The Intelligent Distributed Physical Layer (PHY)

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Motivation

- Plethora of completely new applications for wireless communications
  - inc. in mobility, energy, security, utility services, healthcare, security…
- Many fall under **IoT** or "massive machine-type communications" (**mMTC**)
  - connect **devices** in the service of people, rather than people directly

- Involve very large numbers of devices, with very diverse requirements
  - may be **intermittent, small data packets**, or **high rate streaming**; may require **ultra-low latency**, and/or **ultra-high reliability**
- *It is already estimated that the number of IoT devices exceeds the human population, and there is ultimately no limit to the number of connected devices that might be required*

Challenges for the PHY

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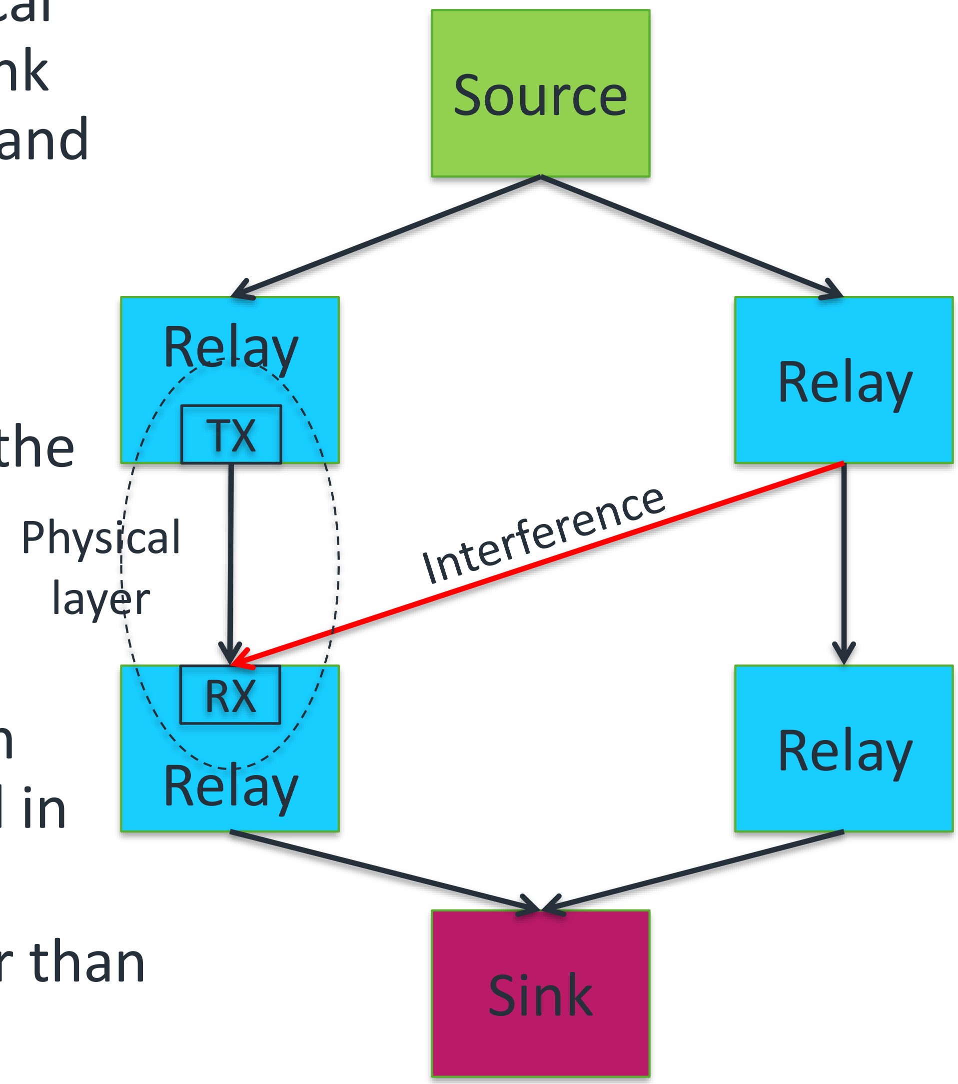
- **Scalability**: the most obvious challenge; likely to require increase in access network density and hence in intra-network interference
- **Latency**: new applications may require latency of 1 ms or less; gives rise to fundamental challenges to current physical layer paradigms
- **Reliability**: e.g. 5G ultra-reliable low-latency communication (URLLC) use case requires availability up to 99.999% (i.e. outage 10^{-5}); severe challenge on fading channels
- **Grant-free access**: mMTC applications likely to require immediate access without prior reservation: difficult in OFDMA
- **Coordination/adaptability**: a much more complex and heterogeneous network requiring rapid reaction; individual nodes need to react directly to received signals
- **Increasingly physical layer challenges not distinguishable from overall network challenges**

