6G Technology Enablers Workshop:
Spectral and Energy Efficient Radio Systems

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Overview of Talk

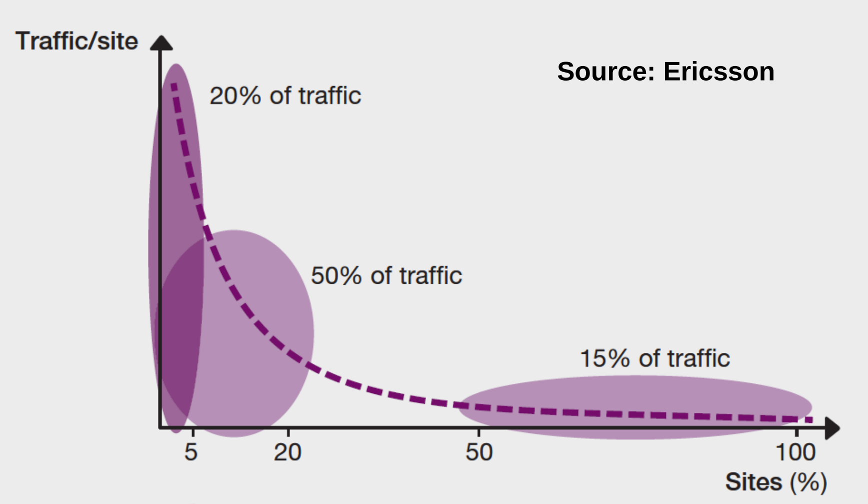
- Energy Consumption in Wireless Networks
- Energy Issues in Wireless and working towards “**net zero**”
- Personal Research in Energy Efficient Transceiver Design
- Current Wireless Related Research directions in IDCOM
- Conclusions

Energy Efficiency in Wireless Networks

- Around 2010, several projects (**Green Radio**, EARTH, GreenTouch) studied wireless energy efficiency

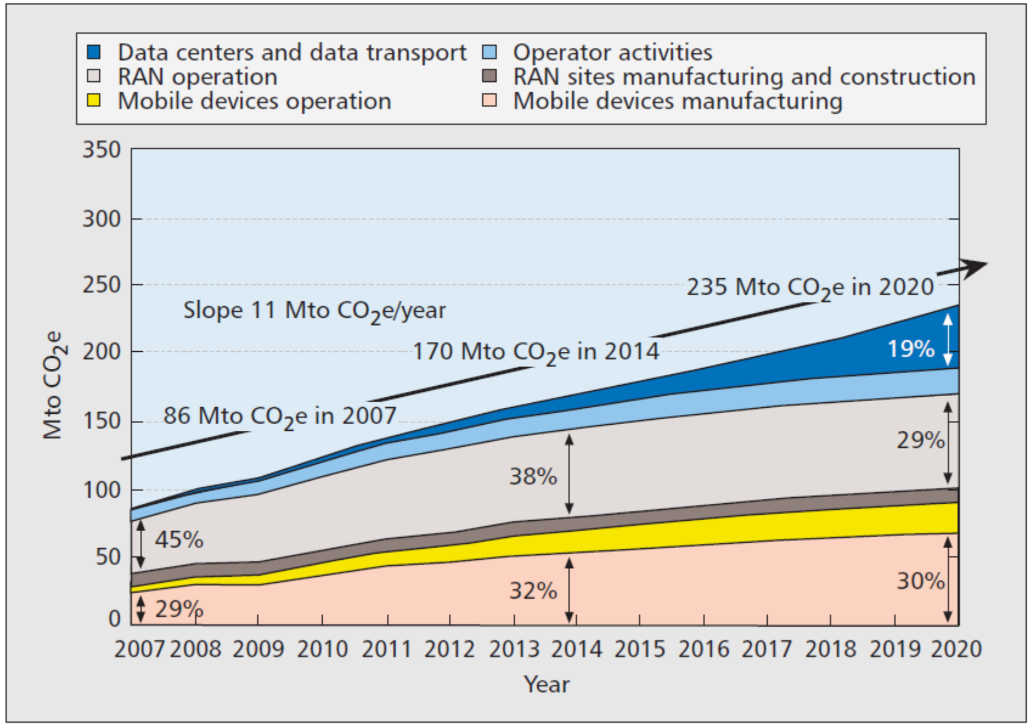
- Some key findings:
  - At the time, base station energy consumption was reducing around **8% per year**
  - Not a simple single solution to achieve significant reductions
  - Need to study the energy consumption of the whole system
  - In cellular networks, data traffic is very non-uniform in time and in area, so we need flexible/adaptive solutions

