WIRELESS TECHNOLOGIES IN 5G

A. Chockalingam

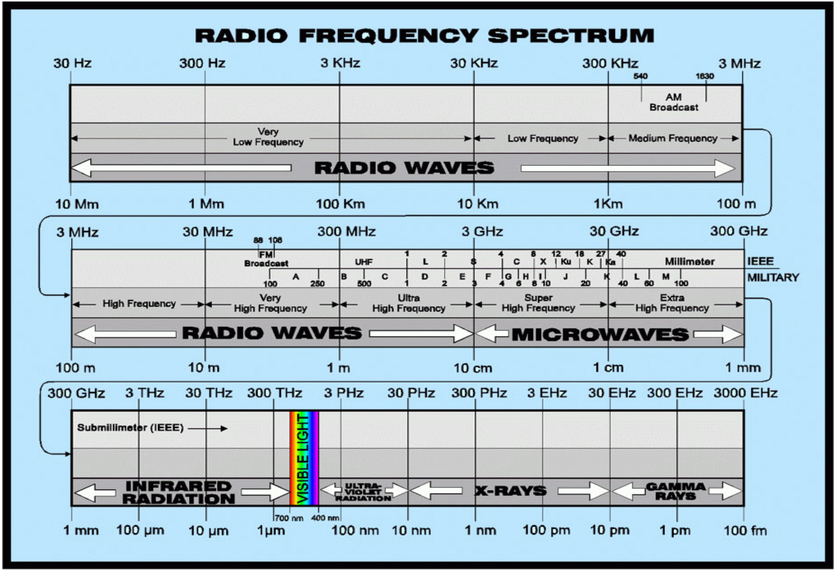
Department of ECE, IISc

Science Academies' SRFP Special Lecture
Bangalore

13 June 2014

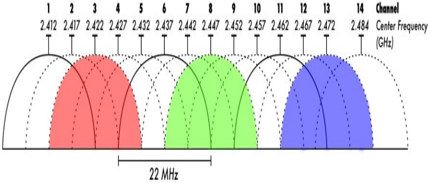
Outline

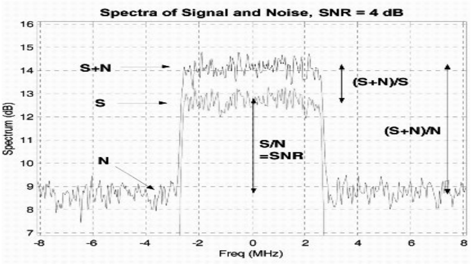
Wireless spectrum



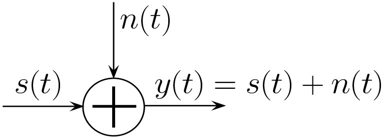
Some wireless terminologies

- Carrier frequency (Hertz; Hz)
- Bandwidth (Hz)
- Data rate (bits per second; bps)
- Spectral efficiency (bps per Hz; bps/Hz)
- Signaling interval (sec)
- Signal-to-noise ratio (SNR)
- Channel capacity (bps)
- Probability of bit error
- Multipath fading





AWGN channel



- e.g., satellite channel

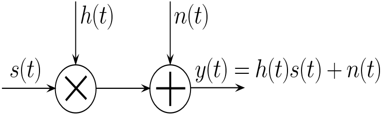
Channel	Error Probability (P_e)	Capacity (C), bps
AWGN	$P_e \propto e^{-SNR}$	$C = W \log(1 + SNR)$

- Prob. of error falls exponentially with SNR $\ddot{\smile}$
- Capacity grows only logarithmically with SNR $\ddot{\frown}$
- Almost error-free communication possible even at -1.6 dB SNR (i.e., even when signal level is below noise level)

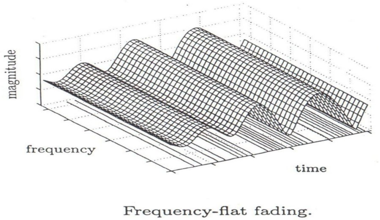
Multipath fading

- Fading channel characterization
  - Variation in time
    - Doppler spread (B_D) and coherence time (T_{coh})
    - $B_D = \frac{velocity}{carrier\ \ wavelength}$, $carrier\ \ wavelength = \frac{speed\ \ of\ \ light}{carrier\ \ frequency}$
    - $T_{coh} \propto {B_D}^{-1}$
    - Slow fading: Coherence time > signaling interval ($T_{coh} > T$)
    - Fast fading: Coherence time < signaling interval ($T_{coh} < T$)
  - Variation in frequency
    - Delay spread (T_D) and coherence bandwidth (B_{coh})
    - $B_{coh} \propto {T_D}^{-1}$
    - Frequency-flat fading: Coherence BW > Signaling BW ($B_{coh} > W$)
    - Frequency-selective fading: Coherence BW < Signaling BW ($B_{coh} < W$)

Fading channel



(a)



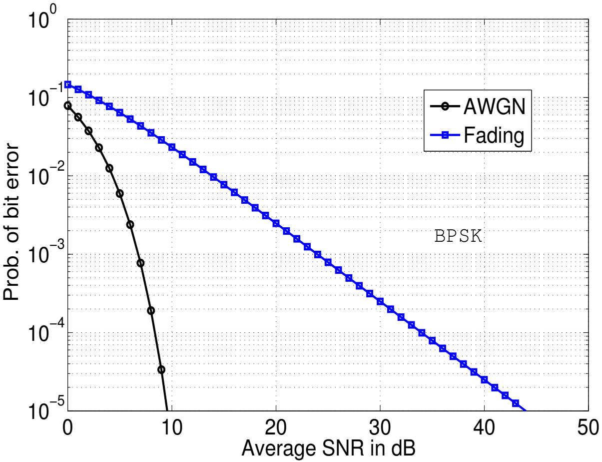
(b)

- e.g., mobile radio channel

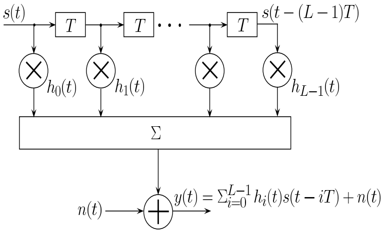
Channel	Error Probability (P_e)	Capacity (C), bps
Fading	$P_e \propto SNR^{-1}$	$C = W \log(1 + SNR)$

