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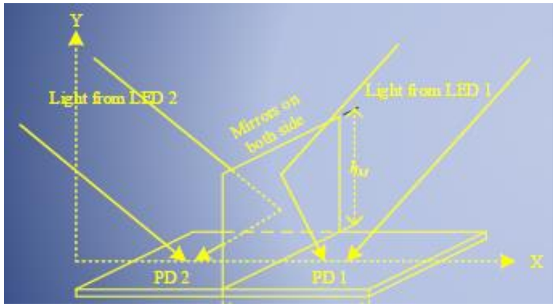
Paving the Way Towards 5G and Beyond



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Growth of Mobile Phone Subscribers & Data Traffic

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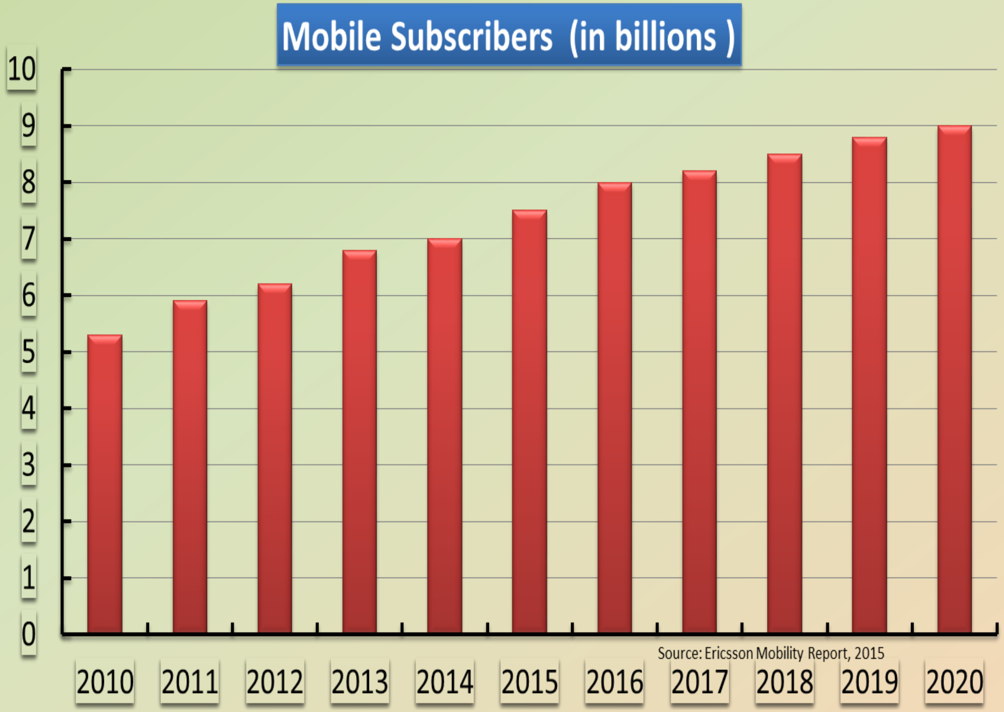

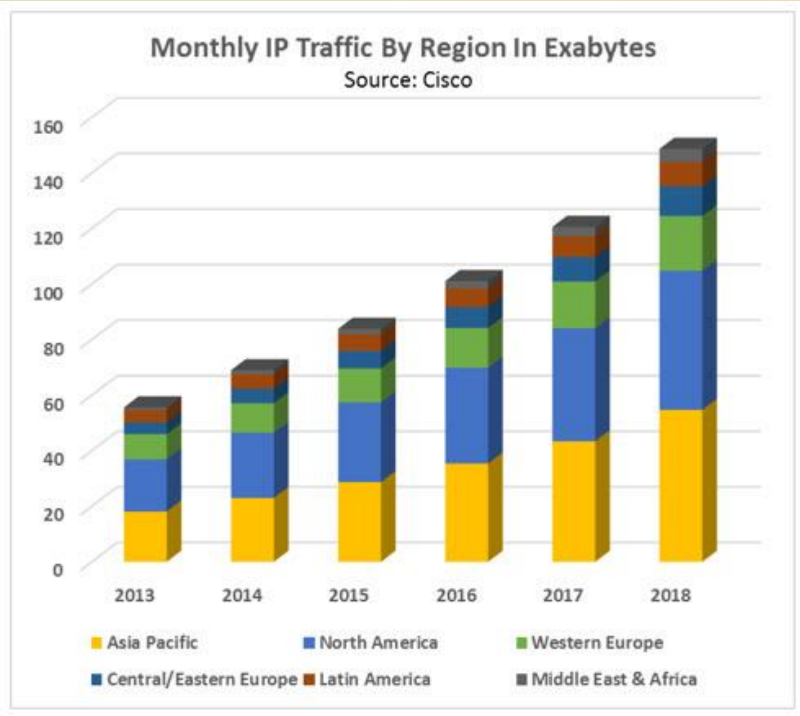

Mobile internet traffic growth is pushing the capacity limits of wireless networks !

