Haberleşme Teknolojilerinin Bugünü ve Geleceği

Mayıs 2019

Doç. Dr. Ertuğrul Başar
Koç Üniversitesi,
Elektrik-Elektronik Mühendisliği Bölümü

Senior Member, *IEEE & IEEE Communications Society*
Editor, *IEEE Transcactions on Communications*
Associate Editor, *IEEE Communications Letters*
Editor, *Physical Communication (Elsevier)*
Member, *Türkiye Bilimler Akademisi - GEBİP*
Member, *Bilim Akademisi - BAGEP*
Director, *CoreLab*

KOÇ ÜNİVERSİTESİ

CORELAB
Communications Research and Innovation Laboratory

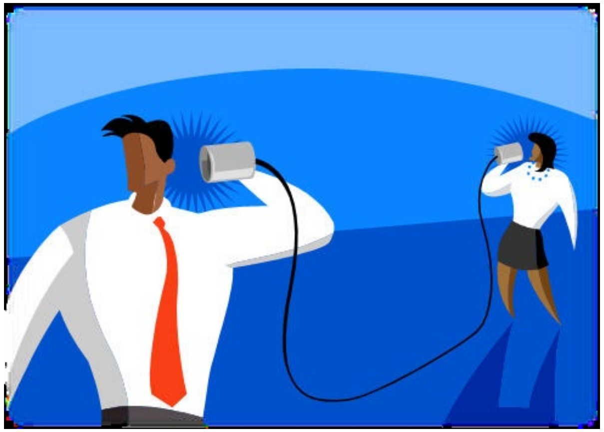
https://corelab.ku.edu.tr/

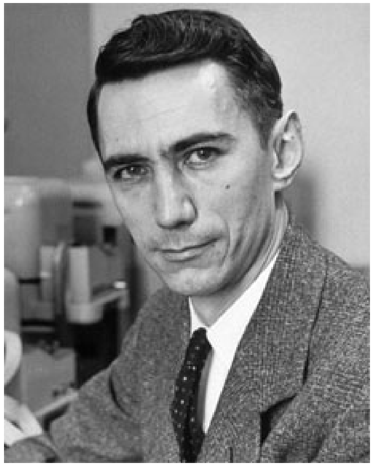
The Fundamental Problem

"The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point"

- The Mathematical Theory of Communication, 1948

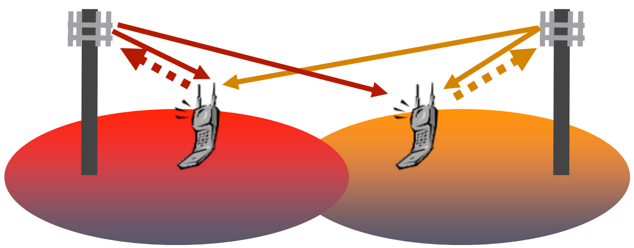
Claude Shannon





Wireless is Everywhere!

- We all know that wireless communication technologies have had a huge impact around the world, especially in the last ten years.
- Today, wireless communications affects almost everything we do on a daily basis.



cellular networks

local area networks

personal area networks

emerging applications

Via Della Conciliazione, Rome

2005/4/4

2013/3/12

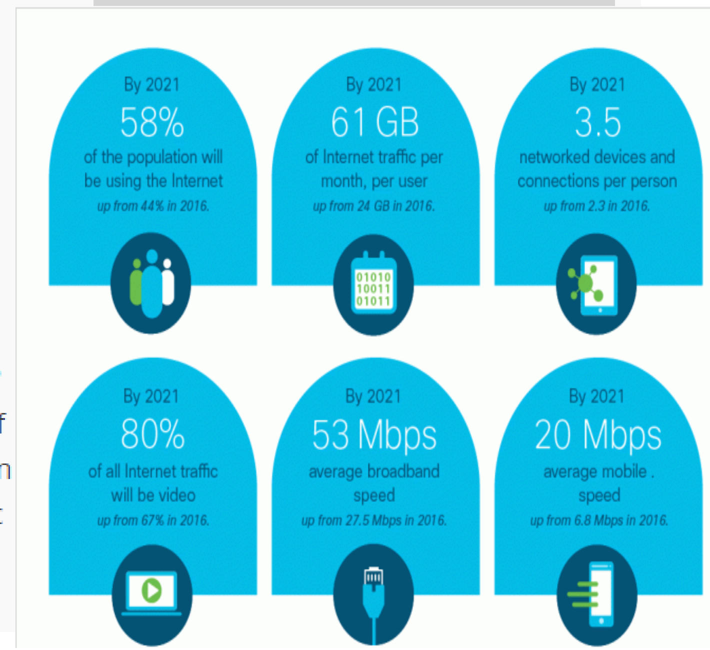
CoreLab

What about the Future?

Cisco: IP traffic shoots up to 3 zettabytes by 2021, video will be 80% of it

Posted Jun 8, 2017 by Ingrid Lunden (@ingridlunden)

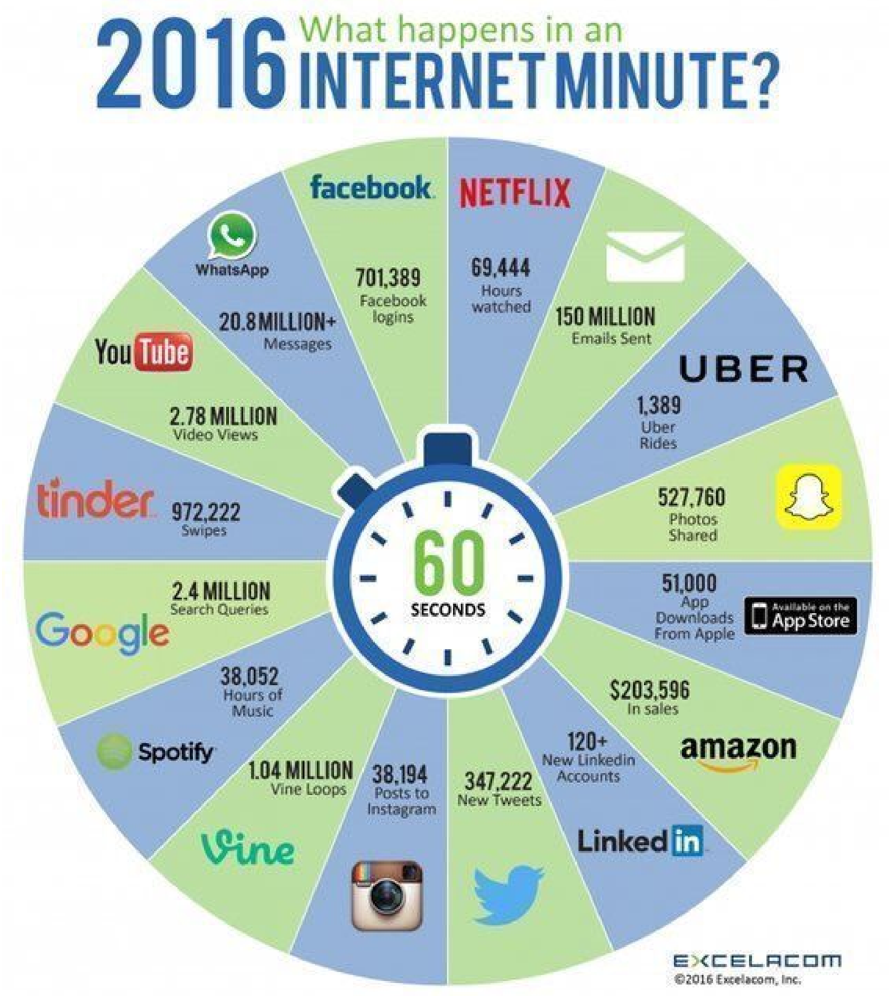
The revolution *will* be televised… over the internet. By 2021, 82 percent of all consumer IP traffic will be video, and that growth will be driven by a boon in live streaming, courtesy of services like Facebook, YouTube and Twitter. In the meantime, the internet will become an even bigger part of the fabric of how we do everything, growing to 3.3 zettabytes of traffic annually by 2021 — up three times compared to internet traffic today (and working out to 278 exabytes per month).

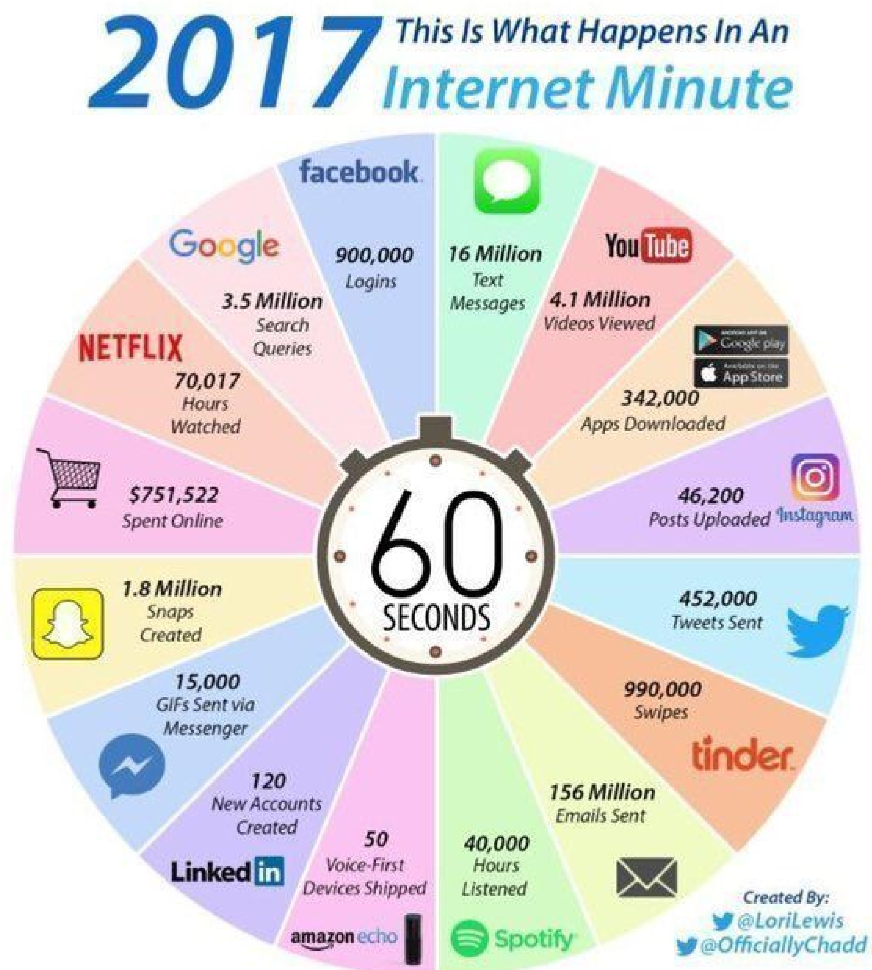


Source: https://techcrunch.com/2017/06/08/cisco-ip-traffic-shoots-up-to-3-zettabytes-by-2021-video-will-be-80-of-it/