- Prob. of error falls only linearly with SNR

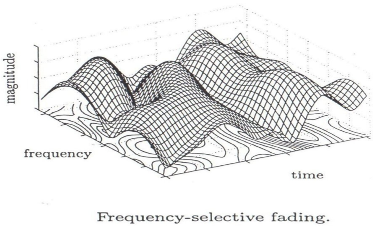
Prob. of bit error performance



ISI channel



(c)



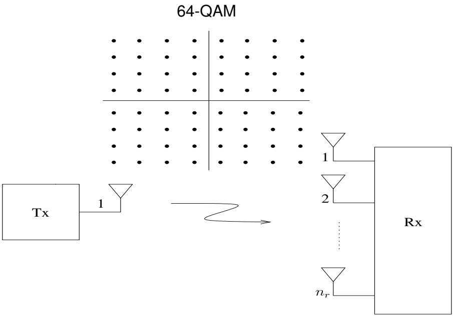
(d)

- e.g., mobile radio channel

Channel	Error Probability (P_e)	Capacity (C), bps
ISI	$P_e \propto SNR^{-L}$	$C = W \log(1 + SNR)$

- Prob. of error falls with Lth power of SNR (multipath diversity)

SIMO channel

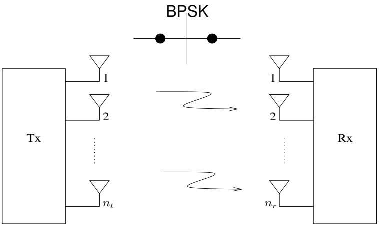


- e.g., mobile radio channel

Channel	Error Probability (P_e)	Capacity (C), bps
SIMO	$P_e \propto SNR^{-n_r}$	$C = W \log(1 + SNR)$

- Prob. of error falls with n_rth power of SNR (receive diversity) ☺

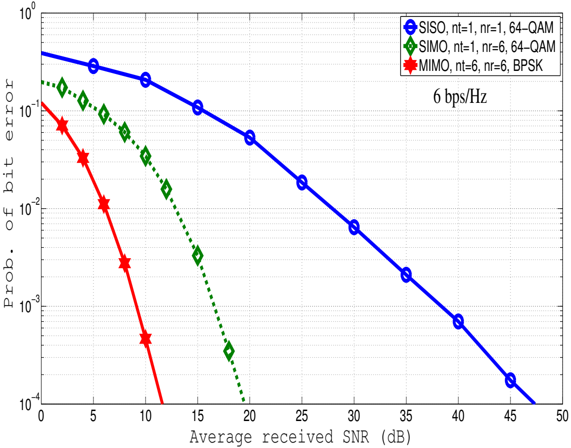
MIMO channel



Channel	Error Probability (P_e)	Capacity (C), bps
MIMO	$P_e \propto SNR^{-n_t n_r}$	$C = \min(n_t, n_r) W \log(1 + SNR)$

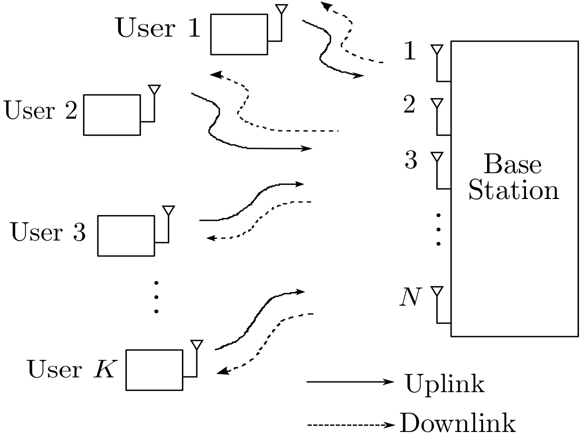
- Prob. of error falls with $n_t n_r$th power of SNR (tx & rx diversity)
- Capacity grows linearly with n_t, n_r
- Large no. of antennas $\Longrightarrow$ large capacity and diversity gains

Prob. of bit error performance



- MIMO
  - spectrally efficient, reliable, power efficient

Multiuser communication



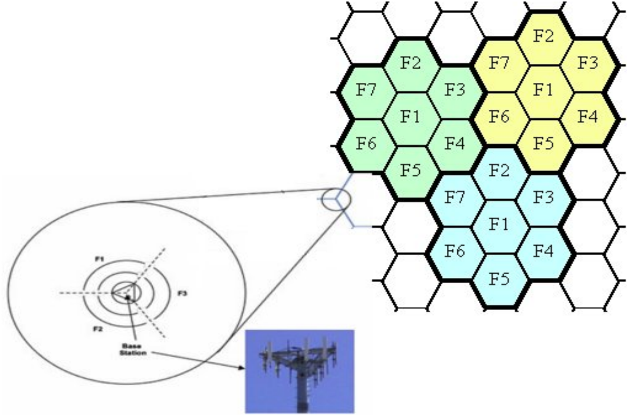
Multiple access

- FDMA (frequency division multiple access) - 1G
- TDMA (time division multiple access) - 2G
- CDMA (code division multiple access) - 2G, 3G
- OFDMA (orthogonal frequency division multiple access) - 4G
- SDMA (Space division multiple access) - 5G

- A performance measure of interest in multiple access
  - No. of users supported in a given system bandwidth

Cellular concept

- Cells, base stations, spatial reuse
- Frequency reuse factor: 7



1G (AMPS)

Service	Voice
Frequency band	850 MHz
Modulation	Analog (FM)
Multiple access	FDMA
BW per user	30 KHz

- Suppose 1.25 MHz of BW is allotted
- Reuse factor: 7
- $\implies$ No. of users supported per cell = $\frac{1.25 \times 10^6}{30 \times 10^3} \times \frac{1}{7} \approx 6$

2G (GSM)

Service	Voice / Data
Frequency band	900 MHz / 1800 MHz
Digitally encoded voice	13 Kbps
Modulation	GMSK
Multiple access	TDMA
BW per TDMA carrier	200 KHz
No. of TDMA slot per carrier	8
Error correcting code	Convolutional code
Equalization	Yes

- Suppose 1.25 MHz of BW is allotted
- Reuse factor: 7
- $\Longrightarrow$ No. of users supported per cell = $\frac{1.25\times10^6}{200\times10^3} \times 8 \times \frac{1}{7} \approx 7$
- Spectral efficiency: $13 \times 10^3 \times \frac{8}{200\times10^3} \approx$ 0.5 bps/Hz