- 5G can reduce energy over 4G as follows [1]:
  - Minimal base station signalling enables “**deep sleep**”
  - **Massive MIMO** Base Stations improve link efficiency
  - **Small cells** can provide high capacity where needed



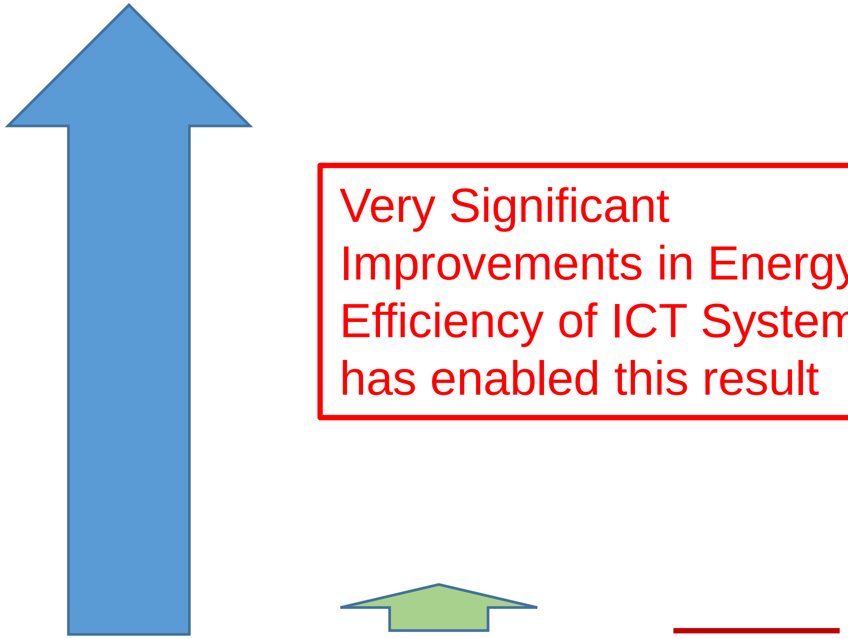
[1] Ericcson Blog: **https://www.ericsson.com/en/blog/2019/9/energy-consumption-5g-nr**

Energy Consumption in Wireless Networks



"Plausible" Model for CO_2 Emissions from Wireless Networks to 2020 (from c. 2010) [1]

So what actually happened from 2010-2020 for the ICT Sector [2]?



Very Significant Improvements in Energy Efficiency of ICT Systems has enabled this result

12 times growth in data in networks

10% increase in electricity usage

CO_2 Emissions static

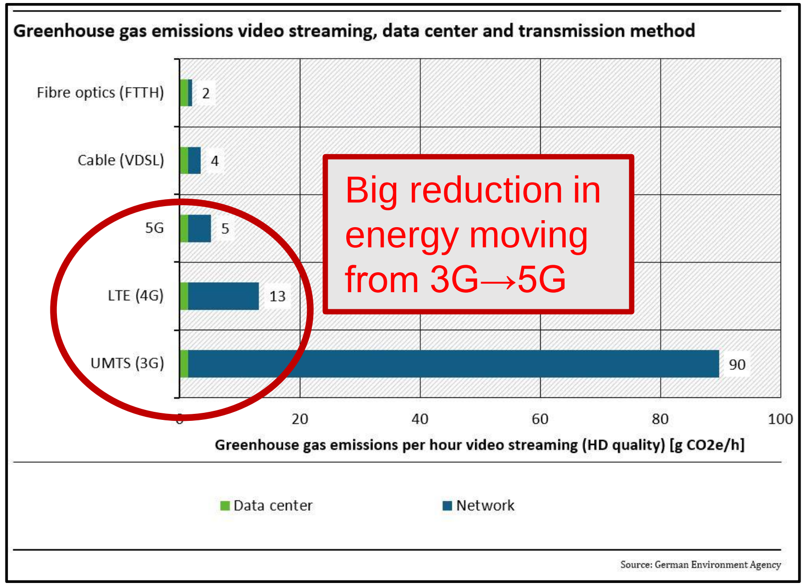
[1] **A. Fehske et al, "The Global Footprint of Mobile Communications: The Ecological and Economic Perspective", IEEE Comms Mag, Aug 2011, pp55-62.**

[2] **J. Malmodin, "Energy Consumption and Carbon Emissions in the ICT Sector", Tech UK conference on Decarbonising Data, 2020**

So What Will Happen in 2020-30?