Outline

- *Motivation/challenges*
- **The traditional *versus* distributed physical layer**
- Evolution of radio access networks
- Implementing the multihop distributed PHY
- The role of intelligence
- Conclusions/Further challenges

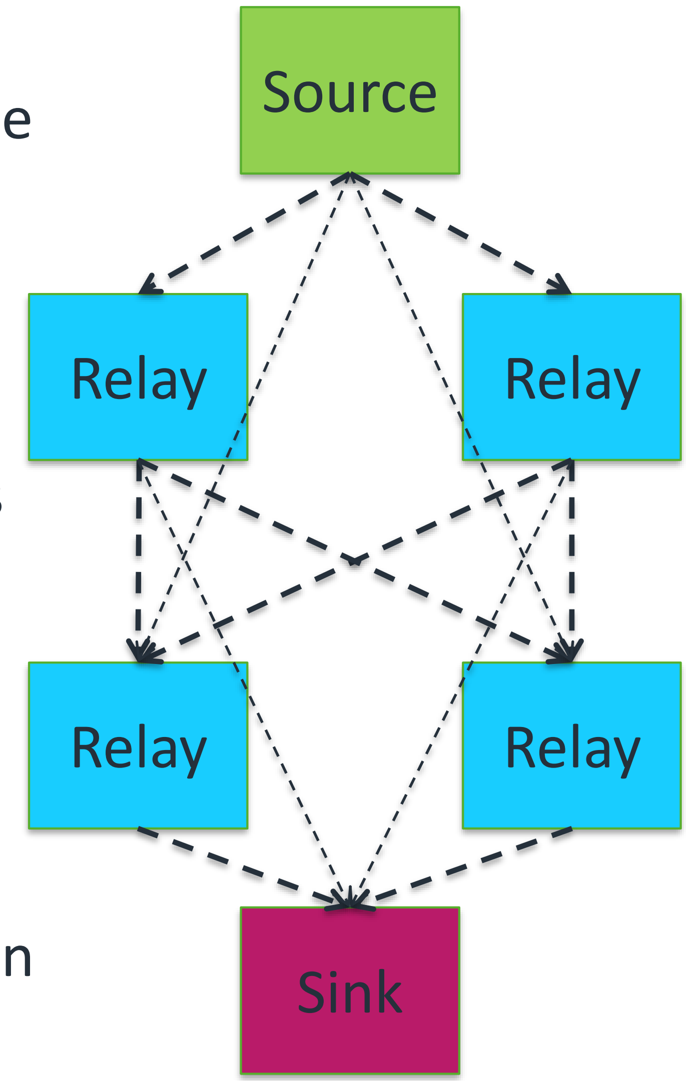
The traditional PHY

- In the traditional ISO model the physical layer is assumed to apply to a single link between the transmitter at one node and the receiver at another
  - signals from any other node are treated as interference
- In wireless systems this assumes that the shared wireless medium is divided into orthogonal timeslots/frequency channels
- Functions such as routing and medium access are carried out at a higher level in the protocol
  - which deals with bit streams rather than signals



The distributed PHY

- This separation is known to be inefficient
  - since information is lost between levels of the protocol
- Also “interfering” paths may also provide alternative routes to transfer information
- The receiver in a **distributed PHY** extracts all relevant information from any signals it receives
  - while the transmitter designs signals to enable optimum processing by any node that may receive it
- Requires PHY of each node to be aware of its place within the network: **network aware**
- Can then route information in distributed fashion through the network