CORELAB

2016 vs 2017: An Internet Minute

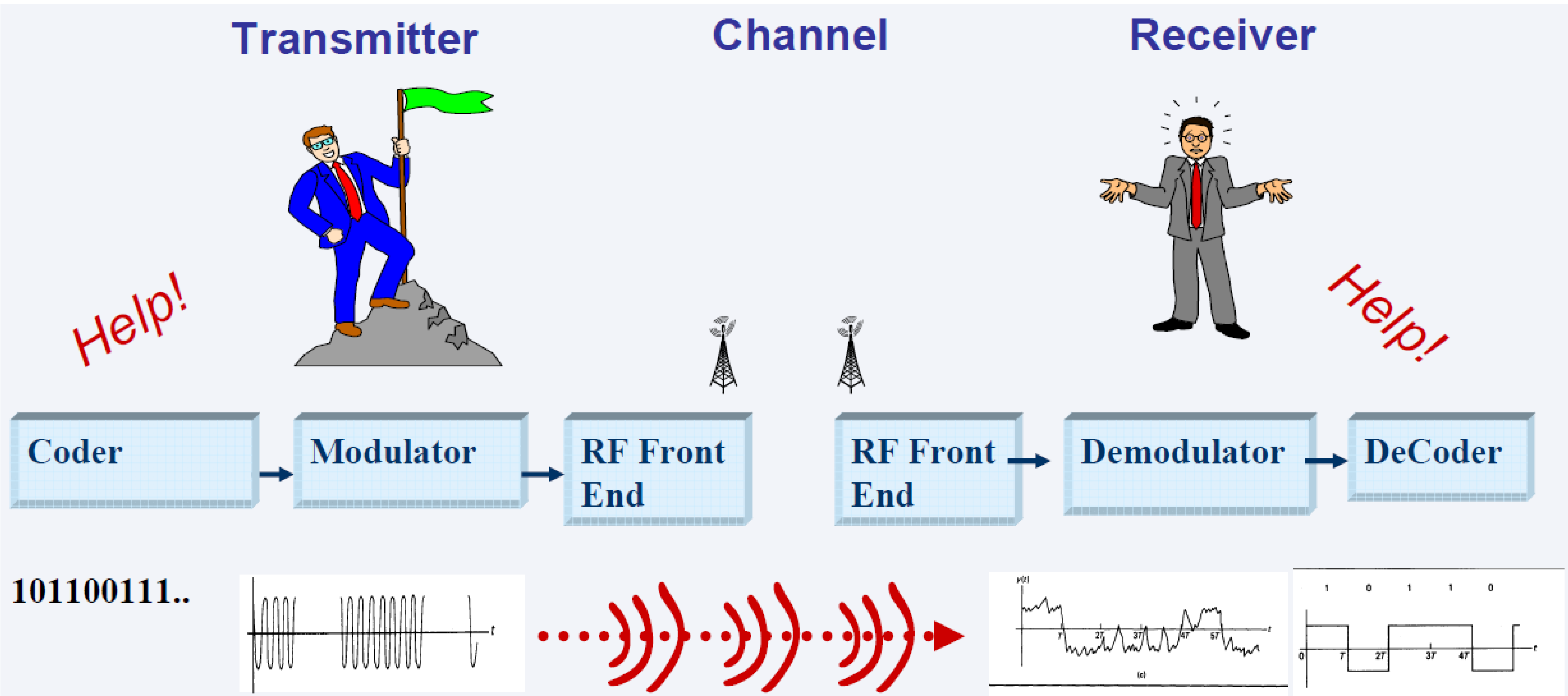




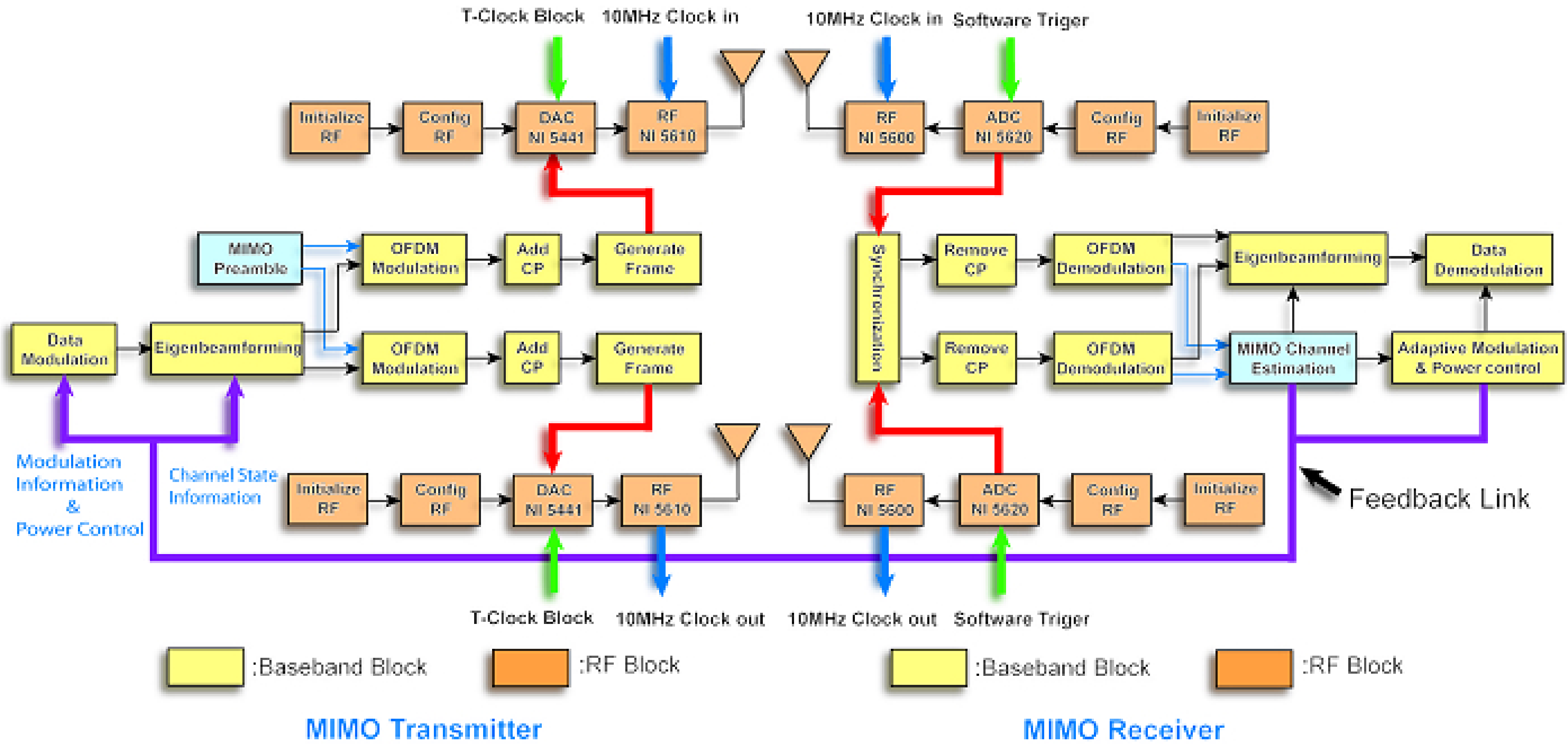
CORELAB

Wireless Communications in Physical Layer

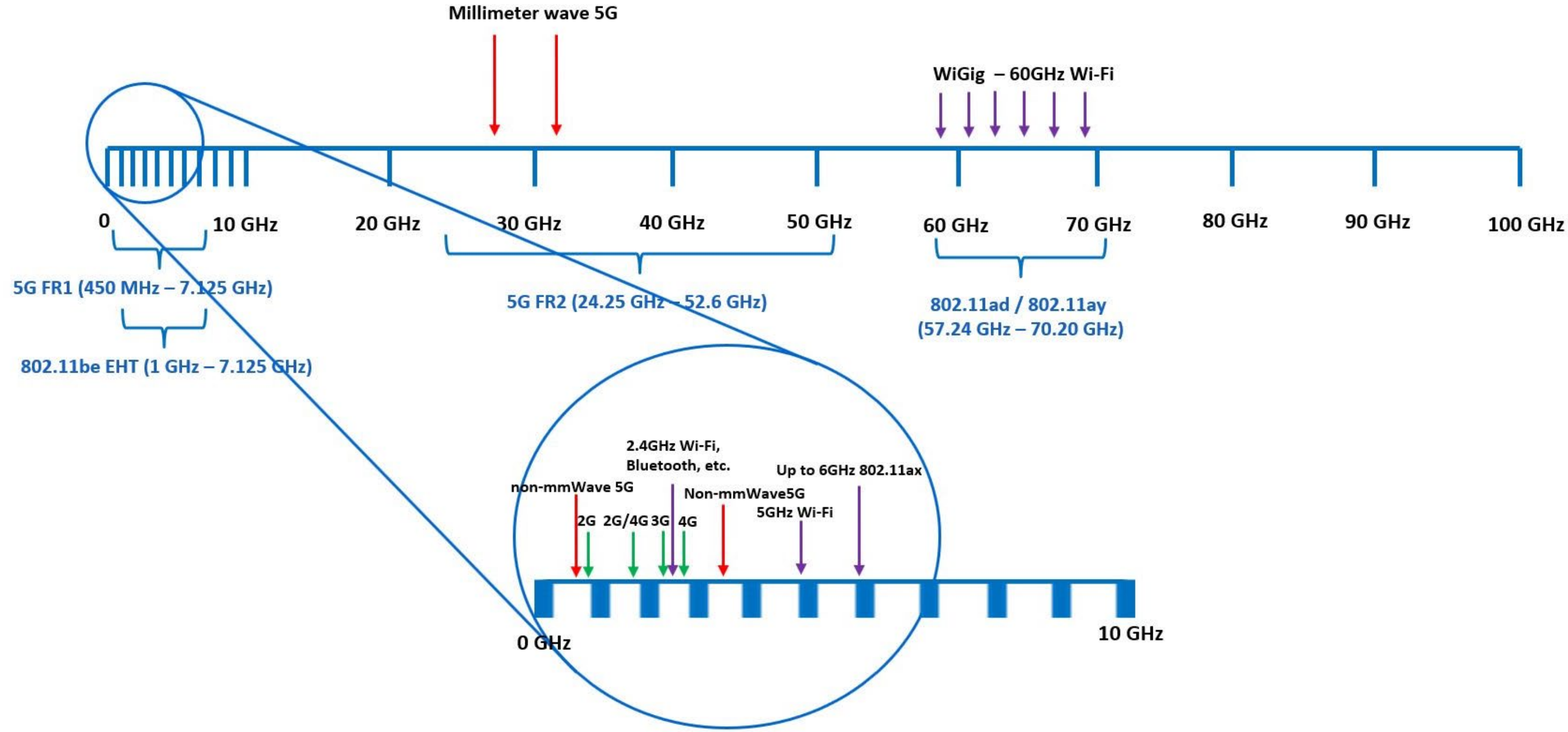
- Information Source → Source Encoder → Coder



Actual System



Popular Frequency Bands



CORELAB

What Makes a Good Communication System

- Good Received Signal Fidelity
  - **Analog System:** high Signal-to-Noise Ratio (SNR)
  - **Digital System:** low Bit Error Rate (BER)

- Low Transmit Signal Power.

- A large amount of information is transmitted.

- Signal occupies a small bandwidth.

- System has a low cost (complexity?)

- Communications engineers must trade off all of these.

Examples of Tradeoffs in Communications Designs

- **Satellite and Deep Space Communications**

➤ Power is expensive to generate in space and transmission distances are enormous
– Must be very energy efficient.

- **Microwave Relay Towers**

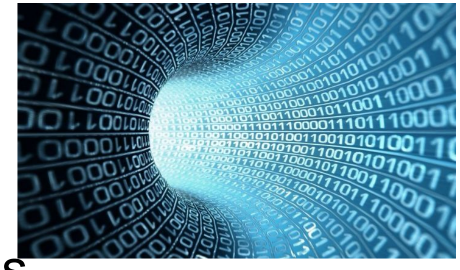
➤ Power is cheap, but available bandwidth is restricted by regulation
- Must be very bandwidth efficient.

- **Cellular Phones**

➤ Power is costly (impacts battery life and size) but bandwidth is also limited
- Must be both bandwidth and power efficient.

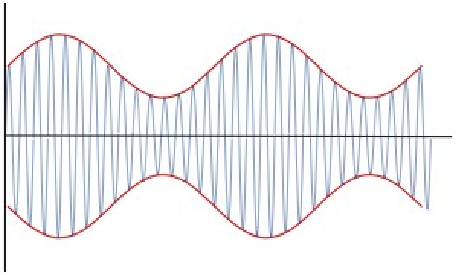
CORELAB

Digital vs. Analog Communications



- **Digital Communication Systems**
  - transmit a finite number of signals.
  - text and data are naturally digital information sources.

- **Analog Communication Systems**
  - transmit a continuous (uncountably infinite) range of signals.
  - voice and video are natural analog information sources.



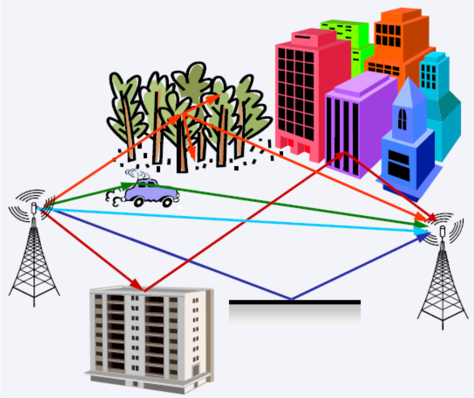
- An analog information source can be converted into a digital source by
  - Sampling the signal in time.
  - Quantizing the signal amplitude to a finite number of levels.