- In the short term may be an **increase** in energy consumption as 5G networks rolled out alongside existing **2G/3G/4G** systems
- However as 5G networks mature and older networks are removed energy consumption is likely to reduce
- **ITU** targets a **45%** reduction in CO_2 emissions in 2030 compared to 2015 to support the net zero carbon target in 2050
  - Need to adopt **renewable energy** sources
  - Further improvements in energy efficiency
  - Using ICT to drive efficiency in other industries

ITU 2030 Connect Agenda

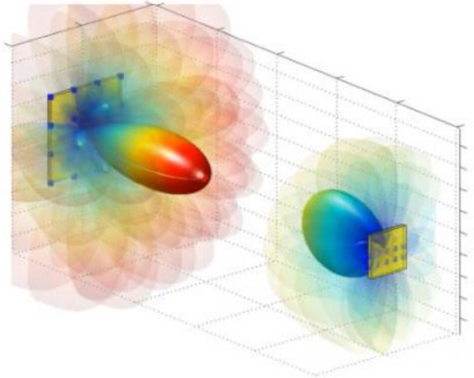


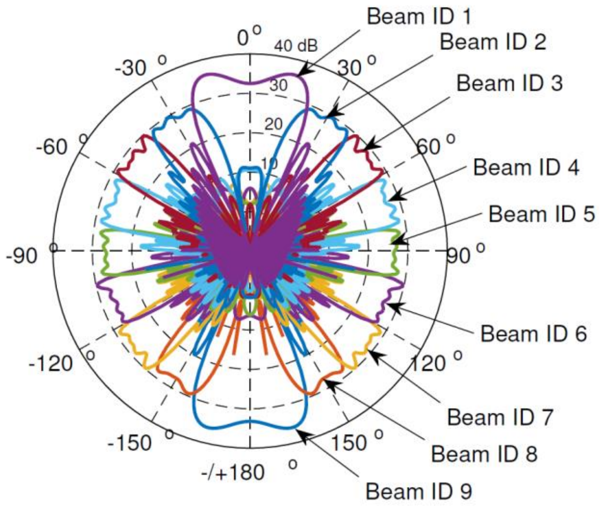
Carbon Emissions of Video Streaming

Source: **https://www.umweltbundesamt.de/en/press/pressinformation/video-streaming-data-transmission-technology**

Energy Efficiency in mm-Wave Networks

- **Millimetre wave bands** provide higher capacity; use directional beamforming to mitigate channel effects
- First systems to launch operate around **24-28 GHz**
- Research needed to develop higher frequency technologies – when should we stop?