2G (CDMA)

Service	Voice / Data
Frequency band	900 MHz / 1800 MHz
Digitally encoded voice (R)	9.6 Kbps
Modulation	BPSK
Multiple access	CDMA
BW per CDMA carrier	1.25 MHz
Chip rate (R_c)	1.2288 Mcps
Processing gain ($G_p = \frac{R_c}{R}$)	128
Error correcting code	Convolutional code

- Key features
  - Users transmissions overlap in both time and frequency
  - Users indentified using different spreading codes for different users
  - Reuse factor 1
  - Power control (to alleviate near-far effect)
  - RAKE receiver (achieves multipath diversity)

2G (CDMA)

- No. of users in CDMA (soft capacity)
  - CDMA exploits voice activation (G_v), sectorization (G_A), coding/diversity gains to increase no. of users

$$\text{No. of users, } K \approx \frac{G_p G_v G_A}{G_f (E_b/I_0)_{req}}$$

  - For typical values of $G_v, G_A, G_f, (E_b/I_0)_{req}$,

$$K \approx G_p$$

  - $\Longrightarrow$ No. users supported per cell ≈ 128
  - Spectral efficiency: $\frac{128 \times 9.6 \times 10^3}{1.25 \times 10^6} \approx 1$ bps/Hz

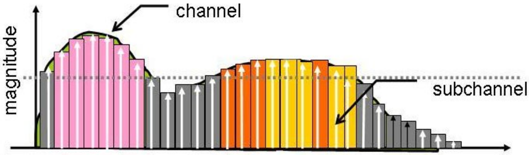
3G (CDMA)

Service	Voice / Data (more speed)
Frequency band	1.8 - 2.5 GHz
Data rate	up to 40 Mbps
Modulation	QAM
Multiple access	CDMA
Bandwidth	5 MHz, 10 MHz
Processing gain	Variable PG
Spectral efficiency	up to 8 bps/Hz
Error correcting code	Turbo code

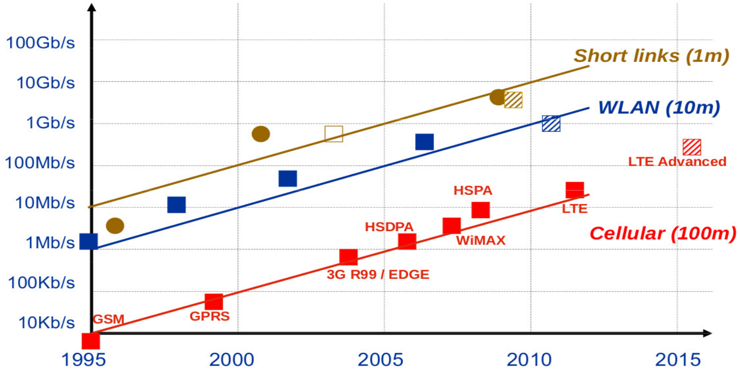
4G (OFDMA)

Service	Voice / Data (even more speed)
Frequency band	2 - 8 GHz
Data rate	100 Mbps - 600 Mbps
Modulation	QAM, MIMO-OFDM
Multiple access	OFDMA, SC-OFDMA
Bandwidth	40 MHz
Spectral efficiency	up to 15 bps/Hz
Error correcting code	Turbo code/LDPC

- OFDM



Moore's law drives wireless data rates



Source: SPAWC'2010 plenary talk slides of Dr. Gerhard Fettweis

Cellular evolution

Generation	Frequency band	PHY features	Data rate	Spectral Eff. (bps/Hz)
1G	850 MHz	FDMA, FM	N/A	N/A
2G	900 MHz, 1.8 GHz	TDMA/CDMA, GMSK/QPSK, FEC, PC	10 Kbps	< 1
3G	1.8–2.5 GHz	CDMA, QAM	1–40 Mbps	1–8
4G	2–8 GHz	OFDMA, SC-FDMA QAM, MIMO-OFDM	100 Mbps– 600 Mbps	15
5G	2.5, 5 GHz mm wave ? visible light?	large-scale MIMO beamforming? spatial modulation?	multi-Gbps	several tens

Increasing wireless data rates

- New spectrum
  - increase BW (e.g., 60 GHz band, mm wavelength, 7 GHz BW)
  - +: unlicensed (free)
  - -: propagation characteristics, devices, short range, cost
- Increase QAM size
  - -: need for high SNRs
- Large-scale MIMO
  - +: Theory has predicted unlimited capacity
  - -: Practicality, complexity, cost
- Dense deployments
  - Femtocells
  - +: 1000x speed up (claimed)
  - -: interference management, backhaul, cost

Large-scale MIMO systems

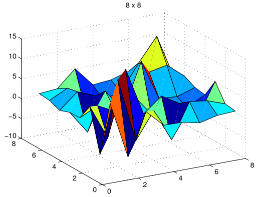
- Larger the number of antennas, better will be the
  - spectral efficiency
  - power efficiency
  - reliability
- Large-scale MIMO systems
  - Use tens to hundreds of antennas
  - Achieve very high spectral efficiencies in the range of tens to hundreds of bps/Hz

Technological challenges

- Placement of large no. of antenna elements
  - Feasible in moderately sized communication terminals
  - Use high carrier frequencies (small carrier wavelengths); e.g., 5 GHz, 60 GHz
  - Compact antenna arrays
- RF technologies
  - Multiple IF/RF transmit and receive chains
  - Spatial modulation
    - Allows use of less number of Tx RF chains than the number of Tx antennas
- Large MIMO signal processing
  - Signal detection, channel estimation, decoding, precoding
  - Channel hardening in large random matrices help

Channel hardening in large random matrices

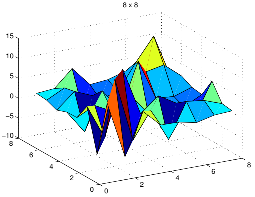
- Magnitude plots of $\mathbf{H}^H\mathbf{H}$ for different sizes of random matrix $\mathbf{H}$



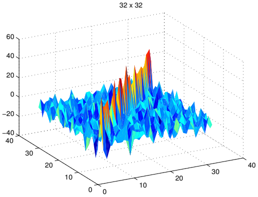
(e) 8×8

Channel hardening in large random matrices

- Magnitude plots of $\mathbf{H}^H\mathbf{H}$ for different sizes of random matrix $\mathbf{H}$



