5	10	8	5	17	10	0	6	7	16	7	2	-	-
3	9	10	2	11	2	5	4	15	16	10	12	16	2	8	5	13	10	6	10	5	10	8	5	17	16	0	6	7	8	7	2	-
4	11	9	10	2	15	2	5	4	16	16	10	12	13	2	8	5	5	10	6	10	17	10	8	5	7	16	0	6	5	8	7	2

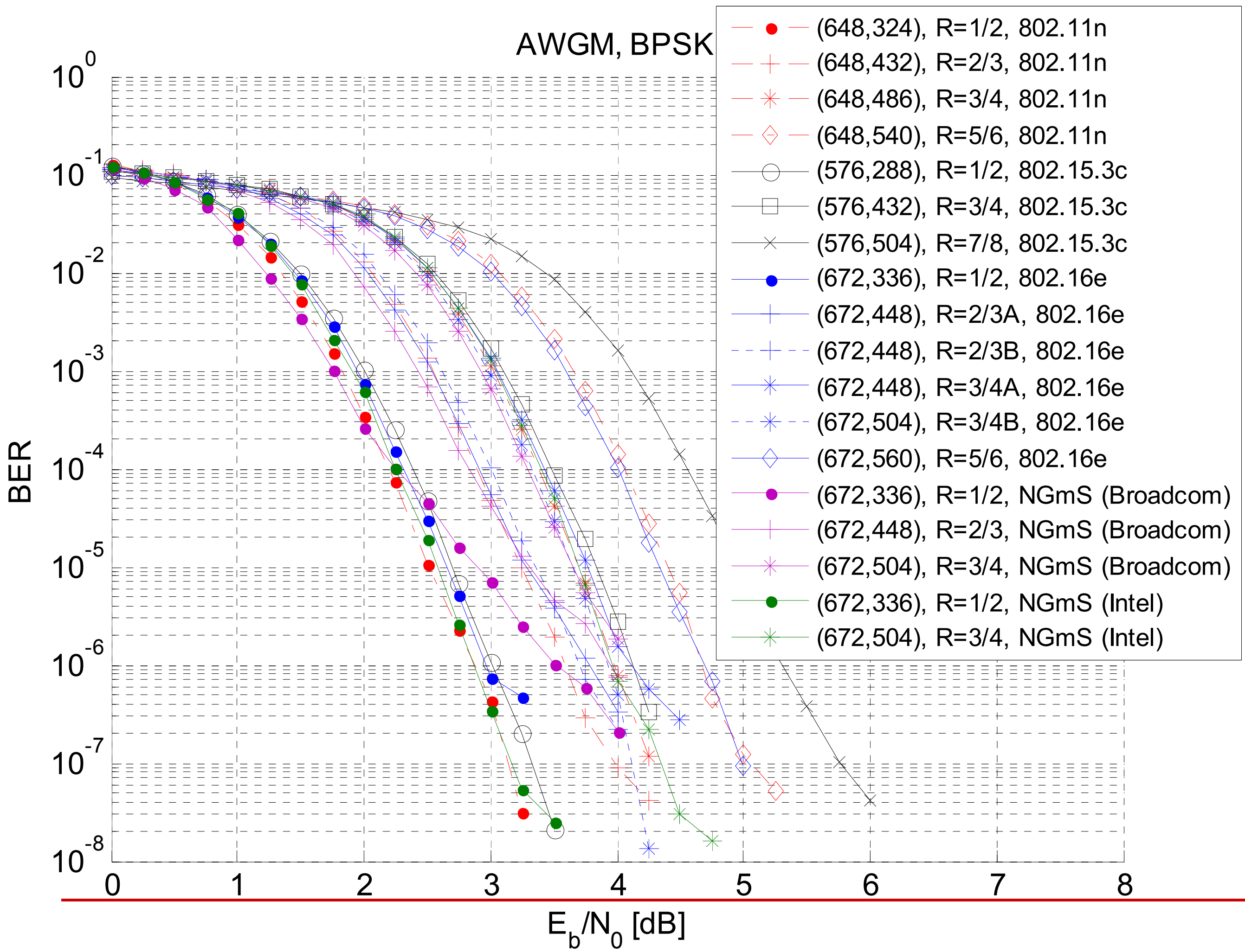
$$\mathbf{P}_0 = \begin{pmatrix} 1 & 0 & \cdots & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ \vdots & 0 & \ddots & 0 & \vdots \\ 0 & \cdots & 0 & 1 & 0 \\ 0 & \cdots & \cdots & 0 & 1 \end{pmatrix}_{k \times k}$$