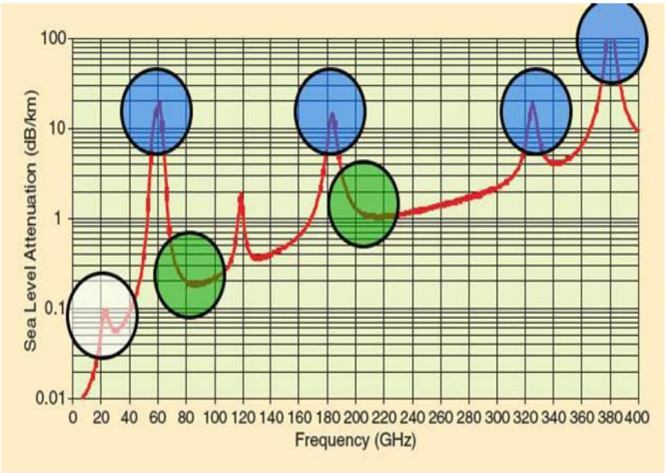
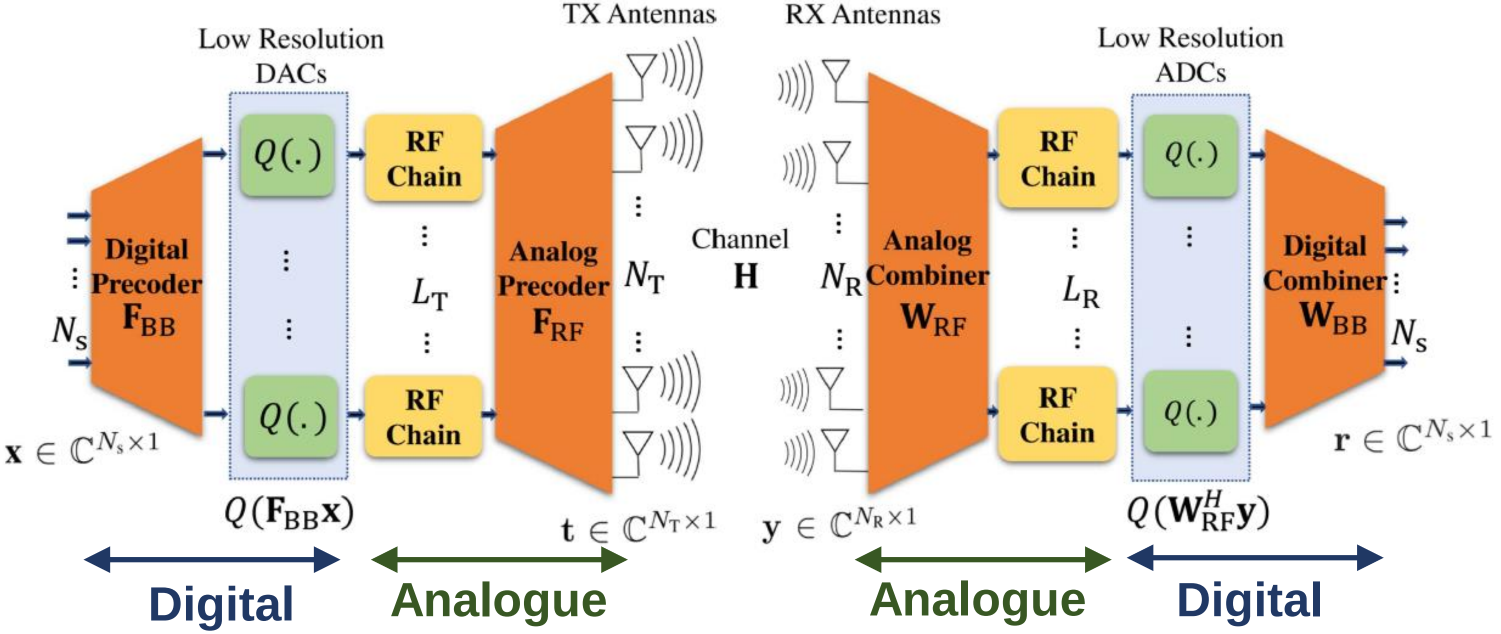


Figure 2 of T.S. Rappaport et al, IEEE Access, May 2013

Source: **P. Cao et. al., "Constant Modulus Shaped Beam Synthesis via Convex Relaxation," IEEE AWP Letters, pp. 617-620, 2017.**

Hybrid Multiple Antenna System



Hybrid Architecture:

- Use small number of RF chains/transceivers
- Use analogue circuitry to connect to large number of antennas
- Use multiple beams for spatial multiplexing

Research Questions:

- How do we design the individual components of the system?
- Consider how to optimise the No of RF chains (yellow) and sampling resolution (green) to improve energy efficiency

Source: **A. Kaushik et. al, "Joint Bit Allocation and Hybrid Beamforming Optimization for Energy Efficient Millimeter Wave MIMO Systems," in IEEE Trans on Green Comms & Networking, pp. 119-132, March 2021.**

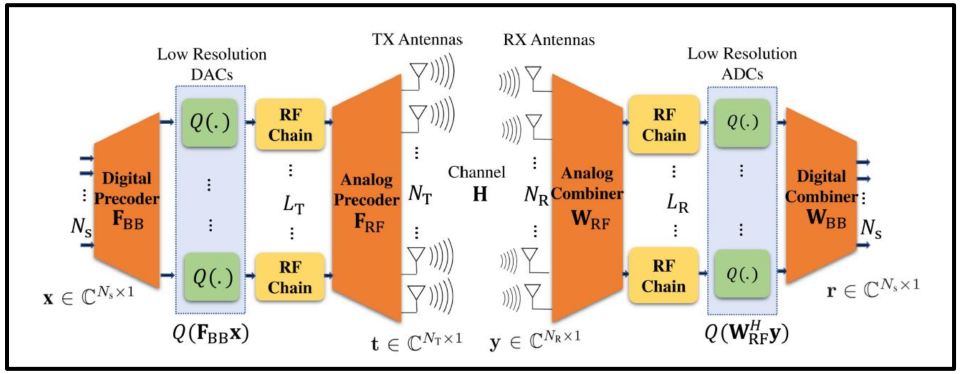
Calculating Energy Efficiency

- Communications system has transmit power levels $\mathbf{P}_{TX}$
- Given the **spectral efficiency** $R(\mathbf{P}_{TX})$
- And the TX/RX **power consumed** $P(\mathbf{P}_{TX})$
- The **Energy Efficiency** is defined by:

$$\text{EE} = \frac{R(\mathbf{P}_{TX})}{P(\mathbf{P}_{TX})} \quad (\text{bits/joule})$$

- Design algorithms to improve **EE** performance

This is a difficult quantity to optimise as it is the ratio of two complicated functions!