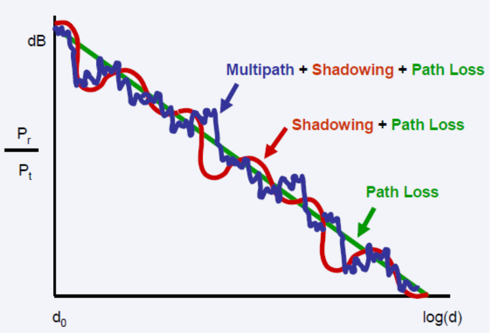
Benefits of Wireless Communication

- Mobility: User is not restricted to single point but can move without hampering the communication.
- Reduced Cabling: Unlike wired communication where all devices are linked by physical transmission medium, in wireless setup the user entity communicate using air interface.
- Easy deployment: These systems can be easily deployed.
- Flexibility: Physical barriers like wall can restrict wired system but radio signals can penetrate walls to provide flexible solution both for indoor and outdoor system.

Challenges in Wireless Communications

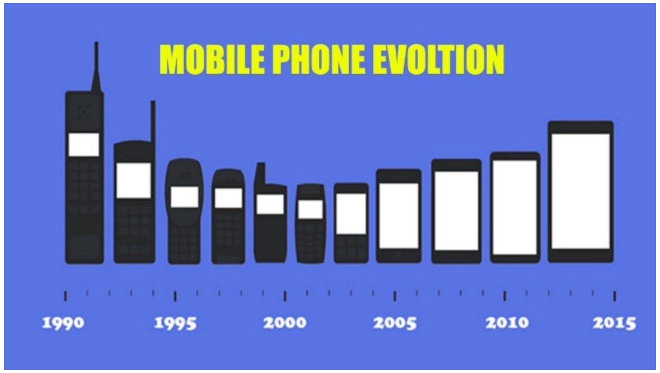
- Spectrum is scarce → License fee
- High data rates → Multimedia applications
- Reliability → Quality of service
- Multiple reflections → Fading
- Mobility → Channel characteristics
- Portability → Low power consumption
- Connectivity in various wireless networks → Multimode
- Interference from other users → Limited user capacity
- Security → Mobile commerce



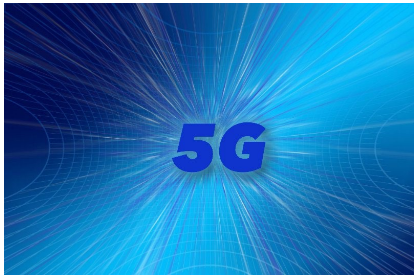


Wireless Network Generations

Technol ogy	1G	2G	2. 5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone



What About 5G?



- The Feb. 2017 draft report of ITU on the key performance requirements of IMT-2020:
  - a downlink peak date rate of 20 Gbps and
  - a downlink peak spectral efficiency of 30 bits/sec/Hz.
- 3GPP successfully completed the first implementable 5G New Radio specification in Dec. 2017
  → *3GPP 5G Standalone Release (June 2018)*.
- 5G PHY Layer: Above 6 GHz, massive MIMO, multiple OFDM numerologies.
- One thing has become certain during standardization of 5G: *There is no single enabling technology that can achieve all of the applications being promised by 5G networking.*
- The necessity of more flexible, new spectrum- and energy-efficient physical layer (PHY) techniques for beyond 5G wireless networks.

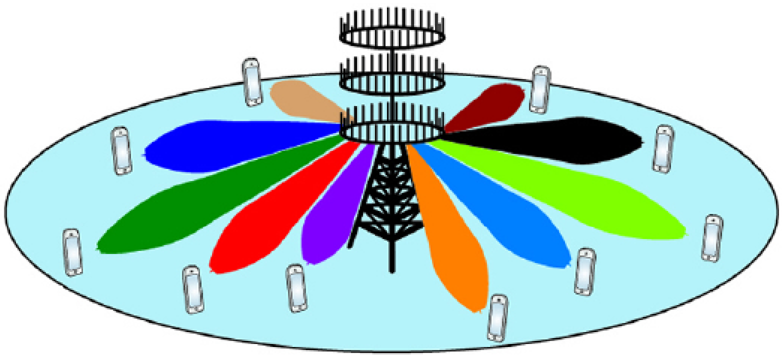
PHY Solutions Towards 5G

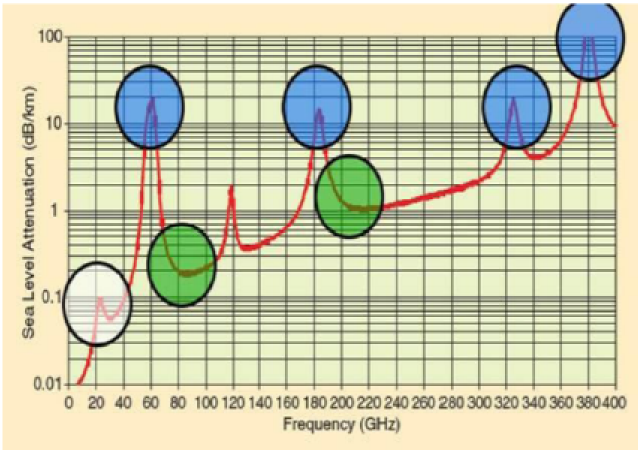
Attractive PHY solutions to meet the goals of 5G NR:

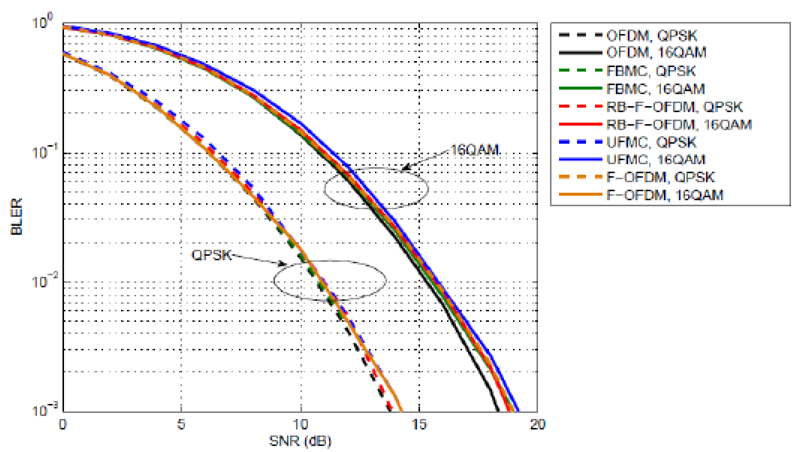
→ *Massive multi-user multiple-input multiple-output (MIMO) systems*