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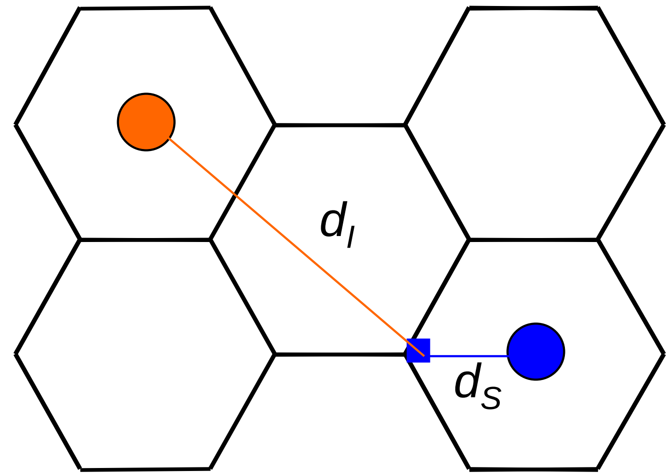
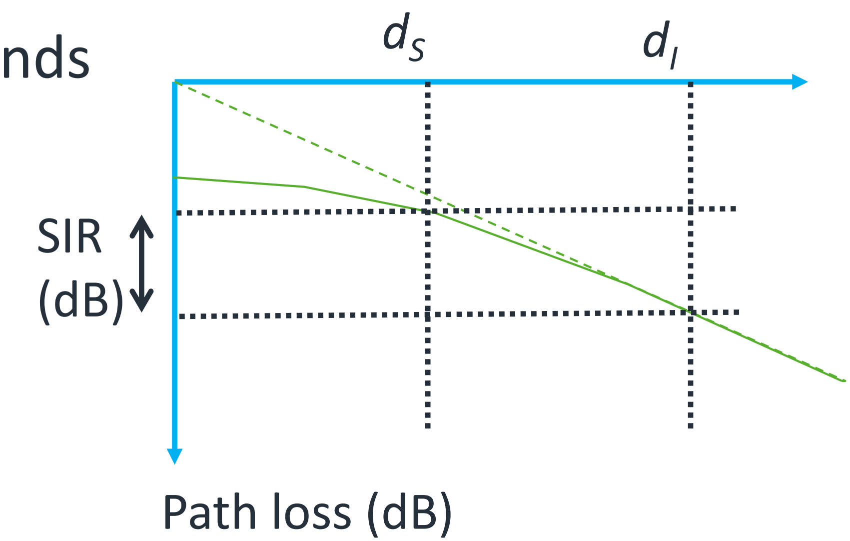
Limits of cellular networks

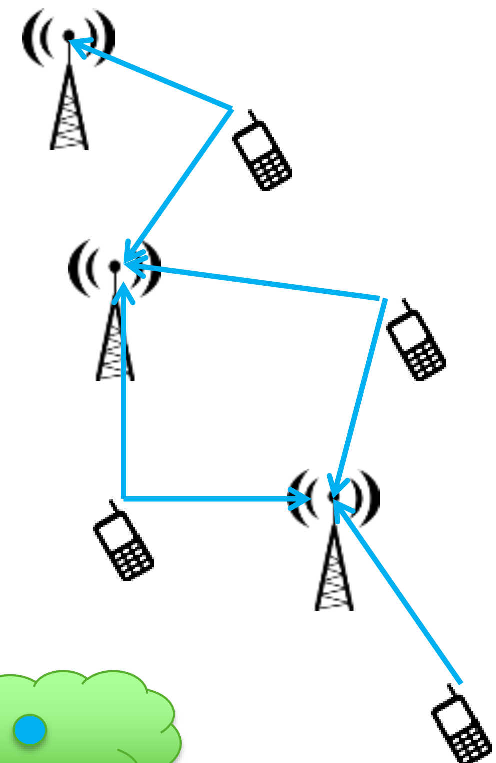
- Cellular networks represent the conventional PHY paradigm
  - avoids interference by physical separation of nodes
  - densification relies on interfering and signal paths scaling in the same way, due to a constant inverse power law
- However at high density the power law tends to flatten out
  - results in greater interference, or reduced spectrum efficiency