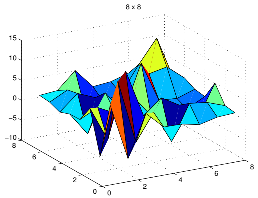
(i) 8×8



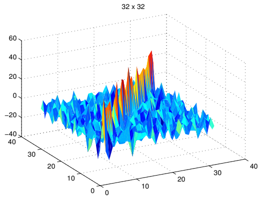
(j) 32×32

Channel hardening in large random matrices

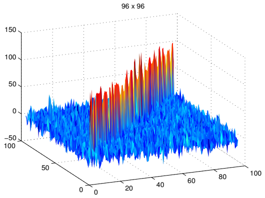
- Magnitude plots of $\mathbf{H}^H\mathbf{H}$ for different sizes of random matrix $\mathbf{H}$



(m) 8×8



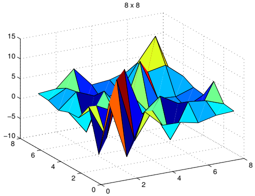
(n) 32×32



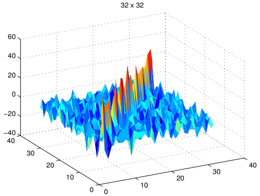
(o) 96×96

Channel hardening in large random matrices

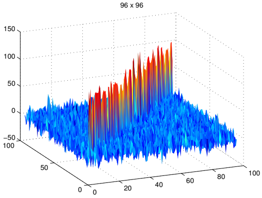
- Magnitude plots of $\mathbf{H}^H\mathbf{H}$ for different sizes of random matrix $\mathbf{H}$



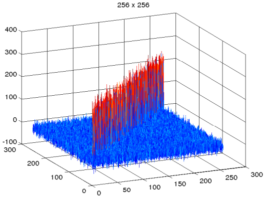
(q) 8×8



(r) 32×32



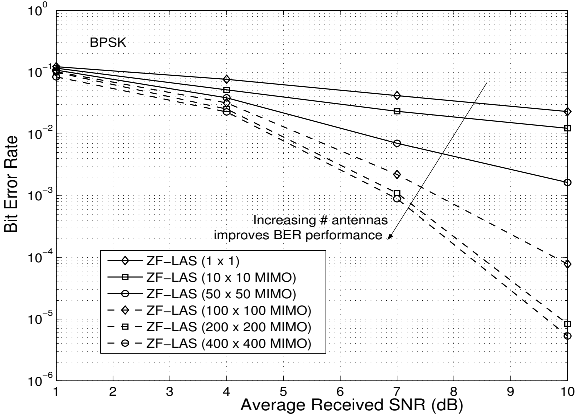
(s) 96×96



(t) 256×256

Simple algorithms – Good performance

- Local search based signal detection



* K. V. Vardhan, S. K. Mohammed, A. Chockalingam, and B. S. Rajan, *A low-complexity detector for large MIMO systems and multicarrier CDMA systems*, *IEEE J. Sel. Areas Commun., vol. 26, no. 3, pp. 473-485, Apr. 2008.*

US patent

US008116411B2

(12) **United States Patent**
Chockalingam et al.

(10) **Patent No.: US 8,116,411 B2**
(45) **Date of Patent: Feb. 14, 2012**

(54) **METHOD TO DETECT DATA TRANSMITTED FROM MULTIPLE ANTENNAS AND SYSTEM THEREOF**

(75) Inventors: **Ananthanarayanan Chockalingam**, Bangalore (IN); **Balaji Sundar Rajan**, Bangalore (IN); **Kalepalli Vishnu Vardhan**, Bangalore (IN); **Saif Khan Mohammed**, Bangalore (IN)

(73) Assignee: **Indian Institute of Science**, Bangalore (IN)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1201 days.

(21) Appl. No.: **11/842,963**

(22) Filed: **Aug. 22, 2007**

(65) **Prior Publication Data**

US 2009/0041145 A1 Feb. 12, 2009

(30) **Foreign Application Priority Data**

Aug. 6, 2007 (IN) 01725/CHE/2007

(51) **Int. Cl.**
H04L 27/06 (2006.01)

(52) **U.S. Cl.** **375/341**; 375/147

(58) **Field of Classification Search** 375/130–132, 375/140, 147, 218, 316, 340, 341, 349
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0083082	A1 *	4/2004	Onggosanusi et al.	703/2
2006/0256888	A1 *	11/2006	Nissani (Nissensohn)	375/267
2007/0280370	A1 *	12/2007	Liu	375/267
2008/0279299	A1 *	11/2008	Reuven et al.	375/267

OTHER PUBLICATIONS

Y. Sun, "A Family of Linear Complexity Likelihood Ascent Search Multiuser Detectors for CDMA Communications", in Conf. Record of the Thirty-Fourth Asilomar Conf. on Signals, Systems and Computers, 2000; pp. 1163-1167; ISBN 0-7803-6514-3.*
J. Fan et al. "Near Maximum Likelihood Detection for Wireless MIMO Systems", IEEE Transactions on Wireless Communications, vol. 3, No. 5, Sep. 2004; pp. 1427-1430; ISSN: 1536-1276.*
H. Jafarkhani, Space-Time Coding: Theory and Practice, Cambridge University Press, 2005.
D. Tse and P. Viswanath, Fundamentals of Wireless Communication, Chapter I, Cambridge University Press, 2005.
G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," Bell Labs Tech. Jl., vol. 1, pp. 41-59, Aug. 1996.
G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Pers. Commun., vol. 6, pp. 311-335, Mar. 1998.