→ *Millimetre-wave (mmWave) communications (above 6 GHz)*

→ *Non-orthogonal waveform designs (GFDM, UFMC, FBMC)*

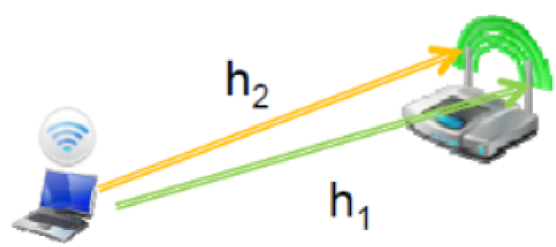




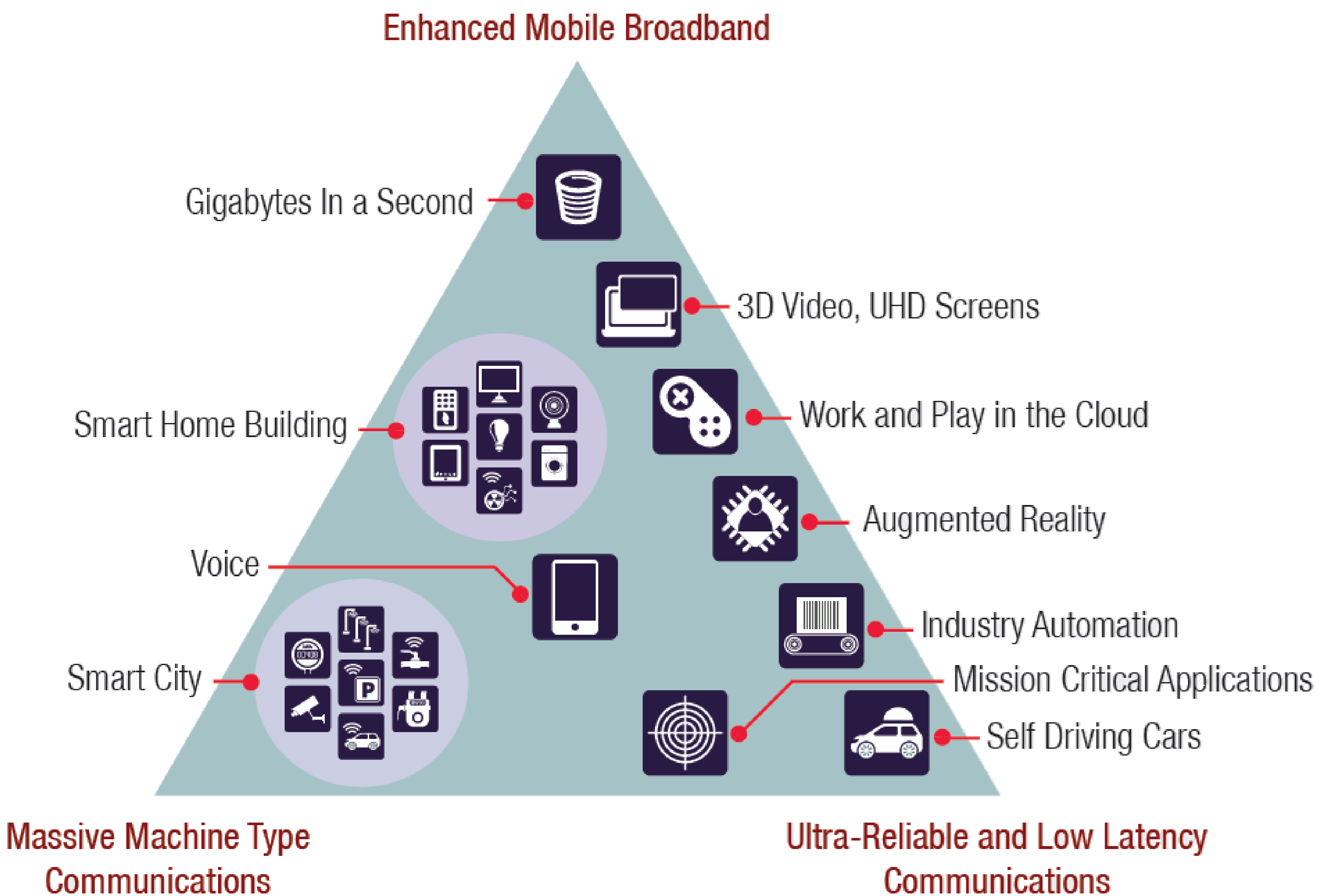


MIMO Technology

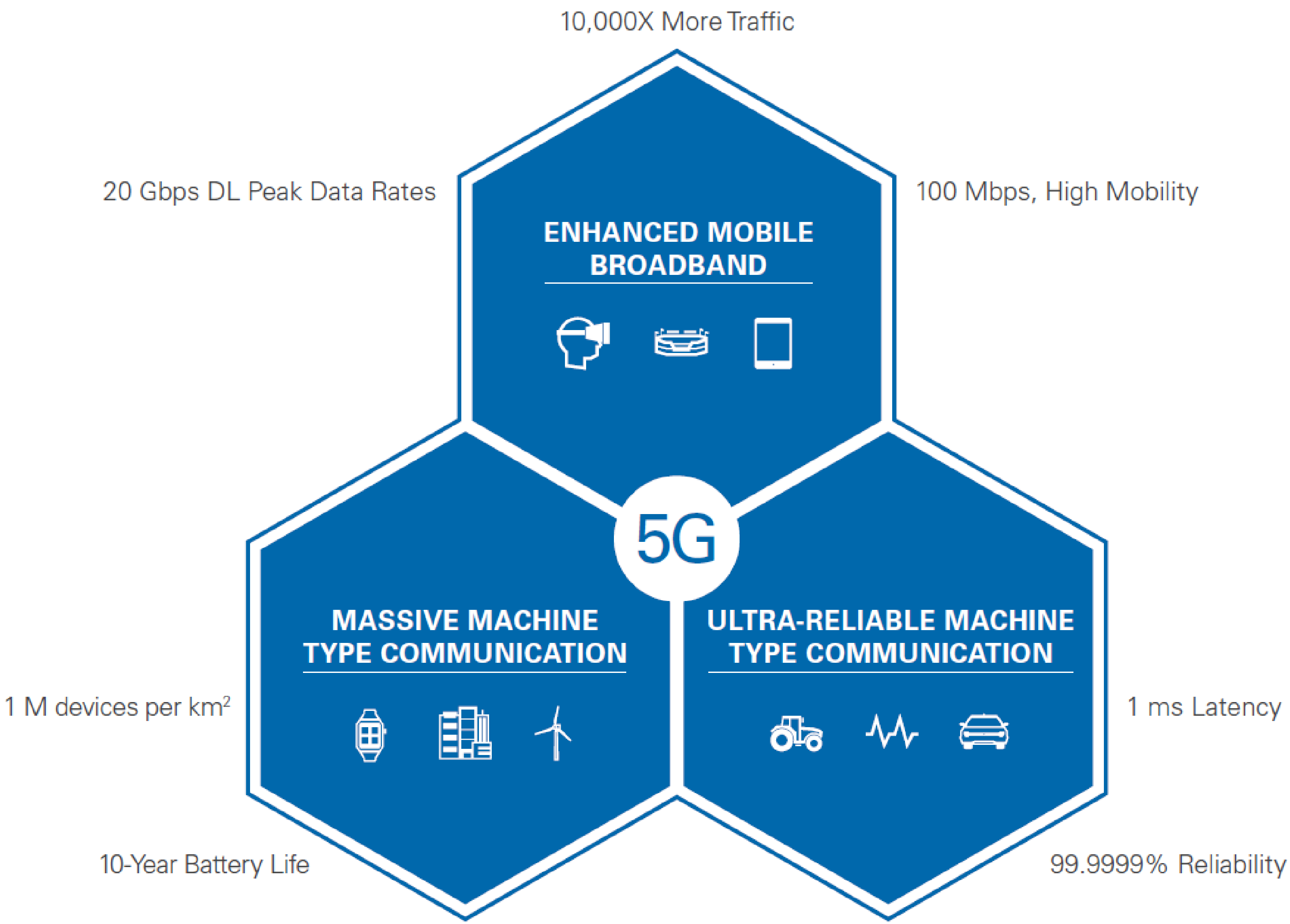
- Multiple-input and multiple-output (MIMO) systems offer:
  → Improvement in error performance
  → Higher data rates
  → Better quality-of-service (QoS)
  → Better coverage
- MIMO in Standards: IEEE 802.11n (Wi-Fi), HSPA+ (3G), IEEE 802.16 WiMAX, Long Term Evolution (LTE) (4G), LTE-Advanced, 5G, Beyond 5G.



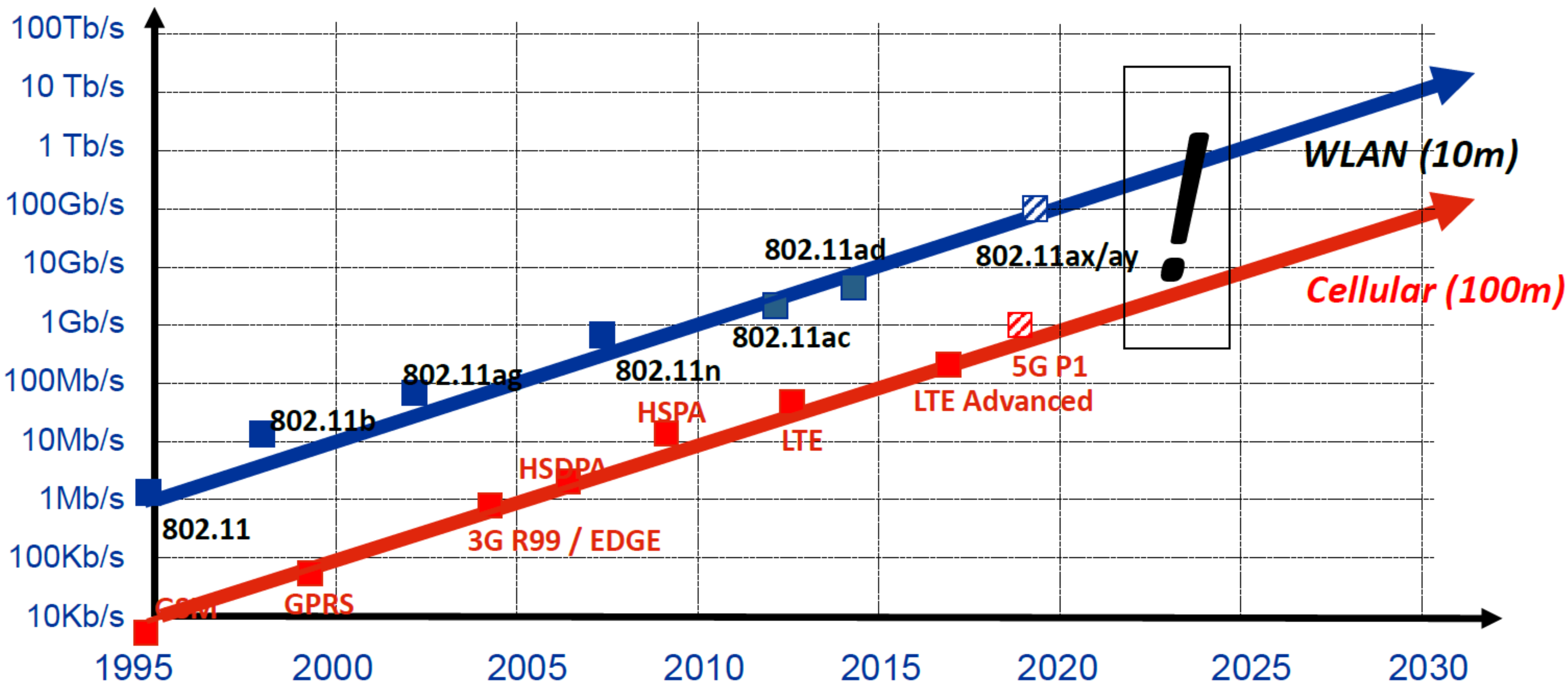
5G Service Categories



5G Requirements (2019-2020)



2030: The Wireless Roadmap



Current/Next-Generation Wireless Systems

Current:

- 4G Cellular Systems (LTE-Advanced)
- Wireless LANs/WiFi (802.11ac)
- mmWave massive MIMO systems
- Satellite Systems
- Bluetooth
- Zigbee
- WiGig

Emerging:

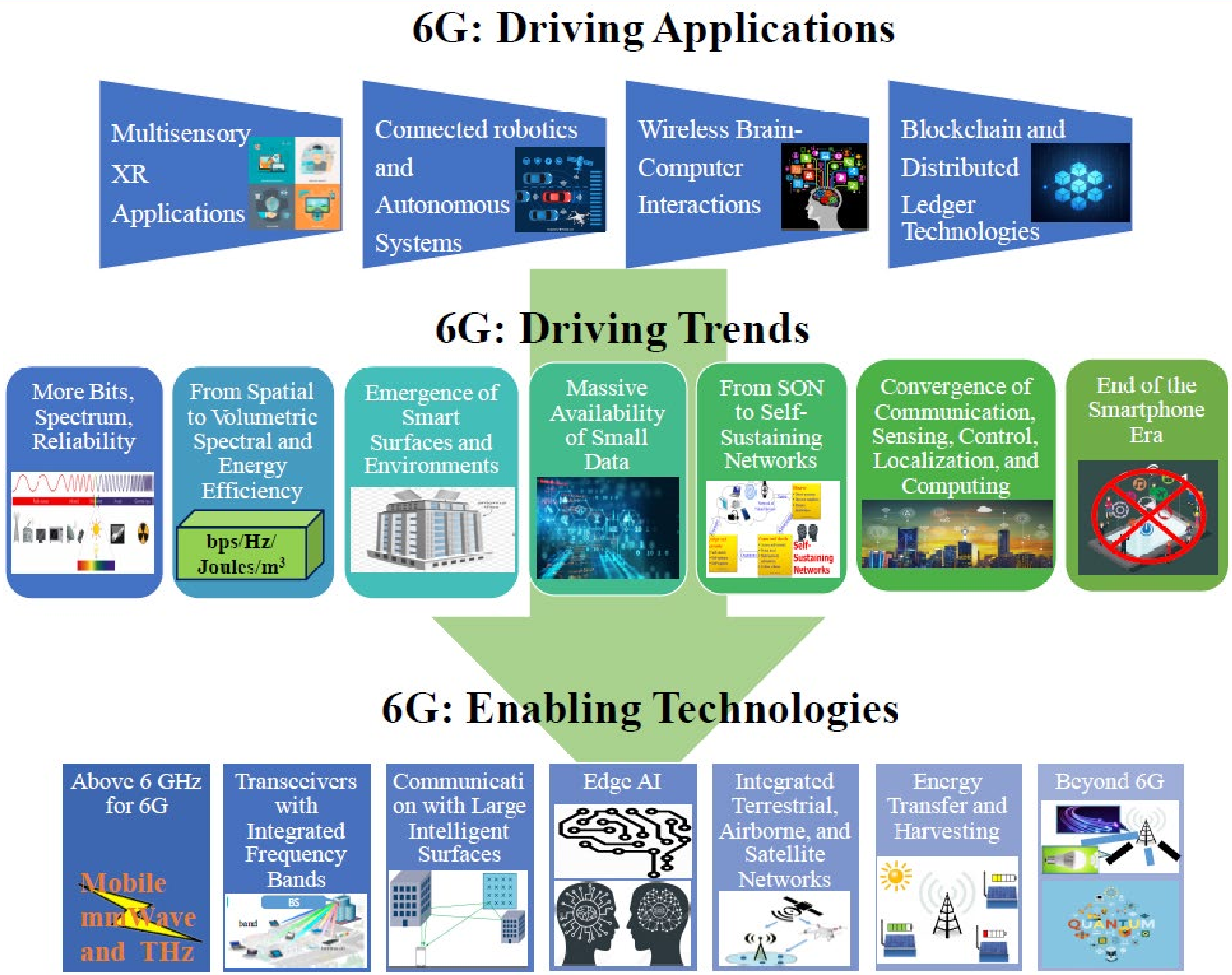
- 5G Cellular and WiFi Systems
- Ad/hoc and Cognitive Radio Networks
- Energy-Harvesting Systems
- Chemical/Molecular Communications
- Optical Wireless Communications
- Reconfigurable Surfaces/Antennas

5G'den 6G'ye: Neden 6G

- Her 10 yılda yeni bir mobil haberleşme jenerasyonu (6G → 2030)
- Gelecek 10-20 yılda kullanıcı ihtiyaçlarının değişimi (özellikle M2M haberleşme)
  → Internet-of-Everthing (IoE)
  → Sanal gerçeklik (virtual reality, VR) > eMBB
- Yazılım tanımlı radyo (software defined radio, SDR) ve yazımlı tanımlı ağ (software defined networking, SDN) alanındaki gelişmeler
  → aynı fiziksel alt yapı ile daha ucuz ve efektif güncellemeler
- 5G → Farklı ağların ve teknolojilerin karışımı
  6G → Kendi kendine bütünleşen (self-aggregating) farklı tiplerde ağlar

- Daha akıllı, otonom, öğrenebilen, tahmin yürütebilen ve adapte olabilen ağlar (AI)
- Daha yüksek veri hızları (bit/sn/m^3), daha yüksek spektral ve enerji verimlilik