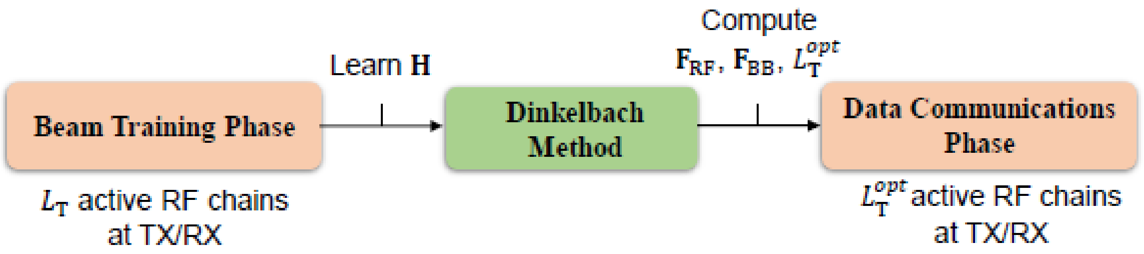


Proposed Approach: Dinkelbach Method

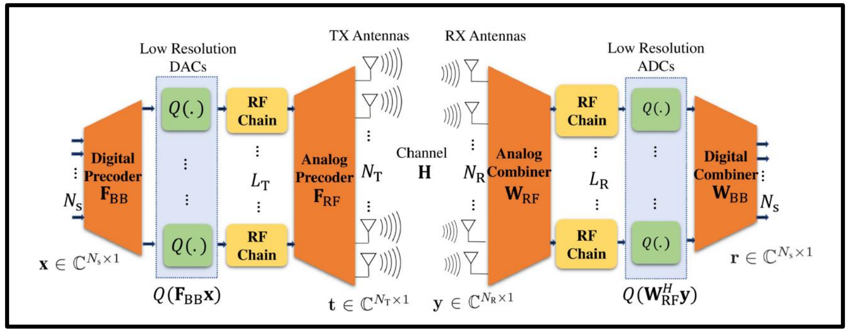
- First idea: Use a **Brute Force** Approach to test all possible setups
- Second idea: We adopt the **Dinkelbach Method**:

$$\max_{\mathbf{P}^{(m)} \in \mathcal{D}^{L_{\mathrm{T}} \times L_{\mathrm{T}}}} \left\{ R(\mathbf{P}^{(m)}) - \nu^{(m)} P(\mathbf{P}^{(m)}) \right\}$$

  - Frequently used to optimize the ratio of two functions
  - 2-3 iterations to find the best transmitter/receiver setup and choice of **EE**
  - Method much simpler than brute force but yields good solutions



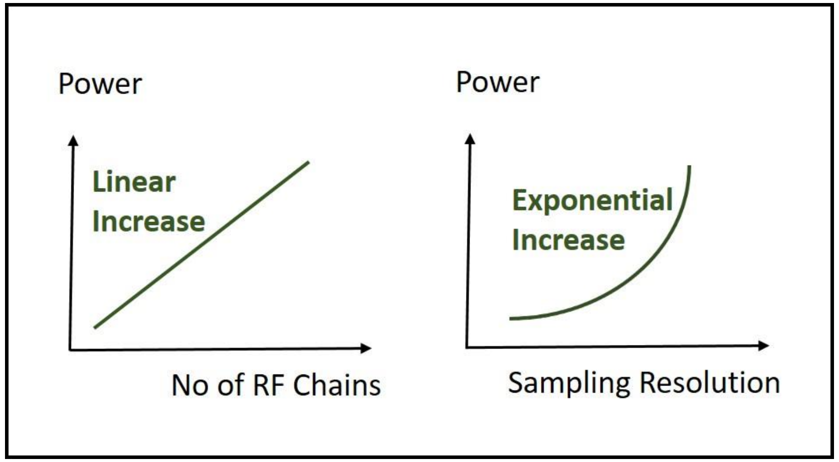
Optimise TX/RX on **packet-by-packet** basis