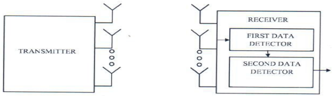
(Continued)

Primary Examiner — David C. Payne
Assistant Examiner — James M Perez
(74) *Attorney, Agent, or Firm* — Perkins Coie LLP; Aaron Wininger

(57) **ABSTRACT**

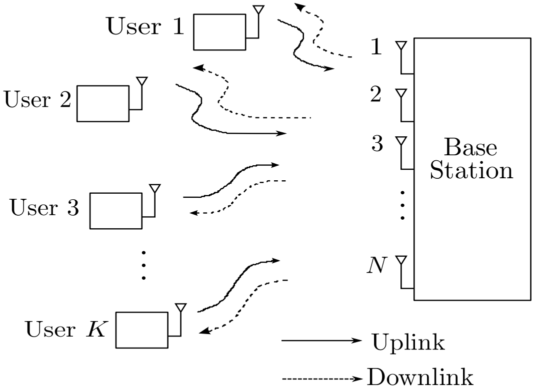
A method to detect data transmitted from multiple antennas, said method comprising steps of: selecting a starting data block and calling it as previous data block; defining a set of indices of bits to be checked for possible flip in the previous data block as a check candidate set; applying update rule to obtain updated data block using the previous data block and the check candidate set, wherein the update is made in such a manner that change in likelihood is positive; checking if the updated data block and several consecutive previous data blocks are the same; if yes, declare the updated data block as the detected data block; if no, make updated data block as previous data block and repeat updation of data block.

28 Claims, 15 Drawing Sheets



Large-scale multiuser MIMO (Massive MIMO)

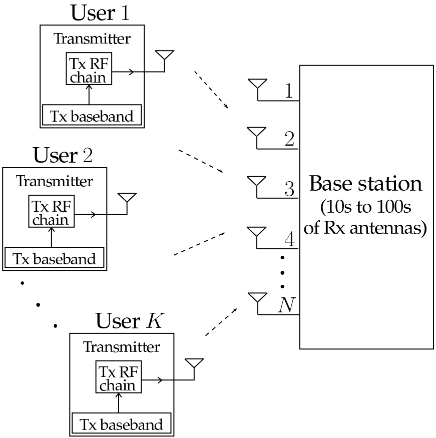
- Proposed architecture for 5G



- N: no. of BS antennas (hundreds)
- K: no. of users (tens)

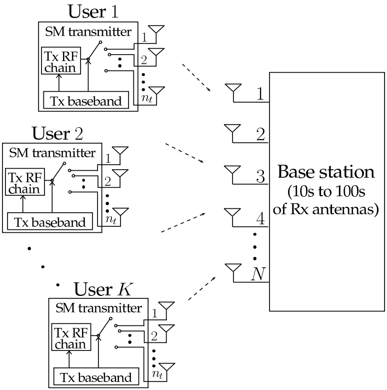
Massive MIMO

- One Tx RF chain for each Tx antenna
- Information bits carried only on modulation symbols (e.g., QAM)



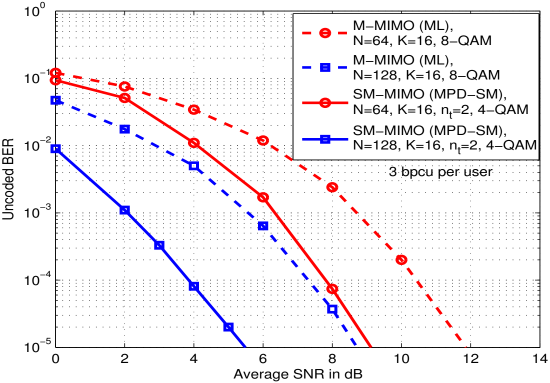
Spatial modulation for 5G

- Only one Tx RF chain and multiple Tx antennas
- One among the multiple Tx antennas is activated at a time
- Remaining Tx antennas remain silent
- Index of the active Tx antenna also conveys information bits
- $(\log_2 M + log_2 n_t)$ bpcu



SM-MIMO versus massive MIMO

- SM-MIMO outperforms massive MIMO by several dBs for the same spectral efficiency
- 4 to 5 dB SNR advantage over massive MIMO

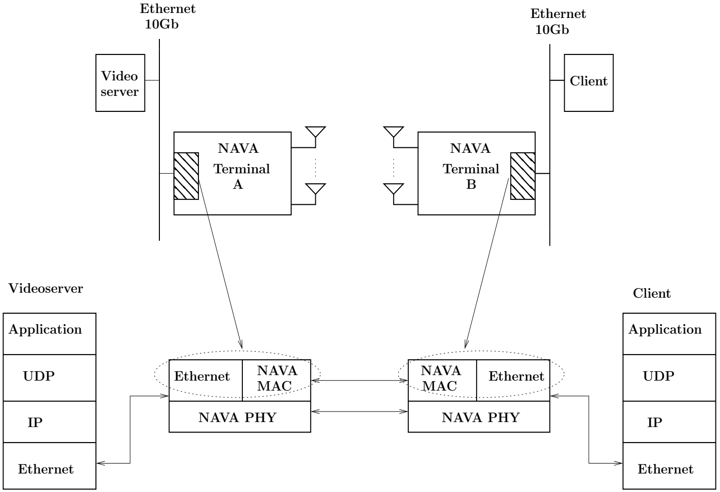


P. Raviteja, T. Lakshmi Narasimhan, A. Chockalingam, *Multiuser SM-MIMO versus Massive MIMO: Uplink Performance Comparison*, Available online *arXiv:1311.1291 [cs.IT] 6 Nov 2013.*

Project NAVA

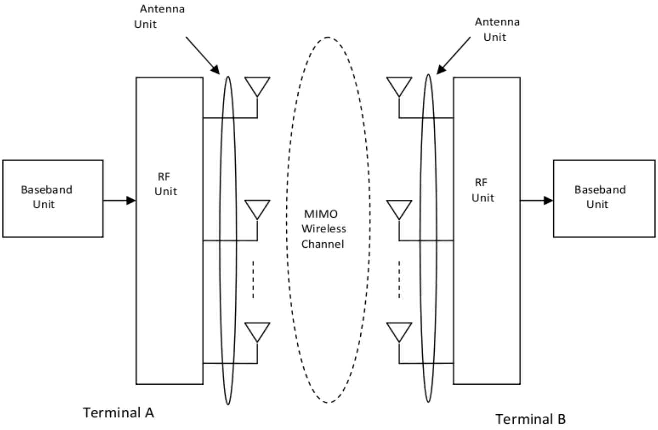
- A large-MIMO technology demonstrator project
- Goal
  - Demonstrate Gigabit transmission over-the-air
- Joint project: IISc, DRDO, and private industry
- IISc provides system design, core algorithms, and IP
- Private industry: develop/manufacture main subsystems

NAVA


Ethernet
10Gb
Video
server
NAVA
Terminal
A
Ethernet
10Gb
Client
NAVA
Terminal
B
Videoserver
Application
UDP
IP
Ethernet
Ethernet
NAVA
MAC
NAVA PHY
NAVA
MAC
Ethernet
NAVA PHY
Client
Application
UDP
IP
Ethernet