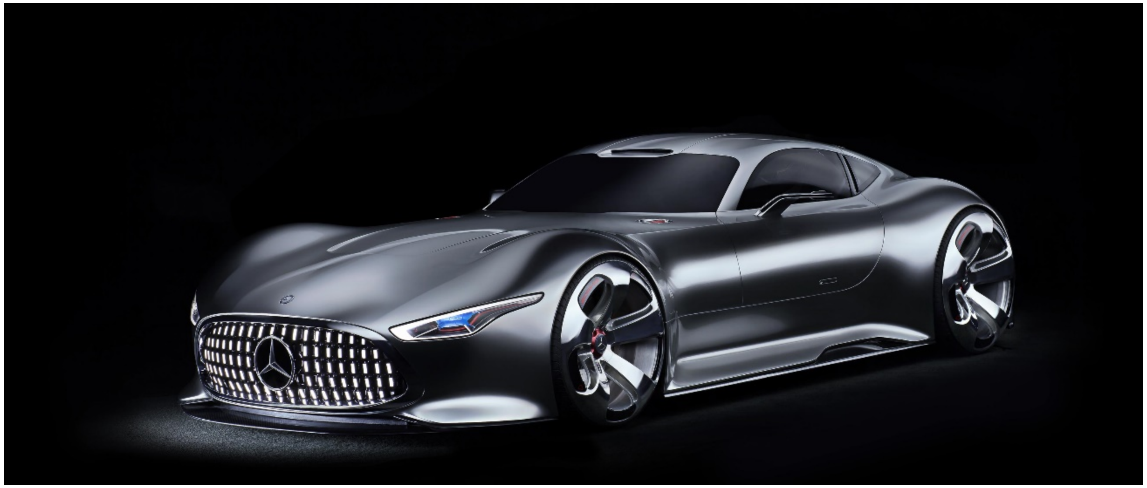
A Vision for 6G Wireless (2030 and Beyond)



A Vision for 6G

5G = Karl Benz Automobile

6G →



6G: Hedef 2030 – Aday Teknolojiler

- 5G'ye yetişemeyen ve/veya olgunlaşması ve geliştirilmesi gereken teknolojiler:

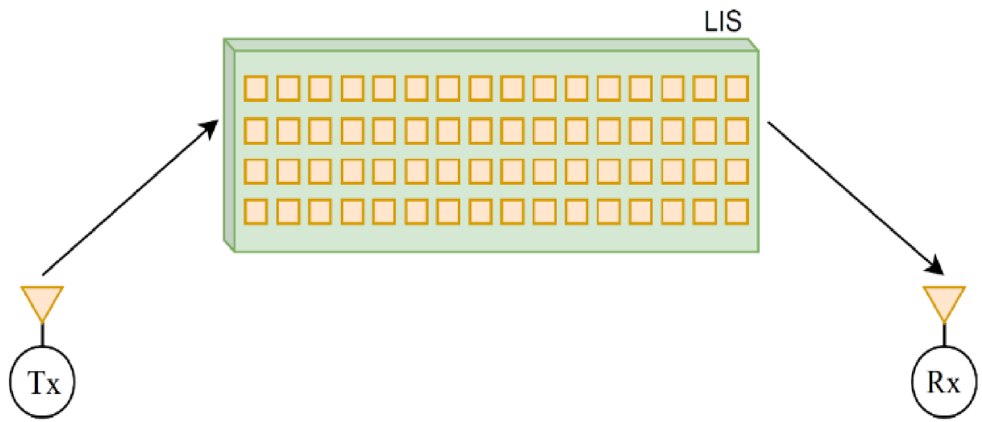
  - Görünür ışıkla haberleşme (visible light communications, VLC) ve hibrit RF/optik çözümleri
  - Alternatif dalga biçimleri (waveforms)
  - Uyarlanabilir (reconfigurable) ve akıllı yüzeyler
  - Yeni anten teknolojileri (nano antenler, meta-materyaller)
  - Düşük maliyetli ve daha efektif masif MIMO sistemler
  - Terahertz haberleşme (300 GHz ve üstü)
  - Moleküler haberleşme (nano ve makro boyut)
  - İndis modülasyonu
  - Fiziksel katman güvenliği
  - Enerji hasatlama ve eş-zamanlı güç ve bilgi aktarımı (SWIPT)
  - Karasal olmayan ağlar (non-terrestrial networks) ve uydu sistemleri

- Halk efsanesi: tek numaralı G'ler (1G, 3G, 5G) ve çift numaralı G'ler (2G, 4G) → 6G (2030 belki daha da öncesi)

- IEEE Future Directions & ITU Focus Group Technologies for Network 2030

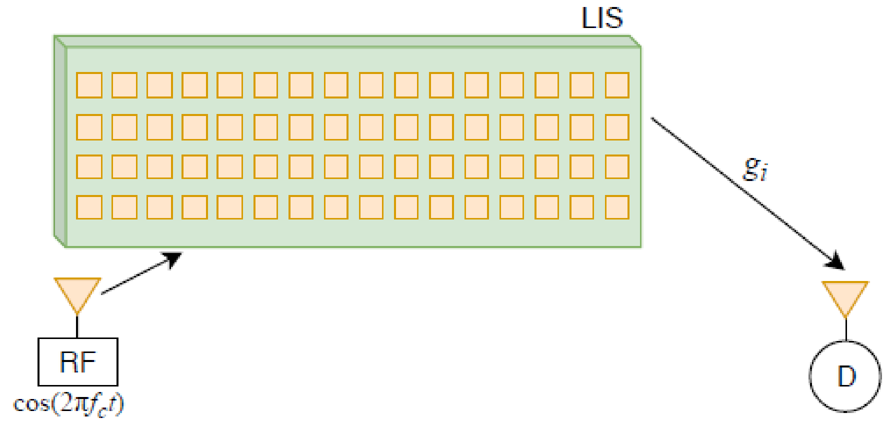
Large Intelligent Surfaces

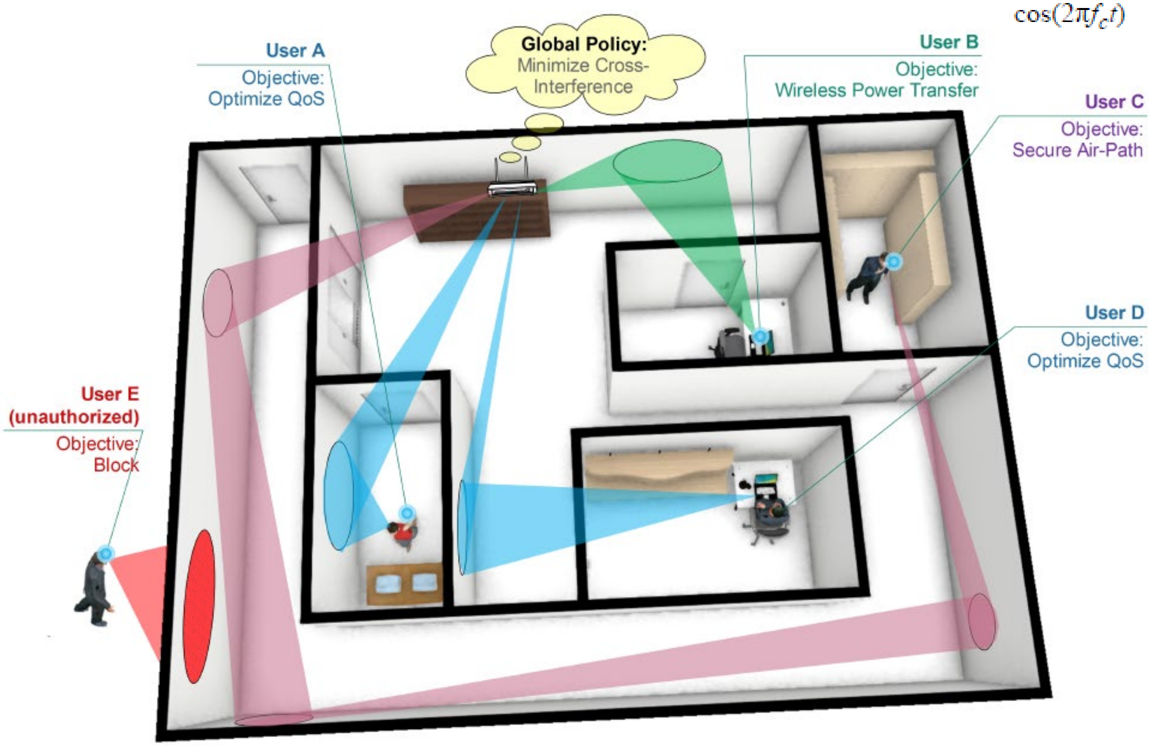
- Large intelligent surfaces/walls/reflect-arrays/metasurfaces are smart devices that control the propagation environment with the aim of improving the coverage and signal quality.
- It is completely different from existing MIMO, beamforming, amplify-and-forward relaying and backscatter communication paradigms.
- Here, the large number of small, low-cost, and passive elements on a LIS only reflect the incident signal with an adjustable phase shift without requiring a dedicated energy source for RF processing, decoding, encoding, or retransmission.



CoReLab

Large Intelligent Surfaces

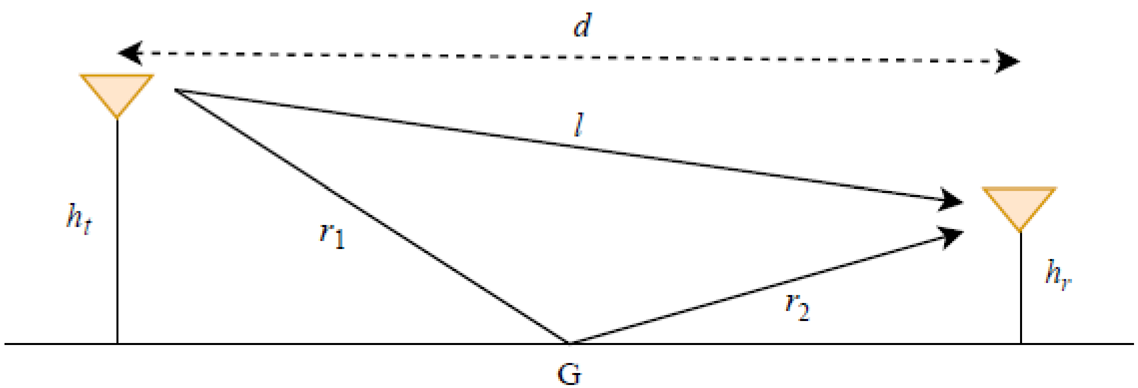




- E. Basar, "Large Intelligent Surface-Based Index Modulation: A New Beyond MIMO Paradigm for 6G", *ArXiv:1904.06704*, Apr. 2019.

- E. Basar, "Transmission Through Large Intelligent Surfaces: A New Frontier in Wireless Communications", *ArXiv:1902.08463*, Feb. 2019.

Ground Reflection vs Free-Space Propogation

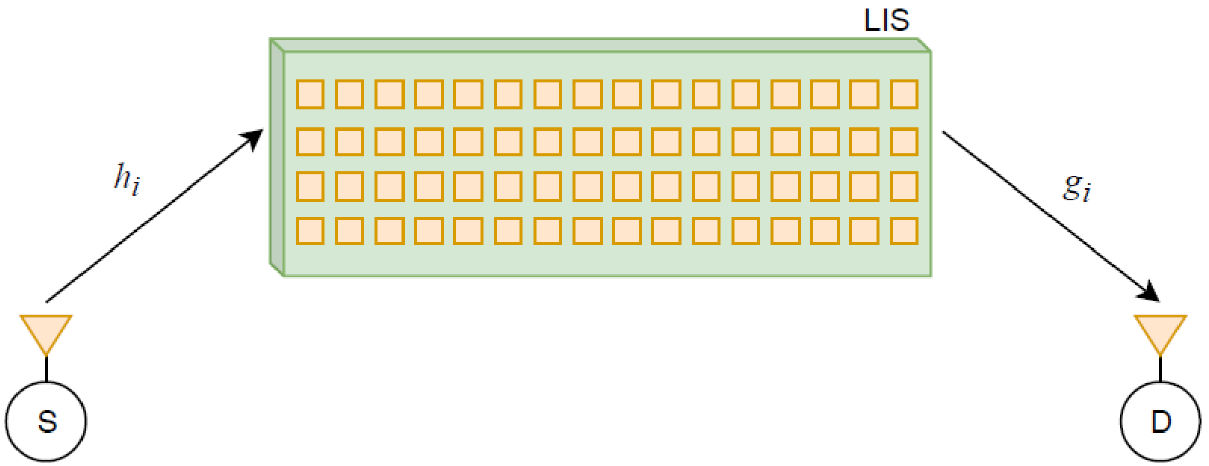


$$r(t) = \frac{\lambda}{4\pi}\left(\frac{e^{-\frac{j2\pi l}{\lambda}}}{l} + \frac{R \times e^{-\frac{j2\pi(r_1+r_2)}{\lambda}}}{r_1 + r_2}\right) x(t)$$

- With ground reflection: $P_r \approx P_t \left(\frac{h_t h_r}{d^2}\right)^2$
- Without ground reflection: $P_r = P_t \left(\frac{\lambda}{4\pi d}\right)^2$
- With intelligent reflection: $P_r \approx 4P_t \left(\frac{\lambda}{4\pi d}\right)^2$

Maximum Received SNR Through Intelligent Reflection

Transmission through a LIS in a dual-hop communication scenario without a line-of-sight path between S and D.