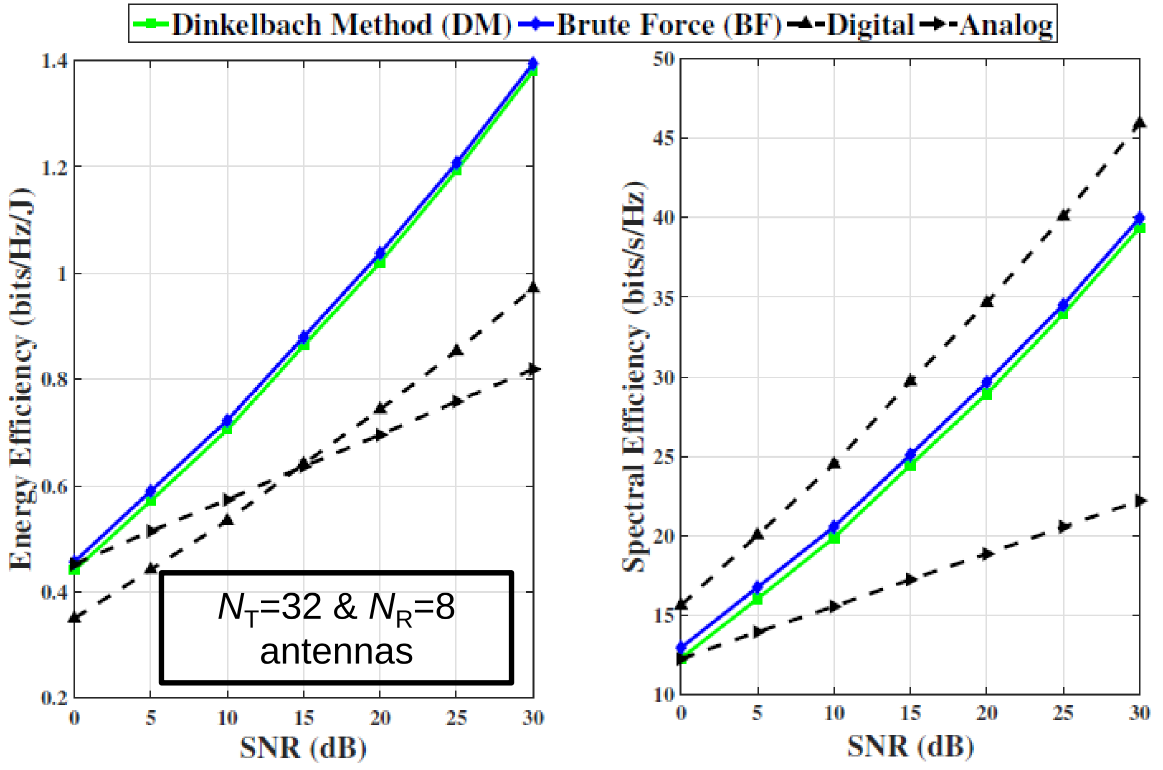
Power Consumption Modelling

- Interested in the **total power** *P* consumed by the transmit-receive system, not just transmit power $\mathbf{P}_{TX}$
- Use a model that computes the power for all elements for TX/RX
- Linear scaling in power for **No of RF chains used**
- Sampling device power scales **exponentially** with No of bits used
- Summing these terms gives total power consumed $P(\mathbf{P}_{TX})$

Power Term	Value
Power required by all circuit components	$P_{CP} = 10$ W
Power required by each RF chain	$P_{RF} = 100$ mW
Power required by each phase shifter	$P_{PS} = 10$ mW
Power per TX/RX antenna element	$P_T = P_R = 100$ mW
Maximum allocated power	$P_{max} = 1$ W



Energy and Spectral Efficiency Results



Systems Studied:

1. **Brute Force**
2. **Dinkelbach**
3. **Analog** – One RF chain
4. **Digital** – One RF chain per antenna

Observations: We have to trade Energy and Spectral Efficiency

Dinkelbach Method achieves similar **EE** to **Brute Force** method but lower **SE** than **Digital**

Where Do We Go From Here

- Significant advances in energy efficient radio technology in 4G and 5G wireless systems in last ten years

- Major Challenges ahead:

  - Efficient Operation over **many frequency bands**, particularly with the move to use mm-wave spectrum