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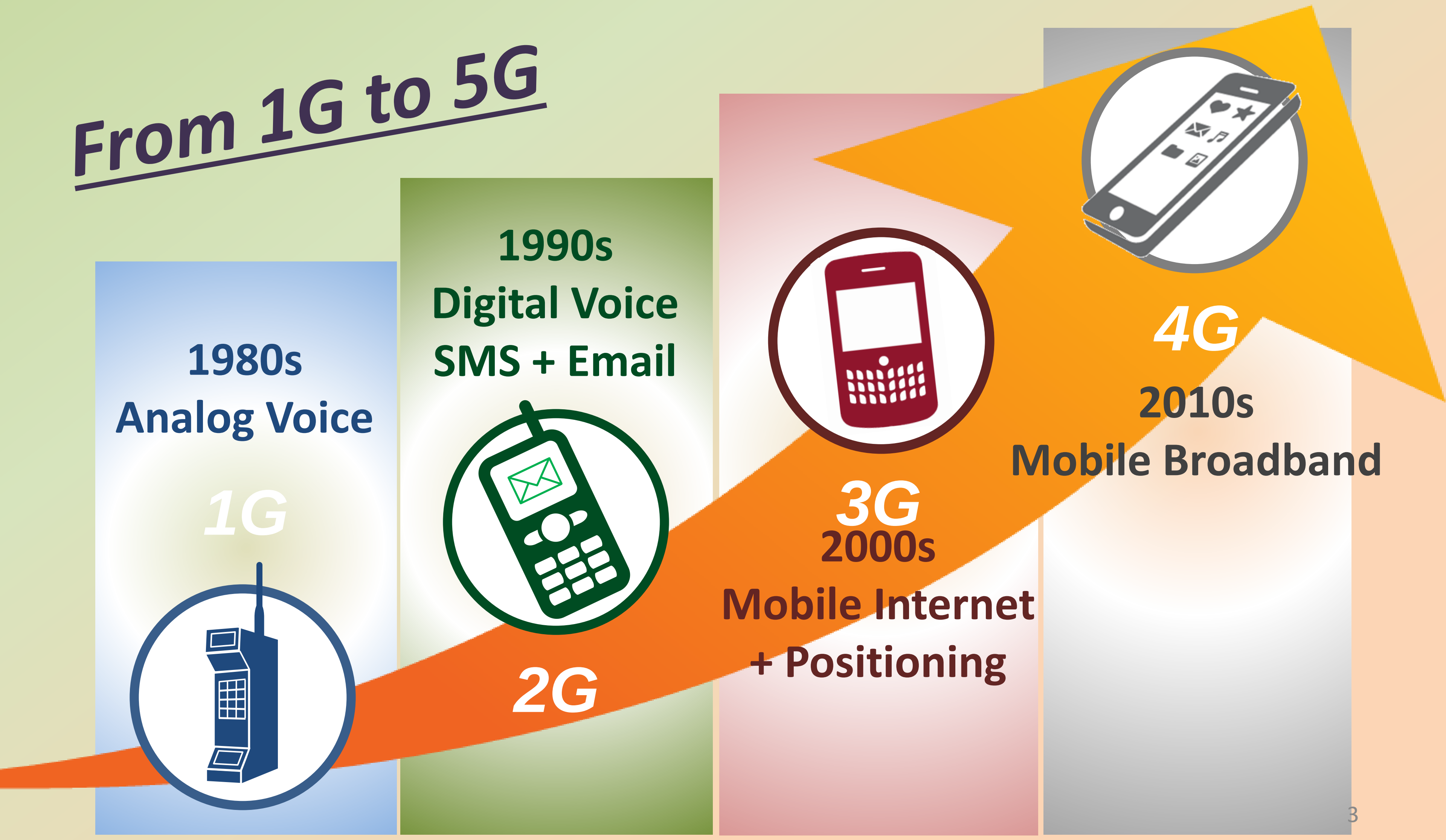
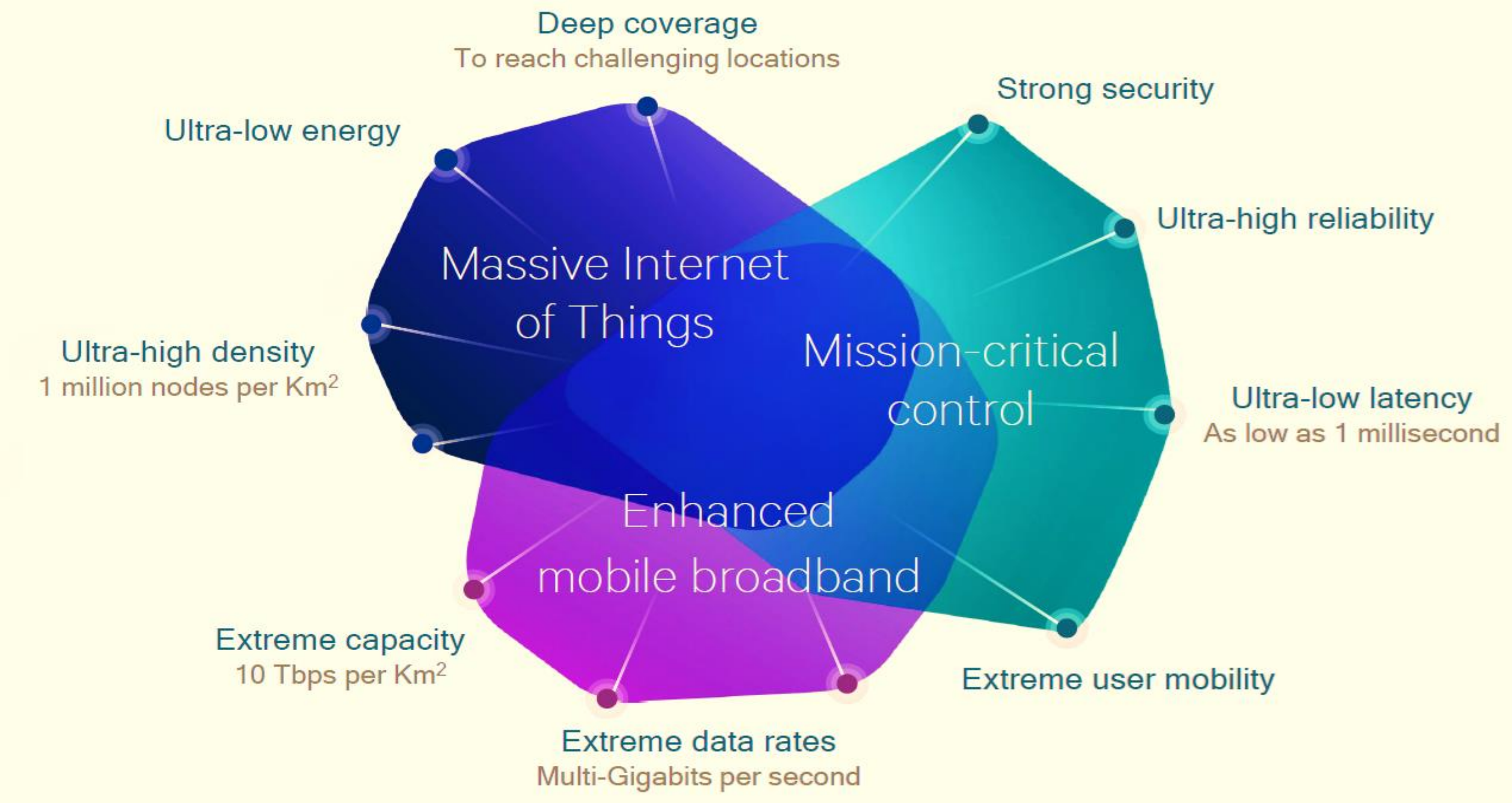
Evolution of Generations