For $h_i = \alpha_i e^{-j\theta_i}$ and $g_i = \beta_i e^{-j\psi_i}$, the instantaneous SNR at D:

$$\gamma = \frac{\left| \sum_{i=1}^{N} \alpha_i \beta_i e^{j(\phi_i - \theta_i - \psi_i)} \right|^2 E_s}{N_0}. \quad (1)$$

γ is maximized by eliminating the channel phases with the help of the LIS-induced phases as $\phi_i = \theta_i + \psi_i$ for $i = 1, \ldots, N$.

Performance of LIS-Assisted Communication Systems

- With the help of the LIS, the maximized instantaneous received SNR

$$\gamma = \frac{\left(\sum_{i=1}^{N} \alpha_i \beta_i\right)^2 E_s}{N_0} = \frac{A^2 E_s}{N_0}. \tag{2}$$

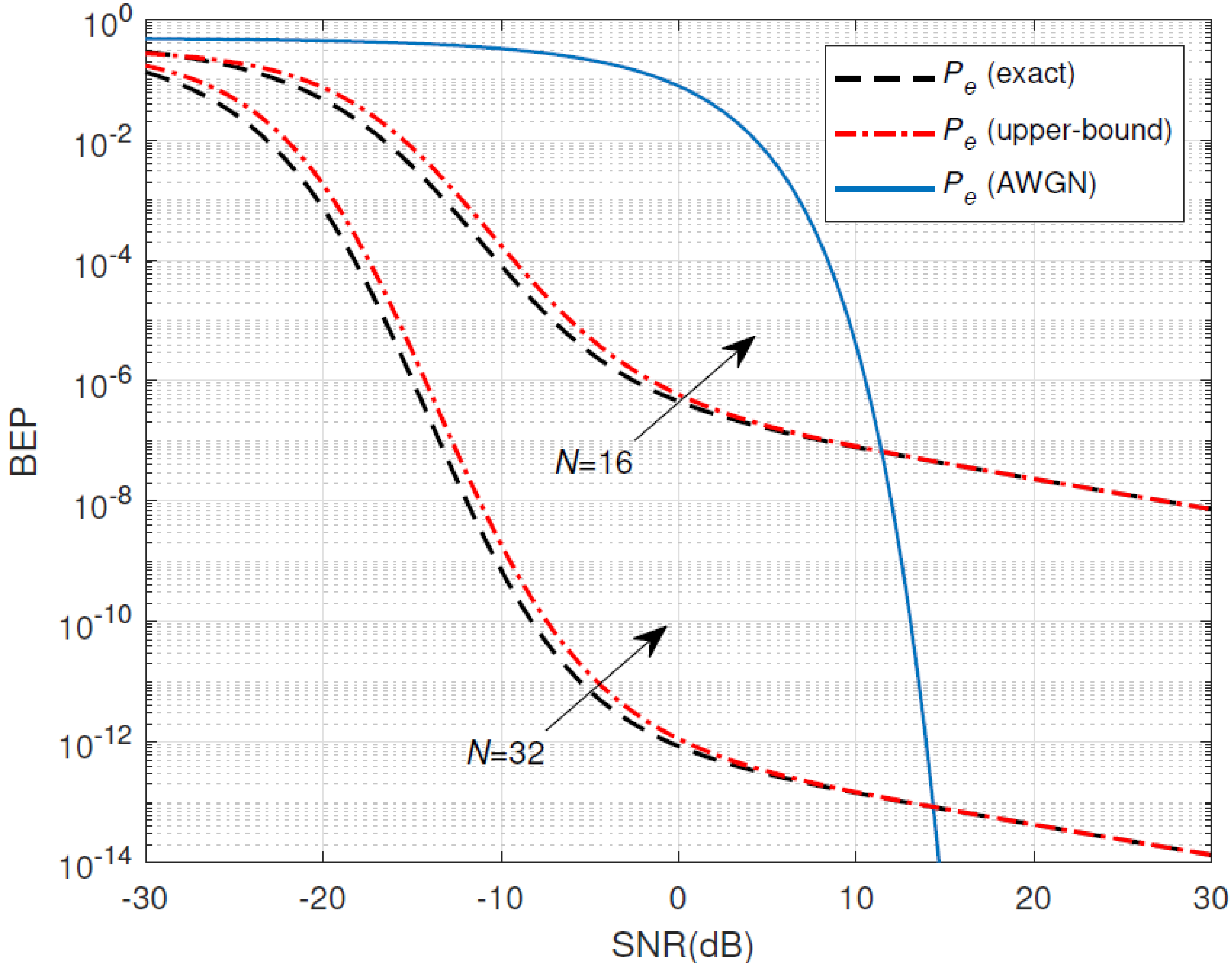
- Under the central limit theorem, we have

$$E\left[\gamma\right] = \frac{\left(N^2\pi^2 + N(16-\pi^2)\right) E_s}{16 N_0} \propto N^2 \frac{E_s}{N_0}. \tag{3}$$

- Bit error probability (BPSK)

$$P_e \leq \frac{1}{2}\left(\frac{1}{1+\frac{N(16-\pi^2)E_s}{8N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{-\frac{N^2\pi^2 E_s}{16N_0}}{1+\frac{N(16-\pi^2)E_s}{8N_0}}\right). \tag{4}$$

LIS-Based Scheme vs AWGN Performance



The Concept of Index Modulation (IM)

- Traditional digital modulation schemes rely on the modulation of the amplitude/phase/ frequency of a sinusoidal carrier signal for transmission, as widely considered in the field of communications over the past 50 years.

→ crowded and inefficient signal constellations.

- IM systems provide alternative ways to transmit information!

- IM schemes have the ability to map information bits by altering the on/off status of their transmission entities:

- E. Basar, "Media-Based Modulation for Future Wireless Systems: A Tutorial", *accepted to IEEE Wireless Communications*, Mar. 2019.

- E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, H. Haas, "Index Modulation Techniques for Next-Generation Wireless Networks", *IEEE Access*, Sep. 2017. [PDF] (Top 5 Most Cited IEEE Access Article in 2017)

- E. Basar, "Index Modulation Techniques for 5G Wireless Networks", *IEEE Communications Magazine*, July 2016. (Web of Science – Hot Paper)

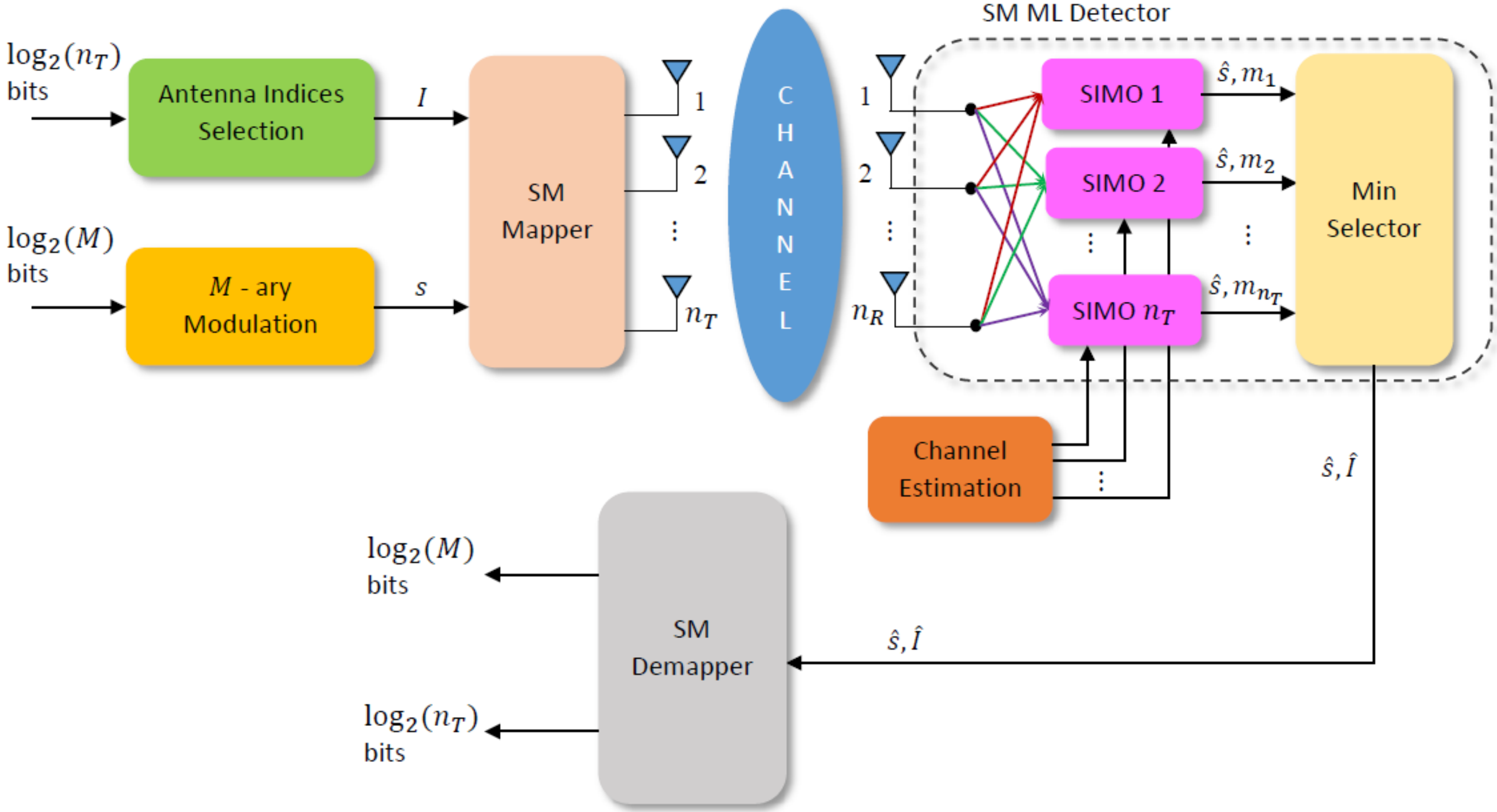
Surge of IM techniques

- Every communication system can be theoretically considered as a special case of IM!
- However, the term of IM is explicitly used to cover the family of communication systems that consider other transmit entities than amplitudes/frequency/phases to convey information.

- The introduction of spatial modulation (SM) and orthogonal frequency division multiplexing with index modulation (OFDM-IM) concepts in 2008 and 2013
  - started a new wave of alternative digital modulation schemes.
- As of today, this wave is increasingly spreading and speeding up.