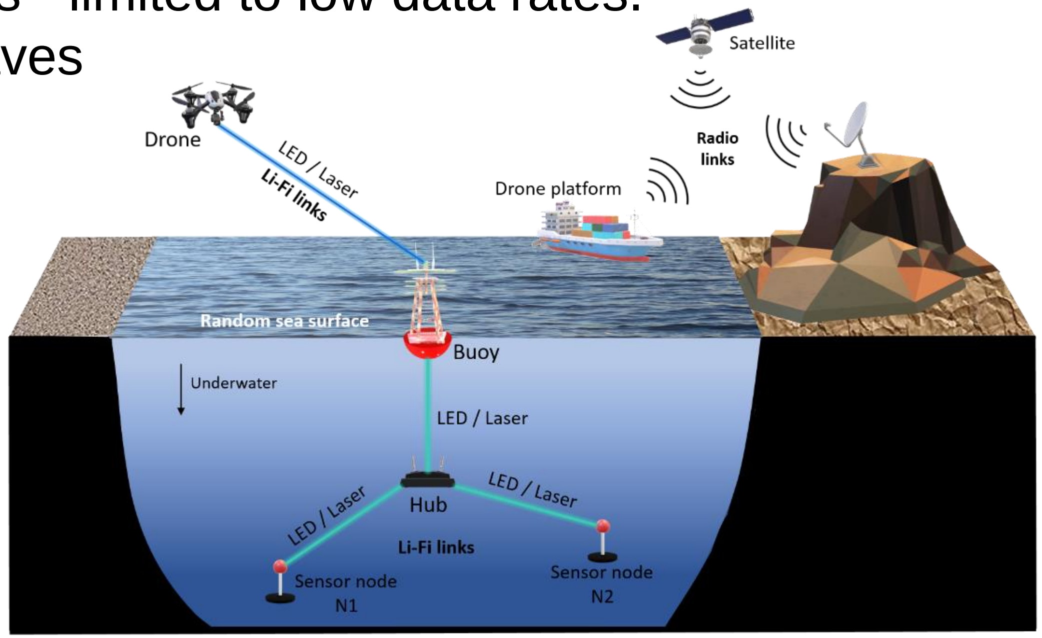
  - **Optimisation and Artificial Intelligence Techniques** to build the "always most energy efficient" networks

  - Improving wireless equipment recycling and the **circular economy**

Wider Network Integration using Radio/Light

Goal: *Connecting underwater/space to high speed wireless networks*
Colleagues: *Wasiu Popoola, Majid Safari*

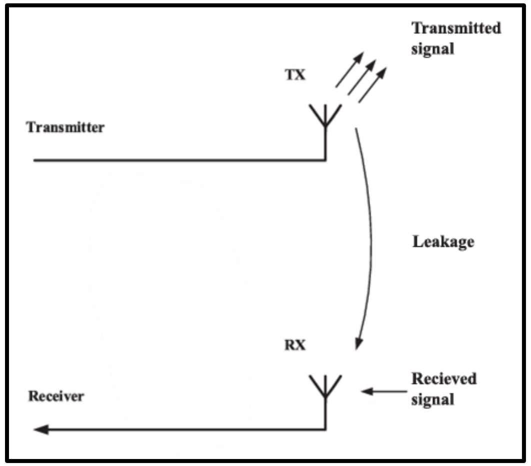
- The **Underwater network** is the final frontier in high speed wireless connectivity
  - Major benefits e.g.: environmental protection, socio-economic and national security.
  - Currently relies on the low frequency acoustic waves - limited to low data rates.
  - Underwater channel is extremely hostile to radio waves
- The **Drone and Satellite networks** can also support communication, especially in remote areas
  - Need to identify the best way to integrate these systems with cellular networks
  - Light communications can complement radio technologies to provide high bandwidth directed communication



Full Duplex Communications

Goal: Effective Communication when data is both simultaneously transmitted and received at the same frequency, ideally using a single antenna element.