NAVA

- System

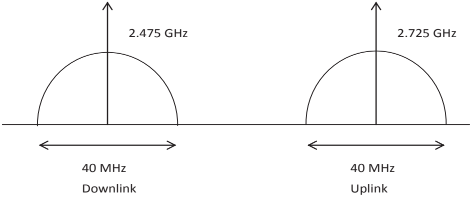

Antenna
Unit
Antenna
Unit
Baseband
Unit
RF
Unit
MIMO
Wireless
Channel
RF
Unit
Baseband
Unit
Terminal A
Terminal B

NAVA

- High level specifications

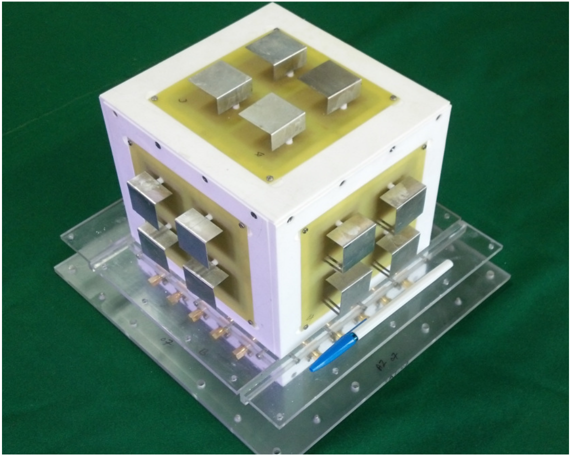
Parameter	Value
Data rate	1 Gbps
Bandwidth	40 MHz
Spectral efficiency	25 bps/Hz
Carrier frequency	2.5 GHz
No. transmit antennas	16
No. receive antennas	20

- Frequency plan



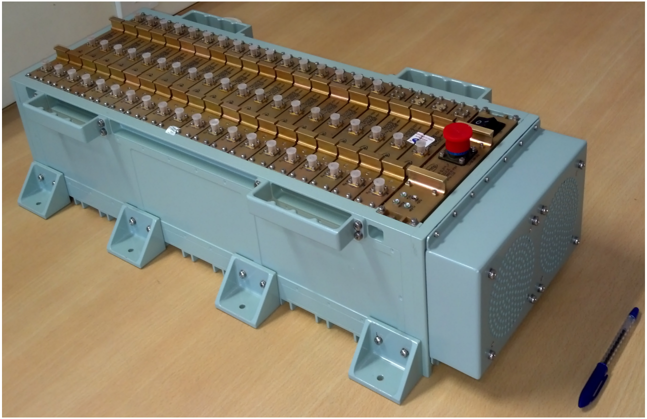
NAVA - Antenna unit

- 20-antenna MIMO cube at 2.5 GHz
- technology: PIFA



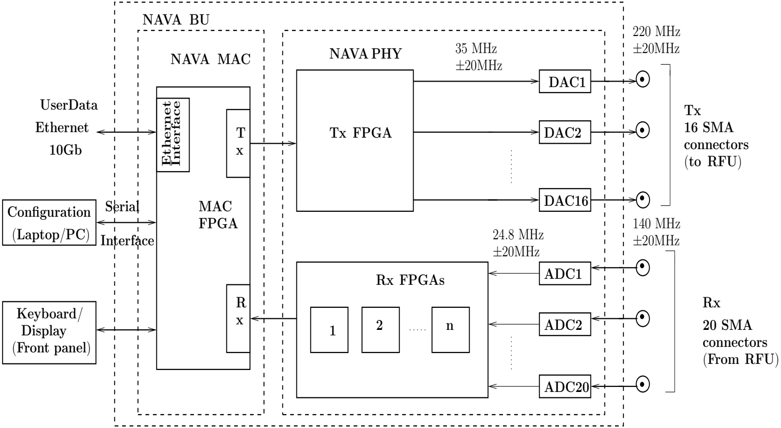
NAVA - RF unit

- 16 Tx chains: IF: 220 $\pm$ 20 MHZ; RF: 2725 $\pm$ 20 MHz
- 20 Rx chains: RF: 2475 $\pm$ 20 MHz; IF: 140 $\pm$ 20 MHz