Evolution Towards Beyond 5G

- Connect over 50 billions of wireless capability devices.
- Need to be green and sustainable.



[1] Qualcomm, "5G – Vision for the next generation of connectivity", March, 2015.

Evolution of the Industrial Revolution

4th Industrial Revolution:

Cyber-Physical Systems

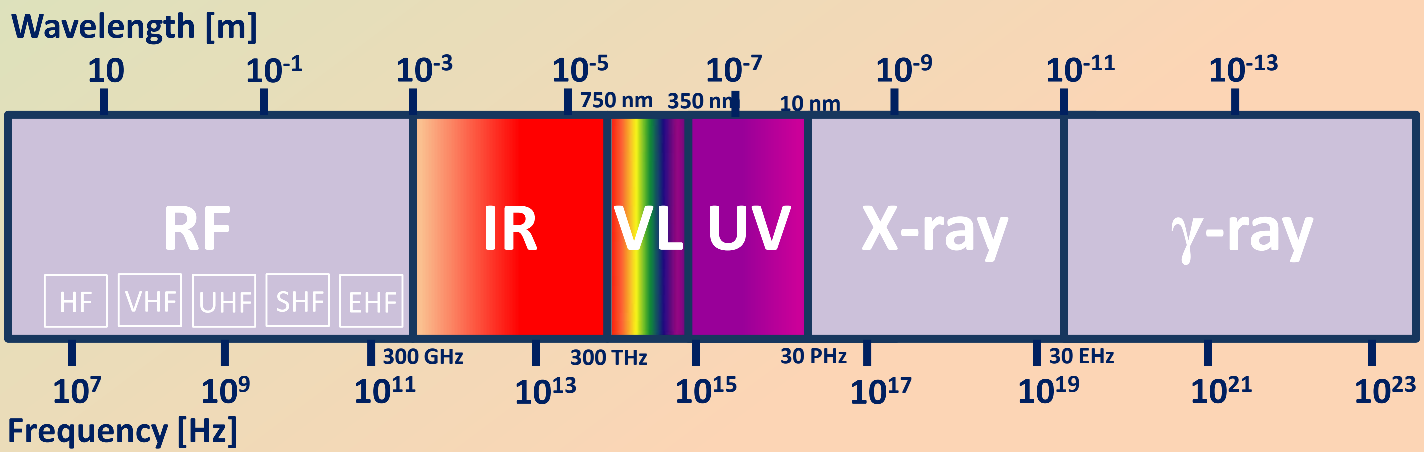
Pervasive Connectivity

5G mobile communications will provide the means to move into the 4th Industrial Revolution by allowing to extend to an all-connected world of humans and objects.