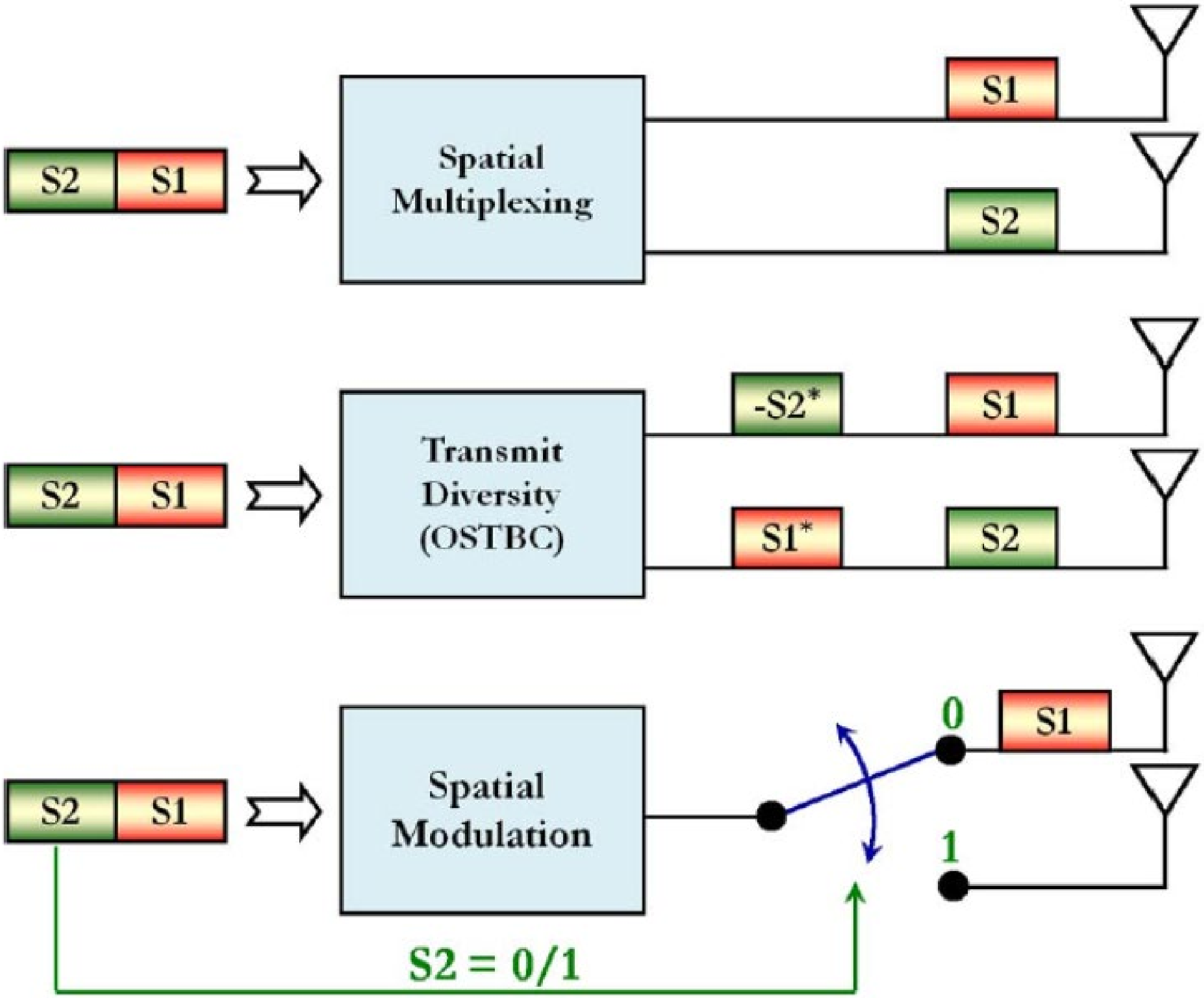
R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, “Spatial modulation,” IEEE Trans. Veh. Technol., vol. 57, no. 4, pp. 2228-2241, Jul. 2008.
E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, “Orthogonal frequency division multiplexing with index modulation,” IEEE Trans. Signal Process., vol. 61, no. 22, pp. 5536-5549, Nov. 2013.

Spatial Modulation



Block diagram of the SM transceiver for an $n_T \times n_R$ MIMO system. s (or $\hat{s}$) and I (or $\hat{I}$) $\in \{1, 2, \ldots, n_T\}$ denote the selected (or estimated) M-ary constellation symbol and transmit antenna index, respectively and $m_n, n = 1, 2, \ldots, n_T$ is the minimum metric provided by the nth SIMO ML detector.

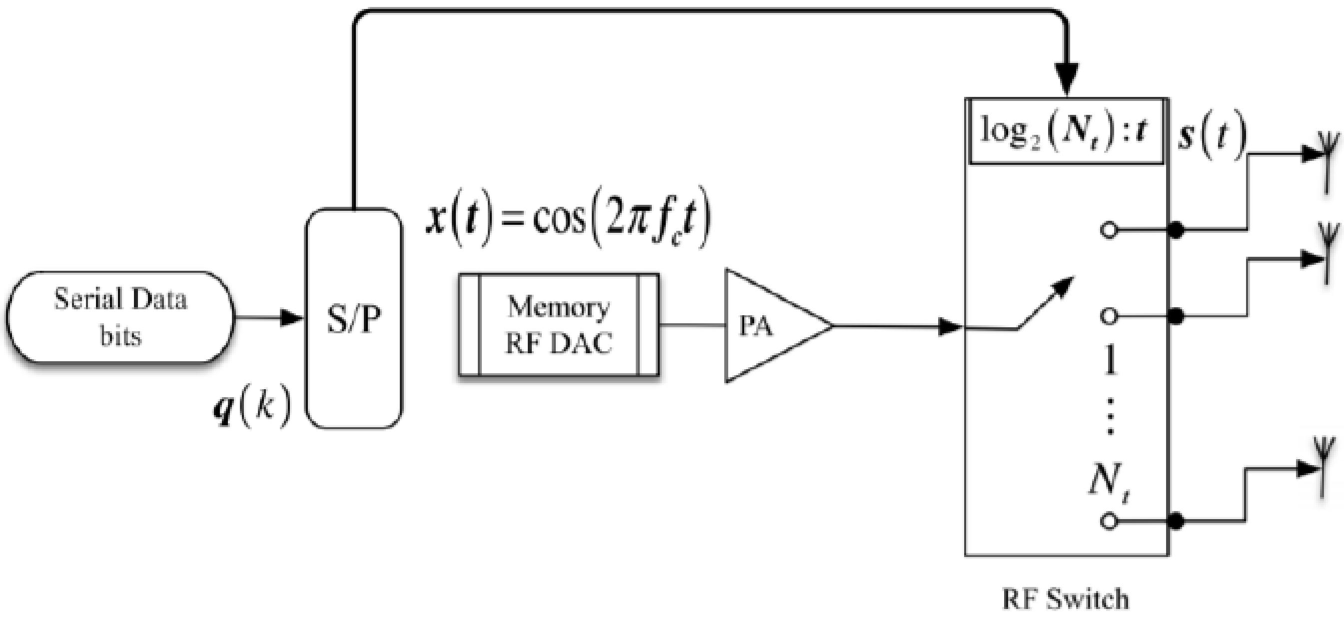
Three MIMO Modes



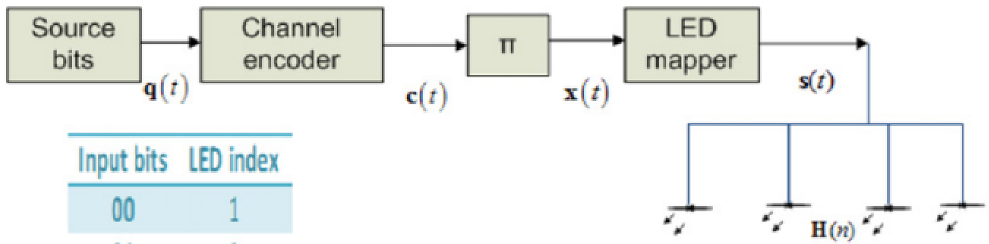
CoReLab

Space Shift Keying (SSK)

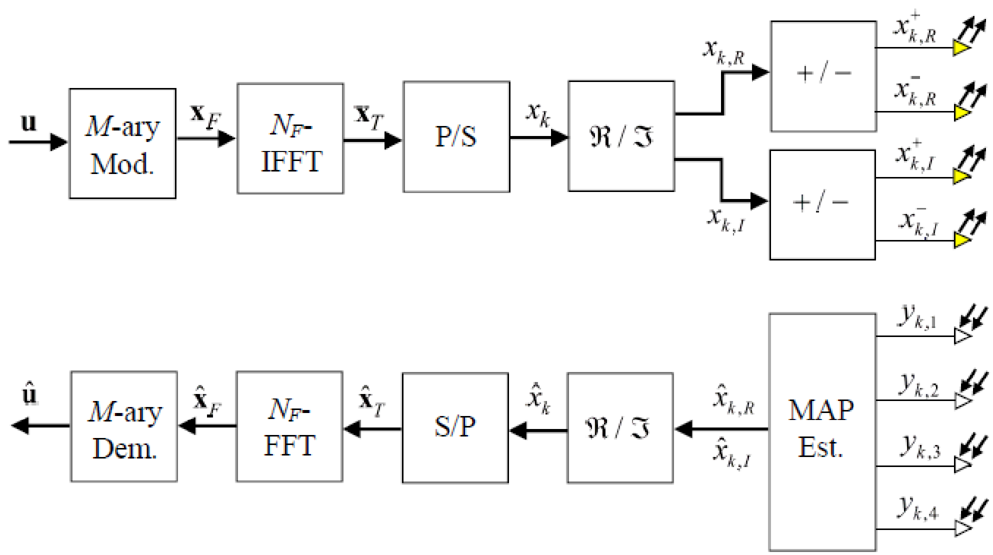
- The simplest form of the family of space modulation techniques.



IM for Optical Communications



Input bits	LED index
00	1
01	2
11	3
10	4

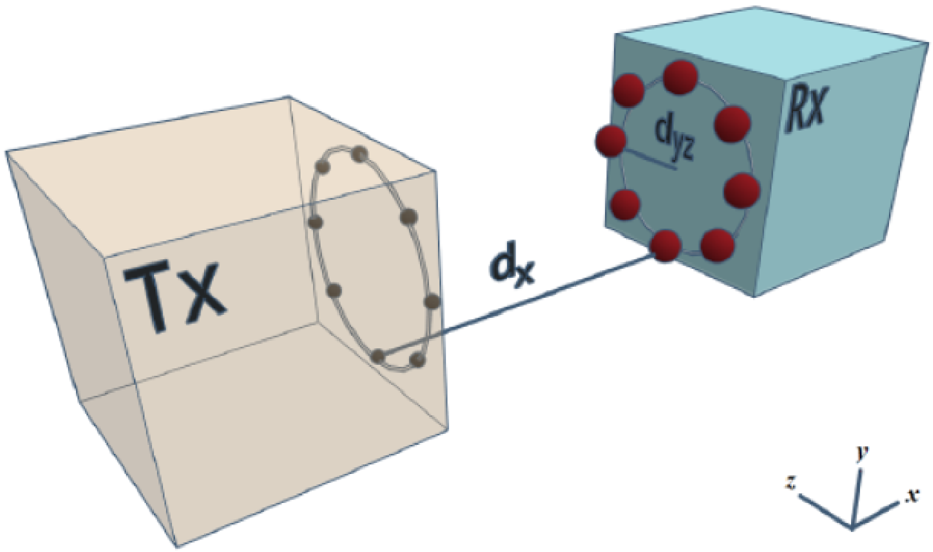


R. Mesleh, H. Elgala, and H. Haas, "Optical spatial modulation," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 3, no. 3, pp. 234-244,Mar. 2011.

E. Basar, E. Panayirci, M. Uysal, and H. Haas, "Generalized LED index modulation optical OFDM for MIMO visible light communications systems," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1-5.

A B

IM for Molecular Communications



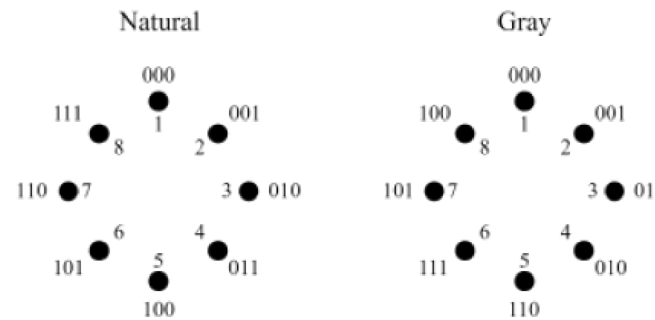


Fig. 1. The molecular MIMO system of interest for $n_{Tx} = n_{Rx} = 8$. Each spherical receiver antenna's closest point is d_{yz} away from the center of the UCA, and the receiver antennas of radius r_r are angular-wise $\frac{\pi}{4}$ radians apart from each other. Note that the radius of the transmitter UCA is equal to $d_{yz} + r_r$ for this topology. d_x denotes the closest point of a receiver antenna to its corresponding transmit antenna, and is also equivalent to $d_{Rx-Tx} - 2r_r$ given d_{Rx-Tx} is the distance between the Tx and Rx blocks' surfaces.