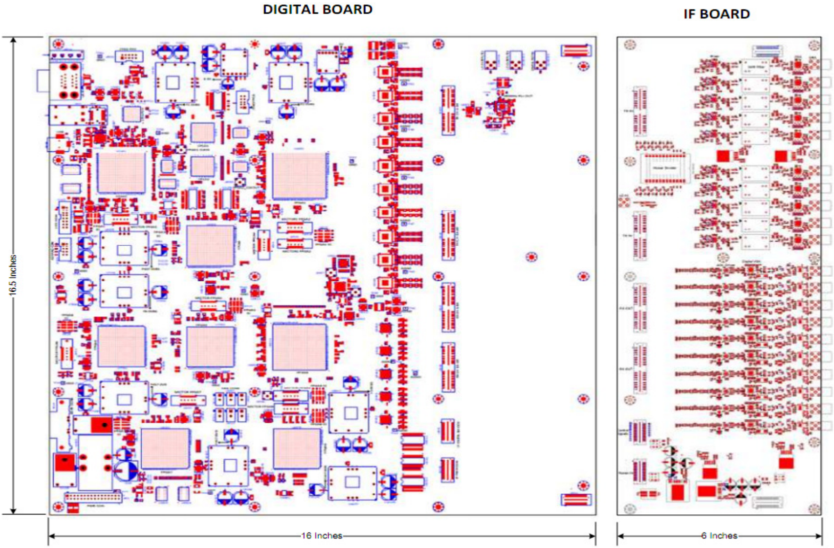


NAVA Baseband unit

–

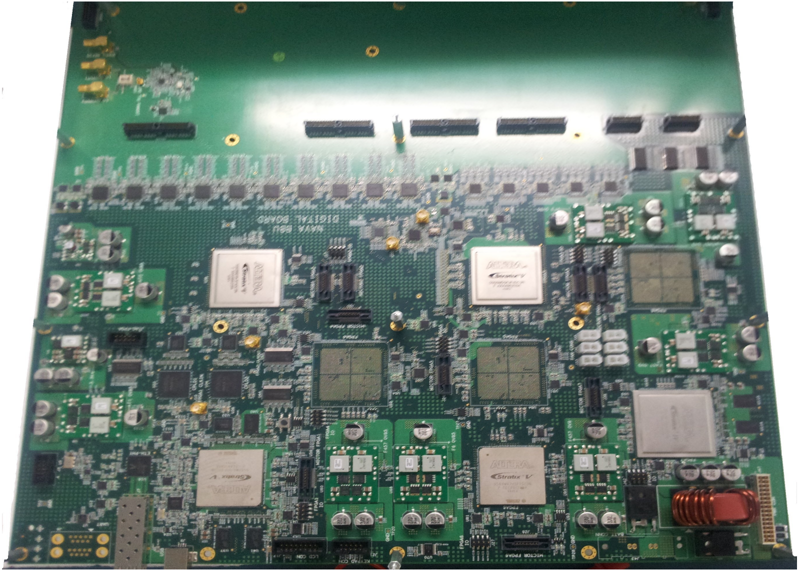


NAVA - Baseband unit



NAVA - Digital board

NAVA - Digital board



Inside NAVA FPGAs

US008116411B2

(12) **United States Patent**
Chockalingam et al.

(10) **Patent No.:** **US 8,116,411 B2**
(45) **Date of Patent:** **Feb. 14, 2012**

(54) **METHOD TO DETECT DATA TRANSMITTED FROM MULTIPLE ANTENNAS AND SYSTEM THEREOF**

(75) Inventors: **Ananthanarayanan Chockalingam**, Bangalore (IN); **Balaji Sundar Rajan**, Bangalore (IN); **Kalepalli Vishnu Vardhan**, Bangalore (IN); **Saif Khan Mohammed**, Bangalore (IN)

(73) Assignee: **Indian Institute of Science**, Bangalore (IN)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1201 days.

(21) Appl. No.: **11/842,963**

(22) Filed: **Aug. 22, 2007**

(65) **Prior Publication Data**

US 2009/0041145 A1 Feb. 12, 2009

(30) **Foreign Application Priority Data**

Aug. 6, 2007 (IN) 01725/CHE/2007

(51) **Int. Cl.**
H04L 27/06 (2006.01)

(52) **U.S. Cl.** **375/341**; 375/147

(58) **Field of Classification Search** 375/130–132, 375/140, 147, 218, 316, 340, 341, 349
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0083082 A1 * 4/2004 Onggosanusi et al. 703/2
2006/0256888 A1 * 11/2006 Nissani (Nissensohn) ... 375/267
2007/0280370 A1 * 12/2007 Liu 375/267
2008/0279299 A1 * 11/2008 Reuven et al. 375/267

OTHER PUBLICATIONS

Y. Sun, "A Family of Linear Complexity Likelihood Ascent Search Multiuser Detectors for CDMA Communications", in Conf. Record of the Thirty-Fourth Asilomar Conf. on Signals, Systems and Computers, 2000; pp. 1163-1167; ISBN 0-7803-6514-3.*
J. Fan et al. "Near Maximum Likelihood Detection for Wireless MIMO Systems", IEEE Transactions on Wireless Communications, vol. 3, No. 5. Sep. 2004: pp. 1427-1430: ISSN: 1536-1276.*
H. Jafarkhani, Space-Time Coding: Theory and Practice, Cambridge University Press, 2005.
D. Tse and P. Viswanath, Fundamentals of Wireless Communication, Chapter I, Cambridge University Press, 2005.
G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," Bell Labs Tech. Jl., vol. 1, pp. 41-59, Aug. 1996.
G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," Wireless Pers. Commun., vol. 6, pp. 311-335, Mar. 1998.

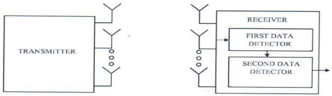
(Continued)

Primary Examiner — David C. Payne
Assistant Examiner — James M Perez
(74) *Attorney, Agent, or Firm* — Perkins Coie LLP; Aaron Wininger

(57) **ABSTRACT**

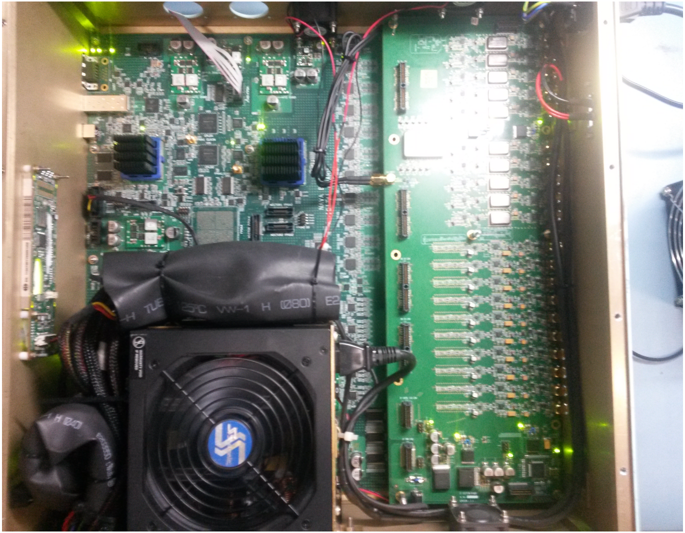
A method to detect data transmitted from multiple antennas, said method comprising steps of: selecting a starting data block and calling it as previous data block; defining a set of indices of bits to be checked for possible flip in the previous data block as a check candidate set; applying update rule to obtain updated data block using the previous data block and the check candidate set, wherein the update is made in such a manner that change in likelihood is positive; checking if the updated data block and several consecutive previous data blocks are the same; if yes, declare the updated data block as the detected data block; if no, make updated data block as previous data block and repeat updation of data block.