- **2020** – **4th** – **Automation** – *Electronics*, *Computers*
- **1950** – **3rd** – **Mass Production** – *Electrification*, *Assembly Line*
- **1840** – **2nd** – **Mechanization** – *Steam Engine*, *Power Loom*
- **1750** – **1st**

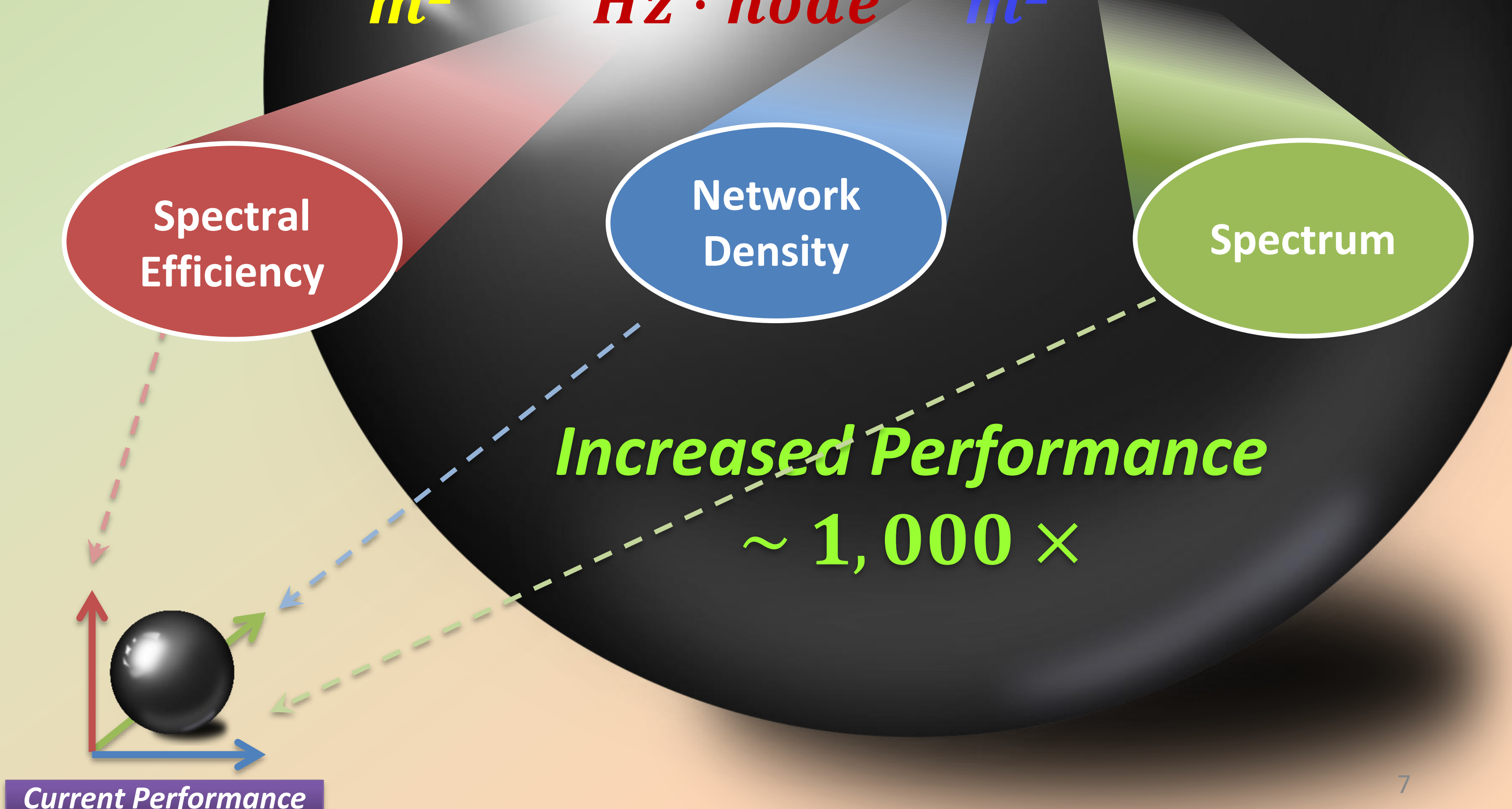
Spectrum

- RF spectrum typically refers to the full frequency range from 3 KHz to 30 GHz.
- RF spectrum is a national resource that is typically considered as an exclusive property of the state.
- RF spectrum usage is regulated and optimized
- RF spectrum is allocated into different bands and is typically used for
  - Radio and TV broadcasting
  - Government (defense and public safety) and industry
  - Commercial services to the public (voice and data)