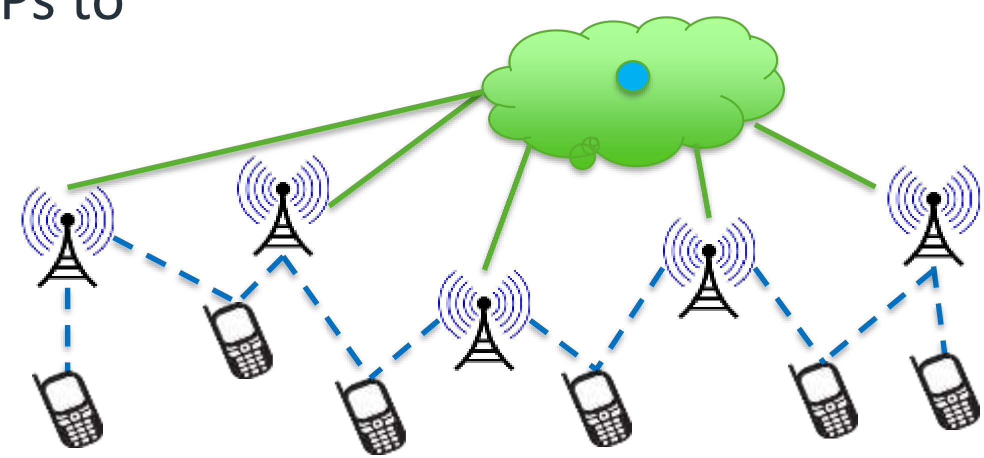




Base station cooperation

- In such networks one user terminal (UT) may be received at multiple BSs (aka access points, AP) with similar power
  - for optimum reception APs should cooperate to decode these signals
  - requires that signals are shared over "**fronthaul**" network
- Can be implemented using "**Cloud-RAN**" (C-RAN)
  - signals are conveyed from APs to "cloud"-based **baseband processing unit** (BBU)
  - where signal processing functions are carried out



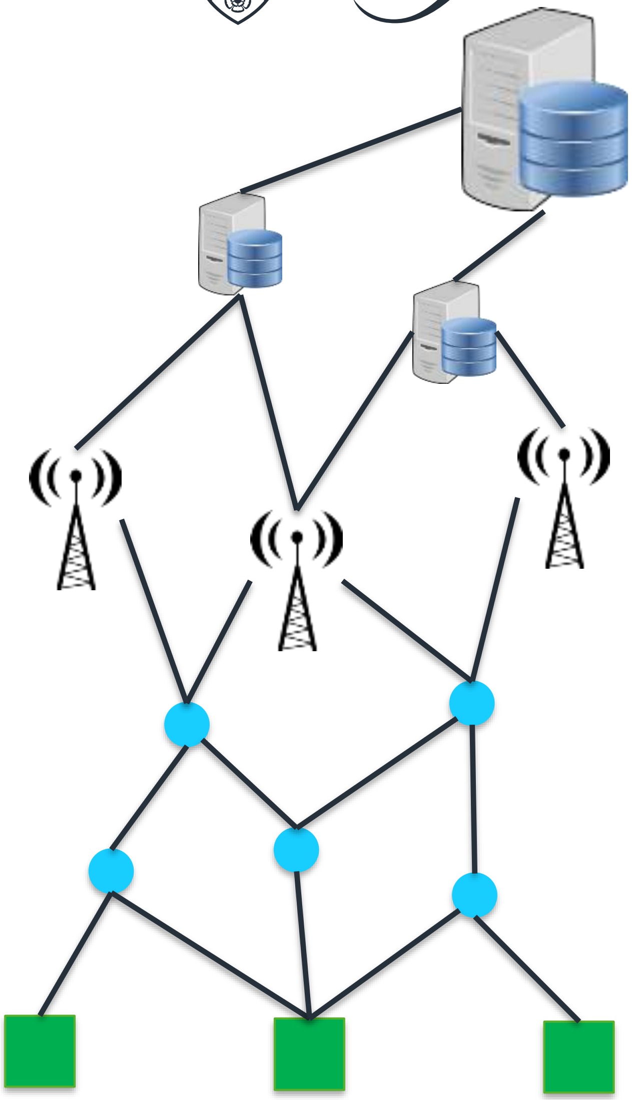


"Fog-RAN"