28 Claims, 15 Drawing Sheets



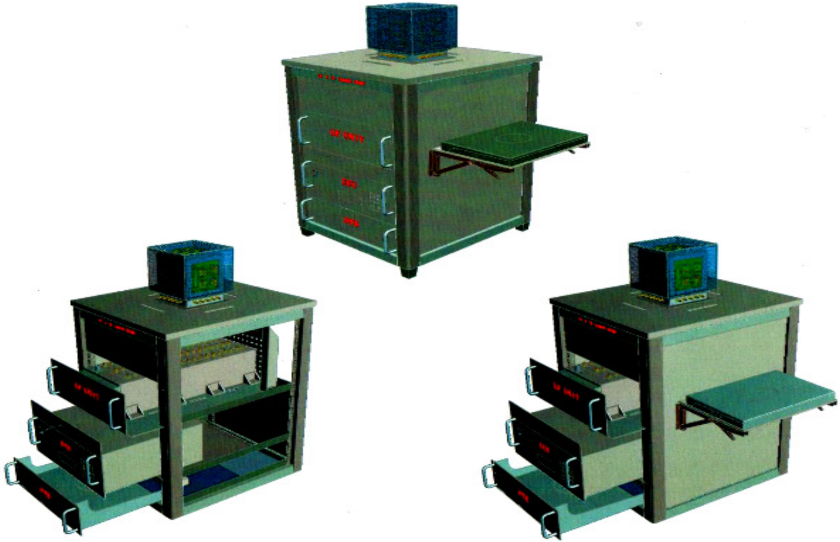
NAVA - IF board

NAVA - Baseband unit

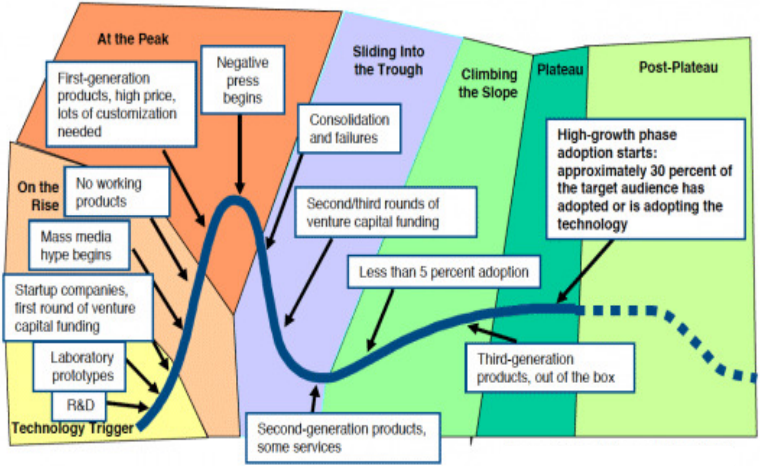


NAVA - Baseband unit

NAVA terminal



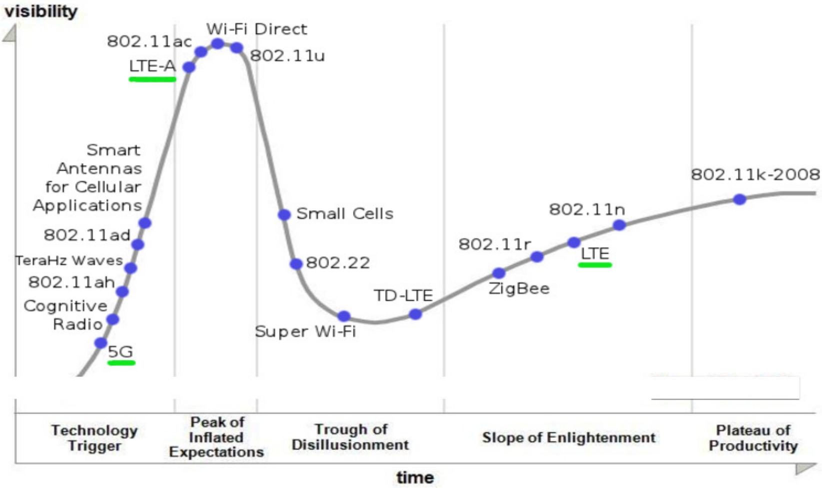
Gartner's hype cycle



Source: Internet

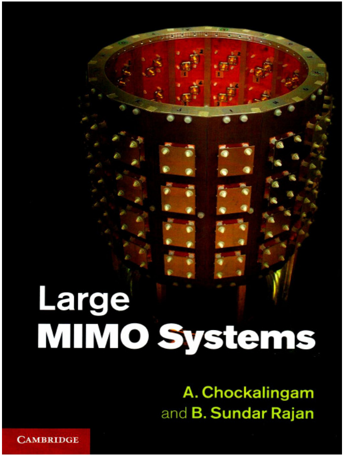
Gartner's hype cycle

- Hype cycle for Communication and Networking, 2013



Source: Internet

Book



- Released February 2014

Book

"This cutting-edge portrayal of large-scale MIMO systems provides a shrewd long-term outlook on this salient wireless subject."

Lajos Hanzo
University of Southampton

"This is a very timely and useful book written by authors who are pioneers in the area of large MIMO systems."

Vijay K. Bhargava
The University of British Columbia

"Large MIMO will power our wireless networks before this decade is out and the race is just starting. Chockalingam and Sundar Rajan and have compiled an excellent companion for this journey."

Arogyaswami Paulraj
Stansford University

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency
  - spatial modulation to reduce number of RF chains

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency
  - spatial modulation to reduce number of RF chains
- Major technological bottlenecks have been cleared

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency
  - spatial modulation to reduce number of RF chains
- Major technological bottlenecks have been cleared
- Under various stages of development and testing worldwide

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency
  - spatial modulation to reduce number of RF chains
- Major technological bottlenecks have been cleared
- Under various stages of development and testing worldwide
- 28 GHz and 60 GHz operation possibilities are open

Concluding remarks

- Large-scale MIMO (Massive MIMO)
  - prime driver of 5G PHY
  - multi-gigabit transmission capability
  - tens of bps/Hz spectral efficiency
  - spatial modulation to reduce number of RF chains
- Major technological bottlenecks have been cleared
- Under various stages of development and testing worldwide
- 28 GHz and 60 GHz operation possibilities are open
- India to participate in and influence 5G standardization efforts
  - India's Telecom Standards body launched in Nov'2013 (TSDSI - Telecommunication Standards Development Society India)

Concluding remarks

- Large-scale MIMO (Massive MIMO)
    - prime driver of 5G PHY
    - multi-gigabit transmission capability
    - tens of bps/Hz spectral efficiency
    - spatial modulation to reduce number of RF chains
- Major technological bottlenecks have been cleared
- Under various stages of development and testing worldwide
- 28 GHz and 60 GHz operation possibilities are open
- India to participate in and influence 5G standardization efforts
    - India's Telecom Standards body launched in Nov'2013
      (TSDSI - Telecommunication Standards Development Society India)
- Visible light communication (may be for beyond 5G)

Thank you