Increasing the Area Traffic Capacity

$$\frac{bits/s}{m^2} = \frac{bits/s}{Hz \cdot node} \cdot \frac{node}{m^2} \cdot Hz$$



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Potential Enabling Technologies

$$\frac{bits/s}{m^2} = \frac{bits/s}{Hz \cdot node} \cdot \frac{node}{m^2} \cdot Hz$$

Better Spectral Efficiency

- Massive MIMO
- Interference Management
- Full Duplex Radio

Higher Network Densification

- Spectrum Sharing
- Cloud-RAN
- Small Cells
- D2D

More Spectrum

- Carrier Aggregation
- Mm-Wave (60GHz)
- THz Com
- Optical Wireless Com

Large Intelligent Surface (LIS) Assisted Wireless Communication

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- A very new concept [2], [3], with the potential of significantly reducing the energy consumption of wireless networks while realizing Massive MIMO gains.
- Base station (BS) communicates with the users through a LIS.
- LIS is a planar array consisting of a large number of nearly **passive, low-cost and low energy consuming, reflecting elements**, with reconfigurable parameters.
- Each element induces a certain phase shift on the incident electromagnetic wave.
- Objective is to make the **propagation channel more favorable** for the users.
- Can be easily integrated into the walls of the building.

Current implementations:

- Reconfigurable reflect arrays,
- Liquid crystal metasurfaces,
- Programmable metamaterials.

[2] C. Huang *et al.,* "Energy efficient multi-user MISO communication using low resolution large intelligent surfaces," in IEEE GLOBECOM, Abu Dhabi, UAE, Dec. 2018.
[3] Q. Wu and R. Zhang, "Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design," in IEEE GLOBECOM, Abu Dhabi, UAE, Dec. 2018.

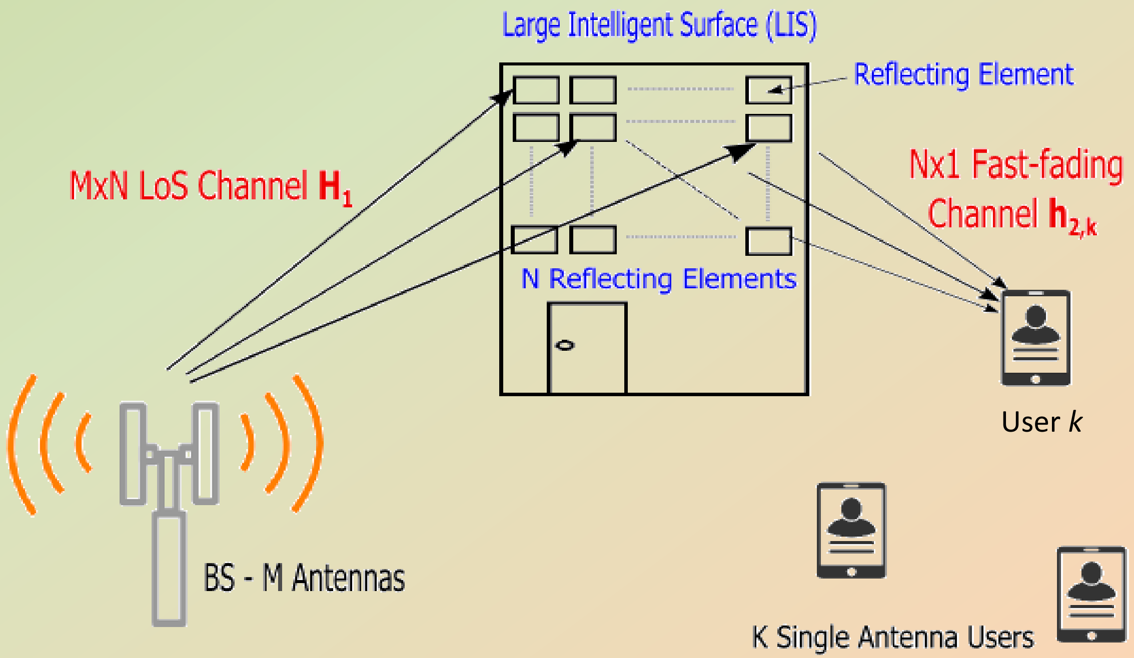
Not to be Confused with:

- **Amplify and Forward Relay**
  - Assists in transmission by actively generating new signals.
  - Requires a dedicated energy source.

- **Active Large Intelligent Surface (LIS) based Massive MIMO**
  - Data transmission with LISs.
  - Massive antenna arrays deployed on these surfaces with a fixed transmit power per volume-unit constraint.
  - Current focus is on indoor scenarios, where the technology is shown to be highly effective in interference suppression.
  - Promising research direction for data-transmission in communication systems beyond Massive-MIMO.