- Disadvantage of C-RAN is excess latency due to distance between APs and BBU
  - "Fog-RAN" moves processing towards the network edge, nearer APs
  - and splits PHY processing between entities in the network
- Example of "**virtualized RAN**" (vRAN)
  - in which functions of physical BS (including PHY functions) are virtualized within network wherever processing is available

Multihop access network

- C-RAN, "Fog-RAN" already implement principles of the distributed PHY
  - in that the PHY is distributed across multiple nodes within the access network
  - and signals are forwarded within this network
- However for ultra-dense, truly "massive" machine-type communications, relaying on **user side** of network may be required to extend "reach" of access network
  - ultimately this may lead to fully multihop radio access networks in which devices relay **signals** between one another



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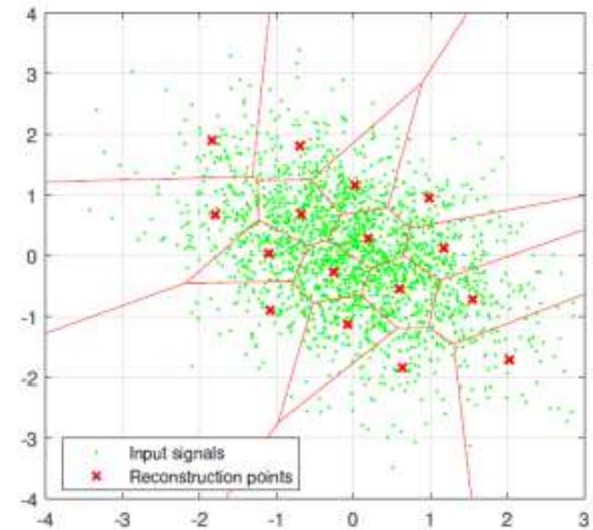
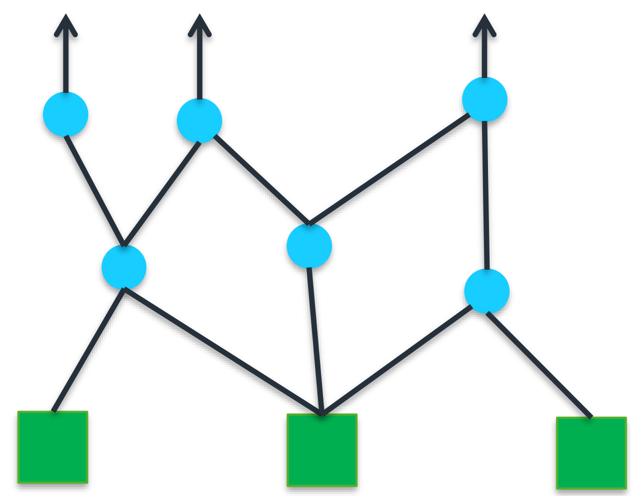
Distributed PHY in practice

- cf C-RAN, in which signals are digitized at APs, and forwarded for central processing
  - requires **quantization** and data compression
  - one possible approach is **lattice quantization**
  - typically the quantized representation requires more data
- However it is not clear that this approach can be directly extended to a multi-hop network
  - since transmission from first layer of relays requires higher rate than user rate
  - and transmission from next layer likely to require higher rate still