$$\mathbf{P}_1 = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ \vdots & 0 & 1 & 0 & \vdots \\ \vdots & \vdots & \ddots & 1 & 0 \\ 0 & \cdots & \cdots & 0 & 1 \\ 1 & 0 & \cdots & \cdots & 0 \end{pmatrix}_{k \times k}$$

$$\mathbf{P}_2 = \begin{pmatrix} 0 & 0 & 1 & \cdots & 0 \\ 0 & 0 & 0 & 1 & \vdots \\ 0 & \vdots & \ddots & \ddots & \ddots \\ 1 & 0 & \cdots & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \end{pmatrix}_{k \times k}$$

Integer entries in the table indicate the cyclic shift number "*n*" of matrix $\mathbf{P_n}$

Performance of Short-Length LDPC Codes Selected by Standards



A GOOD code design favors :

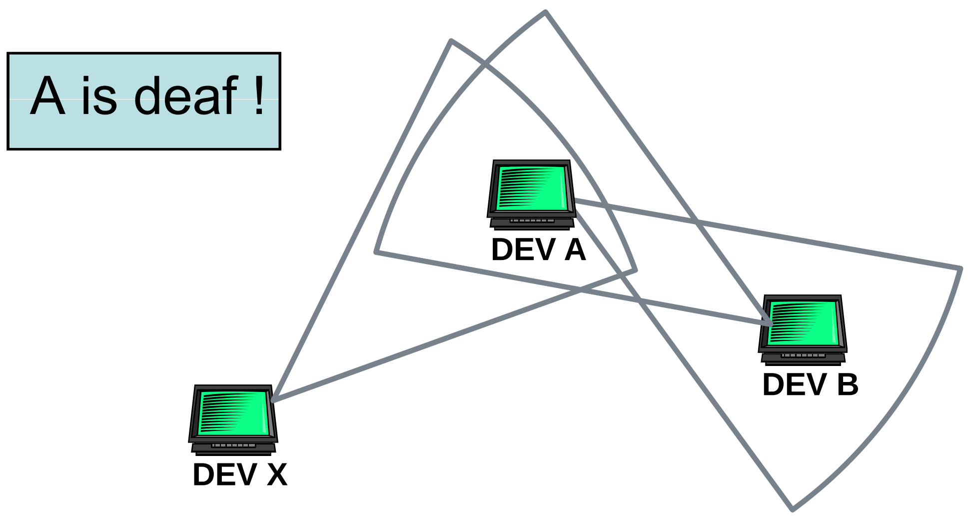
1. **Low decoding SNR**
2. **Low error floor**
3. **Low complexity**

60 GHz mm-Wave Radio: MAC Protocol Design

- 60 GHz WLAN favors directive communication
  - However, conventional WLAN MAC protocols are designed for omni-directional antennas
  - Directional antenna is inherent incompatible with CSMA
    - Deafness and "directional" hidden terminal problems
- We need a MAC protocol that can utilize directional antennas with robust performance
  - Needs to address **high propagation loss** and **blockage**
  - A large number of antennas have to be supported
    - Example: current standards demand at least 32 independent directions to achieve higher antenna gain