[4] B. Sainath and N. B. Mehta, "Generalizing the amplify-and-forward relay gain model: An optimal SEP perspective," IEEE Transactions on Wireless Communications, vol. 11, no. 11, pp. 4118–4127, Nov. 2012.
[5] S. Hu et al., "Beyond massive MIMO: The potential of data transmission with large intelligent surfaces," IEEE Transactions on Signal Processing, vol. 66, no. 10, pp. 2746–2758, May 2018

LIS Assisted MU-MISO System



M x 1 Channel between the BS and user *k* is modeled as,

$$\mathbf{h}_k = \mathbf{H}_1 \mathbf{\Theta} \mathbf{R}_{\mathrm{LIS}_k}^{1/2} \mathbf{h}_{2,k}$$

- $\mathbf{R}_{\mathrm{LIS}_k}$ represents the correlation matrix of the LIS elements for user *k*.
- $\mathbf{\Theta} = \mathrm{diag}(\Theta_1, \ldots, \Theta_N)$ is a diagonal matrix of effective phase shifts applied by the LIS elements.
- Entries of $\mathbf{h}_{2,k} \sim$ i.i.d. CN(0,1).

Optimal Precoder

- The Tx signal **x** is given as $\mathbf{x} = \sum_{k=1}^{K} \sqrt{p_k}\mathbf{g}_k s_k$, where p_k is the Tx power of symbol s_k for user *k* and $\mathbf{g}_k$ is the precoding vector for user *k*.
- Downlink SINR is defined as $\gamma_k = \frac{p_k |\mathbf{h}_k^H \mathbf{g}_k|^2}{\sum_{\substack{i=1 \\ i\neq k}}^{K} p_i |\mathbf{h}_k^H \mathbf{g}_i|^2 + \frac{1}{\rho}}$.
- **Problem (P1):**

$$\begin{aligned} &\underset{\mathbf{P},\mathbf{G}}{\text{maximize}} \ \underset{k\in\{1,\ldots,K\}}{\text{minimize}} && \gamma_k \\ &\text{subject to} && \frac{1}{K}\mathbf{1}^T\mathbf{p} \leq P_{max}, ||\mathbf{g}_k|| = 1, \forall k. \end{aligned}$$

- **Solution:**

$$\mathbf{g}_k^* = \frac{\left(\sum_{\substack{i=1 \\ i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k}{\left|\left| \left(\sum_{\substack{i=1 \\ i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k \right|\right|},$$

$$q_k^* = \frac{\tau^*}{\mathbf{h}_k^H \left(\sum_{\substack{i=1 \\ i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k},$$

$$\tau^* = \frac{K P_{max}}{\sum_{k=1}^{K} (\mathbf{h}_k^H \left(\sum_{\substack{i=1 \\ i\neq k}}^{K} q_i^* \mathbf{h}_i \mathbf{h}_i^H + \frac{1}{\rho}\mathbf{I}_M\right)^{-1} \mathbf{h}_k)^{-1}}$$

$$\mathbf{p}^* = (\mathbf{I}_K - \tau^* \mathbf{DF}/\rho)^{-1} \tau^* \mathbf{D} \mathbf{1}_K / \rho,$$

Case I – Rank-One H_1 ($H_1 = ab^H$)

- Optimal value of SINR is equal to τ^*, so we focus on analyzing τ^*.
- After some tedious calculations involving the use of Woodbury identity, we find,

$$\tau^* = \frac{P_{max}}{Z + P_{max}(K-1)}$$

where $\mathbf{Z} = \frac{1}{K}\sum_{k=1}^{K} \frac{1}{\rho \mathbf{h}_{2,k}^H \mathbf{v}_k \mathbf{v}_k^H \mathbf{h}_{2,k}}$, where $\mathbf{v}_k = \mathbf{R}_{\mathrm{LIS}_k}^{1/2} \mathbf{\Theta}^H \mathbf{b}$.

- Optimal precoder turns out to be matched filter, i.e. $\mathbf{g}_k^* = \frac{\mathbf{h}_k}{||\mathbf{h}_k||}$.

For K=1:

- **Problem (P2):**

$$\begin{aligned} \underset{\mathbf{\Theta}}{\text{maximize}} \quad & \tau^* \\ \text{subject to} \quad & |\Theta_n| = 1, \forall n = 1, \dots, N. \end{aligned}$$

$$\Rightarrow$$

$$\begin{aligned} \underset{\mathbf{\Theta}}{\text{minimize}} \quad & \frac{1}{\mathbf{h}_{2,k}^H \mathbf{R}_{\mathrm{LIS}_k}^{1/2} \mathbf{\Theta}^H \mathbf{b}\mathbf{b}^H \mathbf{\Theta} \mathbf{R}_{\mathrm{LIS}_k}^{1/2} \mathbf{h}_{2,k}} \\ \text{subject to} \quad & |\Theta_n| = 1, \forall n = 1, \dots, N. \end{aligned}$$