"Wireless Cloud" Network

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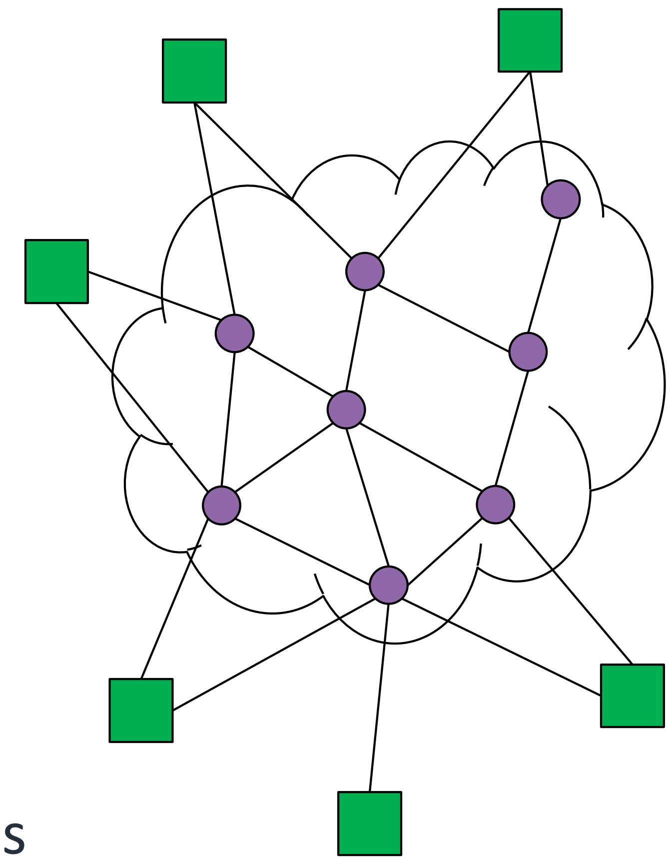
- Project DIWINE proposed the "wireless cloud" network
  - a multihop network in which communication services are provided to end user nodes via a "cloud" of interacting wireless nodes
  - nodes employ **wireless network coding** to forward multiple information streams
- Signal forwarded is based on a combination of coded symbols received
  - one simple example is to forward a symbol based on the XOR of (binary) data symbols, extracted from superimposed received signals
  - but another form – **compute and forward** – uses lattice-based codes



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Organising the distributed PHY

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- We thus have a large, **massively interacting** network of nodes
  - each processing signals in a distributed manner
  - but which need to be coordinated to fulfil overall objectives
- It is not practical to suppose that it is centrally coordinated
  - hence **distributed self-organisation** is required
  - i.e. **distributed machine intelligence**
- E.g. wireless network coding at each node must define **mappings** from received signal to transmitted symbol
  - but the overall result should be that end user can decode data from source nodes
- Another issue (addressed by DIWINE) is **distributed synchronisation**
  - showed that consensus on synchronisation can be reached by **distributed signal processing** methods

Role of ML in PHY

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- There has been some scepticism in PHY research on the value of machine learning
  - because PHY research has focussed on (provably) optimum methods of detection/decoding
- Some experiments in applying ML to known problems (e.g. **auto-encoding**) has derived the conventional result
- Also there are methods (such as **belief propagation** for decoding in LDPC and turbocodes) that already closely resemble ML approaches
- These considerations do not rule out the application of ML
  - especially since many conventional approaches rely on simplifying assumptions
  - **but they suggest that it is important to use what is already known about a problem in designing deep learning networks**

Possible applications of ML

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- **Adaptation to unknown channels**: including non-linear channels; unknown noise/interference; weakly defined waveforms
- **Distributed synchronization and channel estimation**
- **Beam selection** in large scale arrays and massive MIMO
- **Network topology acquisition**: especially where topology may vary due to node movement, channel fading or node failures
- **Learning network code maps**: real scenarios may involve many neighbouring nodes, high order constellations, and unknown channels
- *Many of these apply to large scale, massively interacting networks which cannot readily be centrally controlled*
  - *hence involve the interaction of many autonomous intelligent nodes*

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Further PHY challenges

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- Many other challenges for PHY in 5G and beyond
- **Low latency** requires short frames: what are the optimum codes, especially if high reliability is required?
- **New waveforms**, e.g. for improved spectral confinement, or constant amplitude
- **mm-wave, THz and VLC**: directional structure of channel raises opportunities and challenges; technology also challenging
- **Ultra-low-power and low complexity**: e.g. networks in which nodes rely on energy scavenging or must be very long-lived
- **New technologies**, e.g. spiking neural networks, molecular communications
- **etc…**

Conclusions

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- Plenty more to do!
  - especially to understand the behaviour of a physical layer distributed over a network
  - to implement distributed signal processing techniques required
  - including distributed machine intelligence required for coordination
  - many technological challenges remain…

Physical layer research is not dead!