Colleagues: *Symon Podilchak, Tharm Ratnarajah*

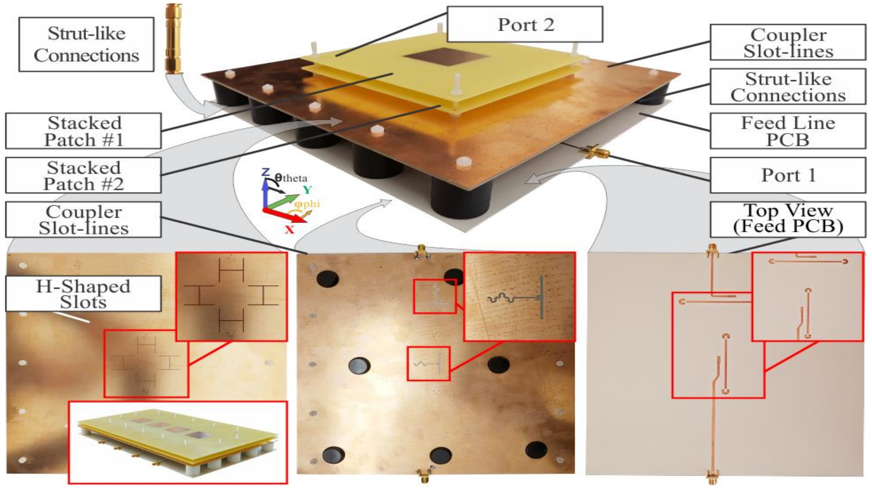


(+) Potential Advantages

- ✓ Bi-directional communications
- ✓ Doubling of the spectral density
- ✓ Suppresses end-to-end delays in wireless networks

(+) Current Research

- ✓ Combining Analogue and Antenna Cancellation Methods
- ✓ Dual Polarization Antennas with up to 50 dB of Cancellation
- ✓ Extension of Concept to Antenna Arrays



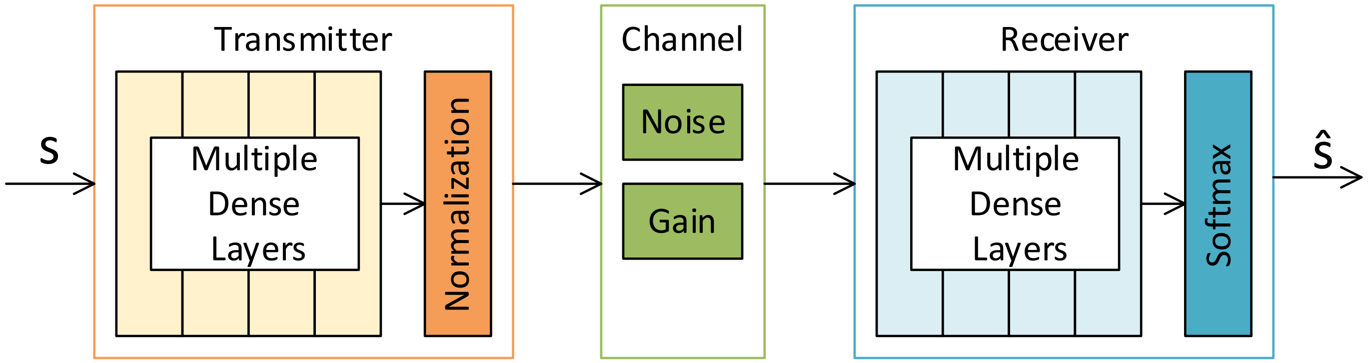
Machine Learning for Communications

Goal: Investigate performance gains of Machine Learning

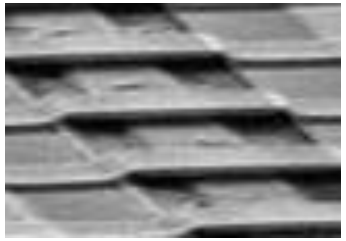
Colleague: *Tughrul Arslan*

Why Machine Learning?

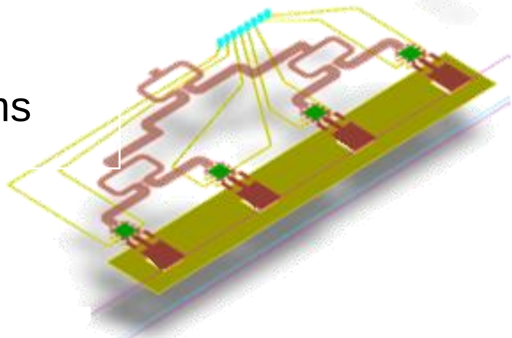
- Higher performance over complex or unmodeled channels
- Automatic compensation of hardware impairments or other unaccounted non-linearities
- Increased performance due to the removal of functional block boundaries of traditional algorithms



Example: Auto-encoder physical layer deep learning system



RF MEMS switches



Tuneable Antenna array

Example: Embedded AI/ML for beamforming with a spinout company

Thanks for your attention!

Questions?