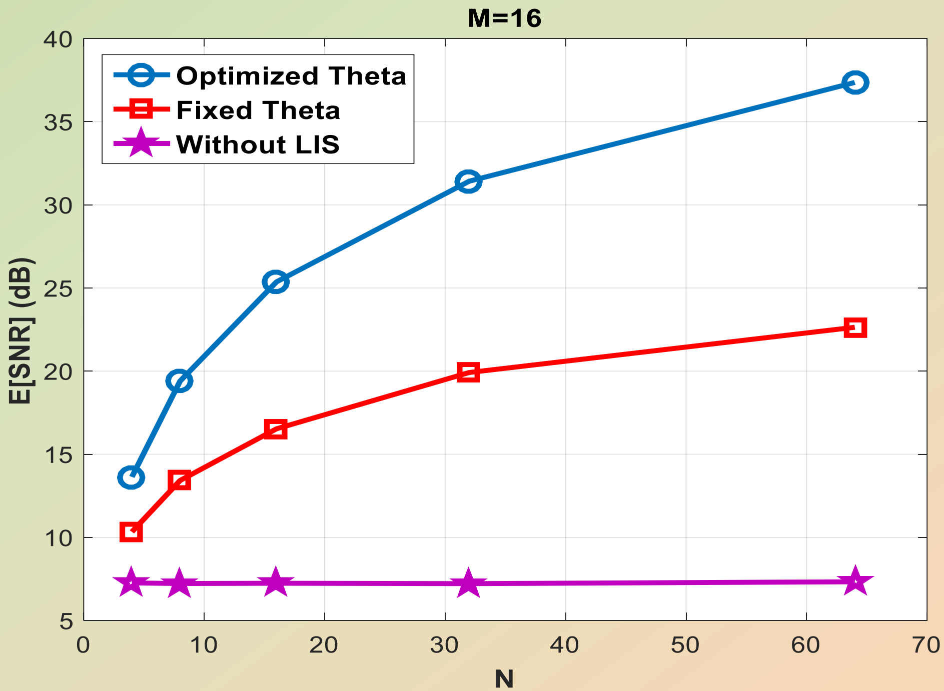
- **Solution:** Let $\mathbf{w} = [\Theta_1, \dots, \Theta_n]^T$, then the (close to) optimal phases are computed as,

$$\mathbf{w}^* = \exp(j \arg(\bar{\mathbf{w}}^*)),$$

$$\bar{\mathbf{w}}^* = \text{Eigenvector corresponding to the max eigenvalue of } \bar{\mathbf{V}}\bar{\mathbf{V}}^H,$$

$$\bar{\mathbf{V}} = (\text{diag}(\mathbf{h}_2^H)\mathbf{R}_{\mathrm{LIS}}^{1/2})^T \mathbf{b}$$

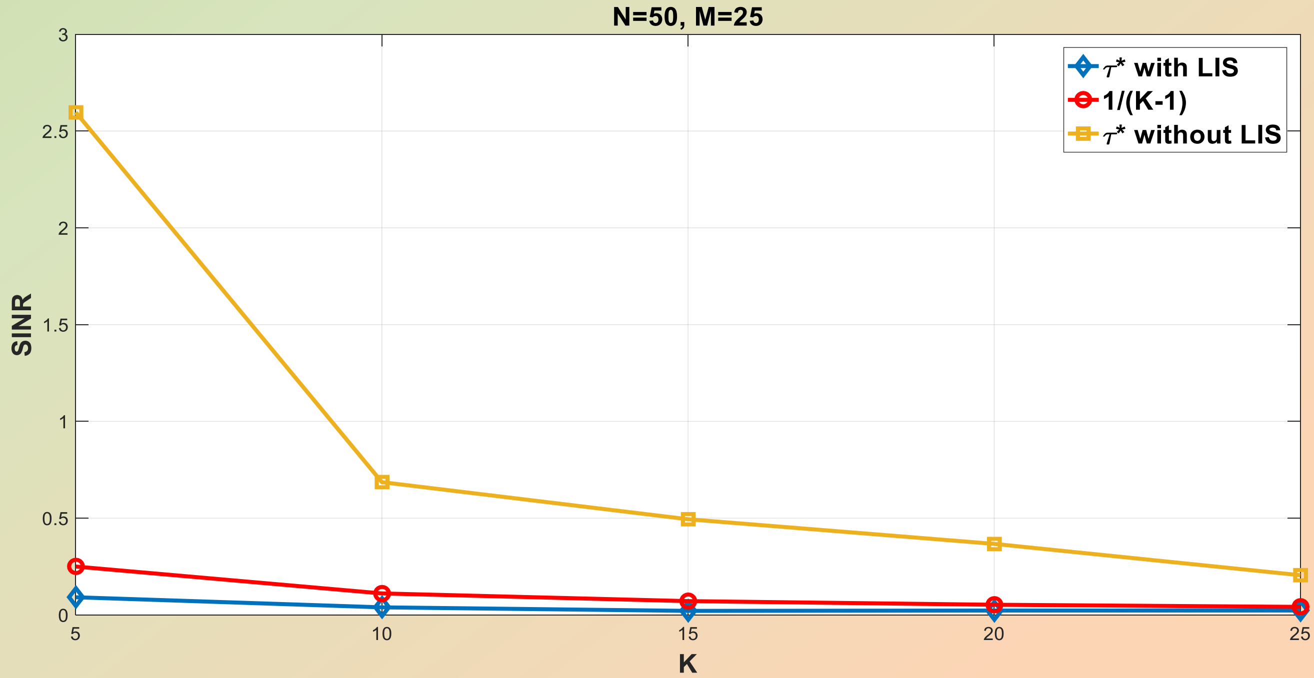
Performance (K=1)