M. C. Gursoy, E. Basar, A. E. Pusane, T. Tugcu, "Index Modulation for Molecular Communication via Diffusion Systems", *IEEE Transactions on Communications (to appear)*, Feb 2019.

Orthogonal Frequency Division Multiplexing

- OFDM has become the most popular multi-carrier waveform in the past decade and has been included in LTE (4G), IEEE 802.11x WLAN, DVB, and IEEE 802.16e-WiMAX.
- The first step towards 5G NR was the PHY design, whose one of the core components is the waveform → the selection of the corresponding waveform has paramount importance.
- After a long debate on alternative waveforms for the 5G NR, cyclically prexed-OFDM (CP-OFDM) has been chosen by 3GPP for both UL and DL of 5G NR Phase 1 → due to its attractive advantages experienced in the previous generations.
- Intensive research activities are still ongoing for the design and test of modied OFDM schemes, exible and mixed numerologies, and candidate waveforms, such as GFDM, FBMC, and UFDM, for later phases of 5G.

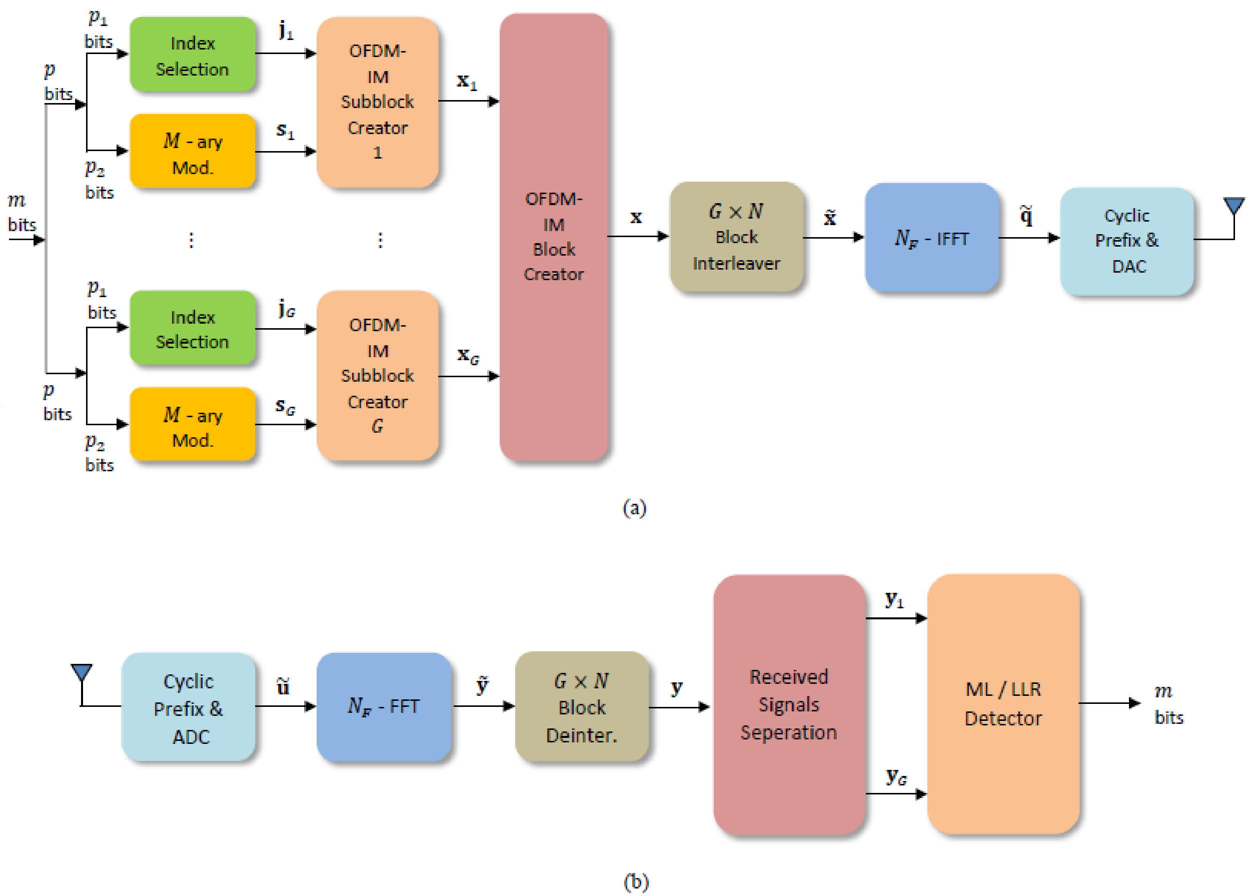
OFDM with Index Modulation

$$m = pG = \left(\left\lfloor \log_2 \binom{N}{K} \right\rfloor + K \log_2 M\right) G$$

$$p_1 = \left\lfloor \log_2 \binom{N}{K} \right\rfloor$$

$$p_2 = K \log_2 M$$

$$p = p_1 + p_2$$

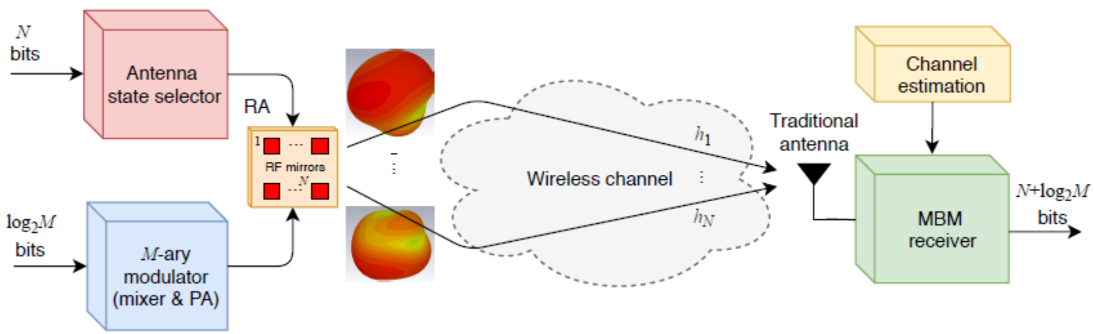


Transceiver structure of the OFDM-IM scheme

(a) transmitter structure (b) receiver structure

Reconfigurable Antennas: A New IM Frontier

- IM can be also implemented for the RF mirrors of an RA.
- An RF mirror is an RA element that contains a PIN diode, which can be turned on or o according to the information bits to alter the radiation pattern of an RA.
- Media-based modulation (MBM), which can be implemented by RAs, offers a completely new dimension for the transmission of digital information: the realizations of wireless channels themselves.

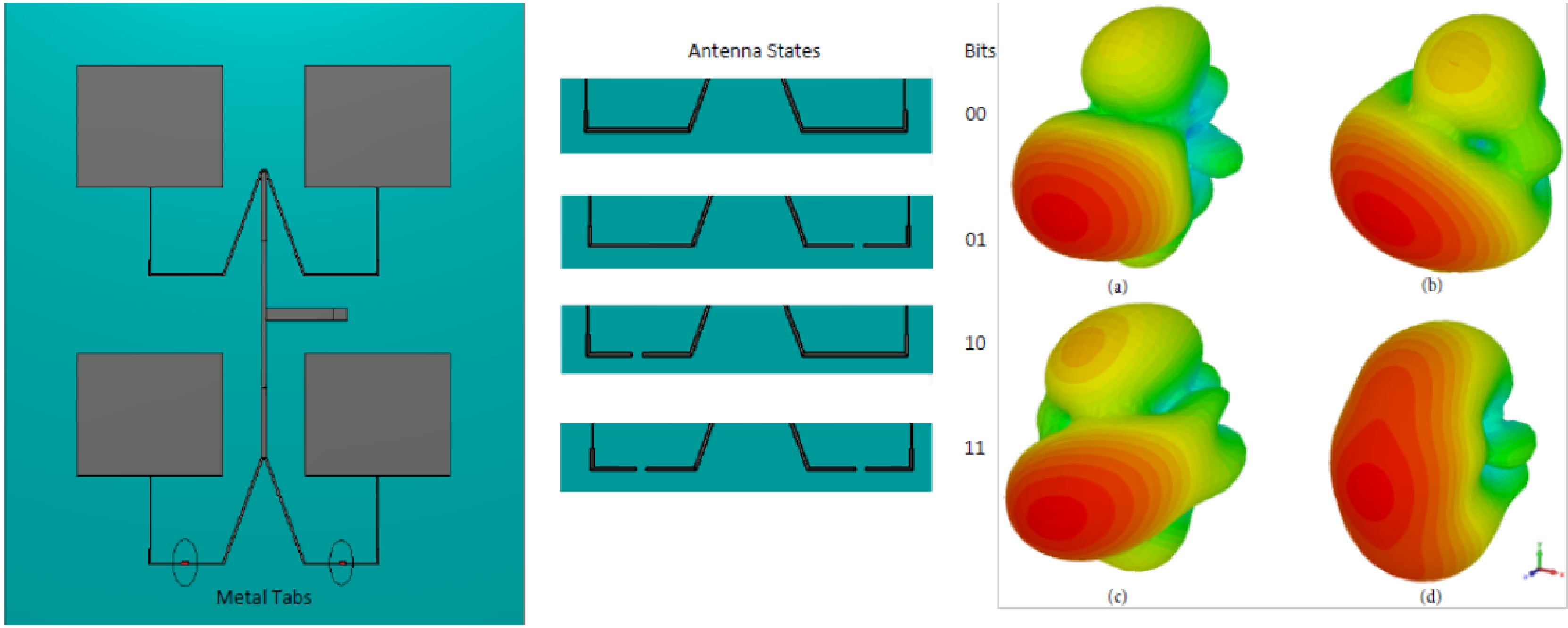


SISO-MBM transceiver equipped with a transmit RA that contains N RF mirrors.

A. K. Khandani, "Media-based modulation: A new approach to wireless transmission," in *Proc. IEEE Int. Symp. Inf. Theory*, Istanbul, Turkey, Jul. 2013, pp. 3050-3054.

E. Basar, "Media-Based Modulation for Future Wireless Systems: A Tutorial," *IEEE Wireless Communications (to appear)*, Mar. 2019.

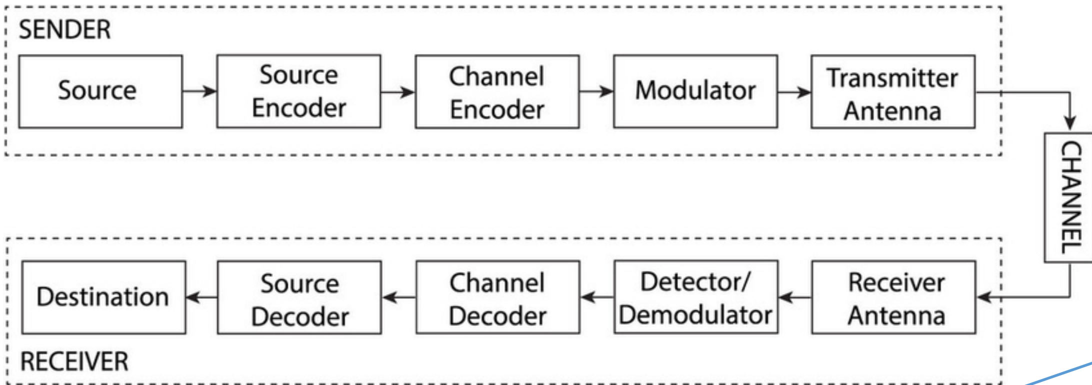
The Concept of Media-Based Modulation



A simple RA simulation model for MBM, its front view with two ideal metal tabs at lower horizontal connections, and the corresponding four antenna states obtained by altering the status of these two metal tabs.

Generated four different radiation patterns that can be used in transmission of two bits: (a) State 1, (b) State 2, (c) State 3, (d) State 4.

What We Do at KU-CoreLab?



Conclusion

- The wireless vision encompasses many exciting applications.
- Technical challenges transcend all system design layers.
- Innovative wireless design needed for 5G and beyond (6G) cellular/WiFi, mmWave systems, massive MIMO, and IoT connectivity.
- Standards and spectral allocation heavily impact the evolution of wireless technology.
- Perfect time for 6G research → 2030 and beyond

Teşekkürler!

Visit https://corelab.ku.edu.tr/ to learn more about research!