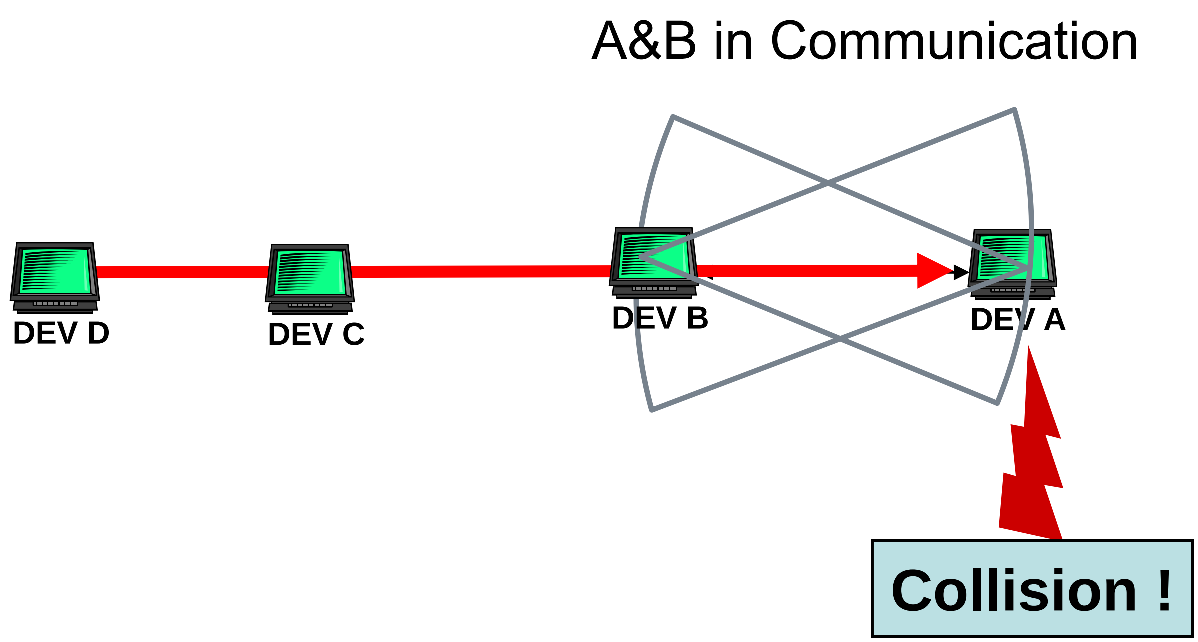
Directional MAC Design Challenge for 60 GHz – Deafness Problem

- Device X has a packet for Device A
  - "X" will send a directional RTS to "A" first.



Directional MAC Design Challenge for 60 GHz – Hidden Terminal Problem

- Device D has a packet for Device C.
  - Unfortunately, D's RTS accidentally falls into A's receiving range.



60 GHz mm-Wave Radio: More on MAC Design

- Handover Integration
  - Takes place at link layer
  - Fast context transfer necessary between radios
  - Not suitable for latency -sensitive applications
- Upper MAC Integration
  - Designed for upper MAC functions such as association, security function and channel time allocation
  - Mainly software changes
- Full MAC Integration
  - Requiring major MAC modification (both software and hardware)

Conclusions

- Commercial success of 60 GHz WPAN/WLAN devices will depend on:
  - Design of efficient multi-antenna beamforming techniques to combat heavy path losses and penetration losses at 60 GHz
  - Design of low-cost and low-power CMOS circuits that operate efficiently at 60 GHz
  - Design of suitable modulation schemes that take into consideration restrictions imposed by CMOS circuits
  - Development of high-throughput and low complexity decoder architecture for LDPC codes
  - Design of a suitable directional MAC protocol (D-MAC)

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Commercial

A Forthcoming Edited Book

Cooperative Cellular Wireless Networks

Editors:

Ekram Hossain – University of Manitoba

Dong In Kim – Sungkyunkwan University

Vijay Bhargava – University of British Columbia

Cambridge University Press, Fall 2010

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