- Comparison done with direct channel between the BS and user, $\mathbf{h}_d = \mathbf{R}_{BS}^{1/2}\mathbf{h}_3$, where entries of $\mathbf{h}_3 \sim \mathcal{CN}(0,1)$, with optimal Tx beamforming, i.e. $\mathbf{g}^* = \frac{\mathbf{h}_d}{||\mathbf{h}_d||}$.
- Average optimal SNR scales with the number of reflecting elements in the order N^2.
- **Array gain of N** and **beamforming gain of N.**
- Significant improvement with only passive phase shifters – **more spectral and energy efficient.**

Multi-User (MU) Setting

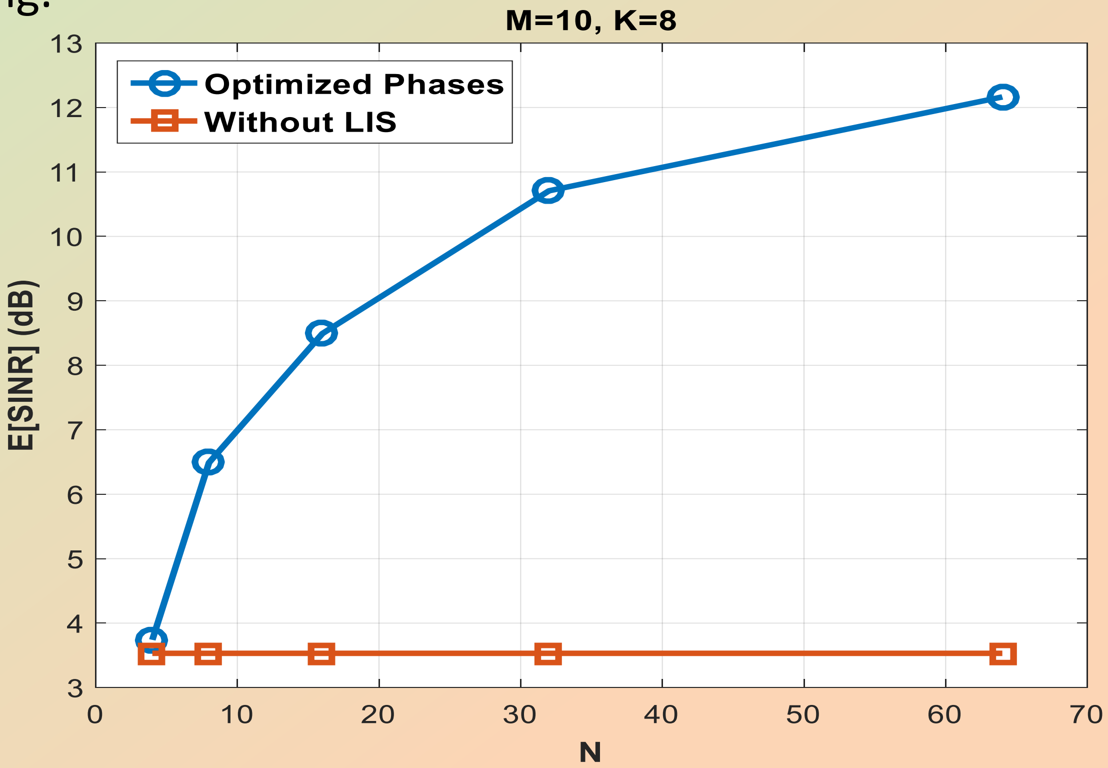
During our derivations we find that with a rank-one channel between the BS and the LIS the optimal SINR is bounded as, $\tau^* \leq \frac{1}{K-1}, \quad \text{for } K > 1$



- **Received average SINR of each user remains within a bound that goes to 0, no matter what value of N or what phases are used.**
- **Harmful to deploy LIS in a MU setting with a rank-one LoS BS-to-LIS channel.**

Case II – Full Rank H_1

- Phases that maximize the deterministic equivalent of τ^* are computed using projected gradient descent.
- Performance compared with the case where BS directly communicates with the users using optimal precoding and power allocation.
- Result shows that by introducing rank in $\mathbf{H}_1$, average optimal SINR scales even in the MU setting.



Further Research Directions

- Low-overhead signal exchange and channel estimation design to provide the LIS with the CSI to adapt the phases.
- Optimal positioning of the LIS, such that the channel is LoS but not rank-one.
- Correlation characterization for the LIS, based on the underlying technology used.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Thank You
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