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Physical Layer Network Coding for 4G and beyond

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Outline

- The challenge of next generation wireless networks
- Multi-user and Network MIMO
- Physical Layer Network Coding
- Visiting Fellowship programme
- Collaborations

The dream

- To provide full Internet connectivity to **everyone**, **anywhere**
  - which means wirelessly
- In densely-populated cities a network for everyone must provide extremely high ***capacity densities***
  - more important than “headline rate”

Required capacity density

- Average population density in European cities ranges from 3400 - 5400/km^2
  - however in commercial district in working hours it will be much higher
  - say 8000/km^2
- Suppose 10% subscribe, and 20% of those require access at busy hour
- Expected data rate 5 Mbit/s

8000/km^2 $\times$ 10% $\times$ 20% $\times$ 5 Mbit/s = 800 Mbit/s/km^2

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Current and 4G systems

- Currently one base station serves about $1km^2$
  - 4G bandwidths proposed are ~ 40 MHz
  - Best available *bandwidth efficiency* averages about 2 bits/s/Hz across cell
  - hence capacity density is 80 $Mbit/s/km^2$
  - assumes 100% frequency re-use
- We need an order of magnitude more!
- 10$\times$ more bandwidth unlikely to be available

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Wireless backhaul

- To meet capacity density requirements will probably require a combination of
  - Increased spectrum
  - Advanced MIMO techniques
  - Increased frequency reuse
  - **Increased BS density**
- Simple comparison with 4G proposals suggests we may need ~**10 BSs per km^2**!
- We believe that the only cost-effective way to provide this is by **wireless backhaul**
- However must allow for spectrum used by backhaul links

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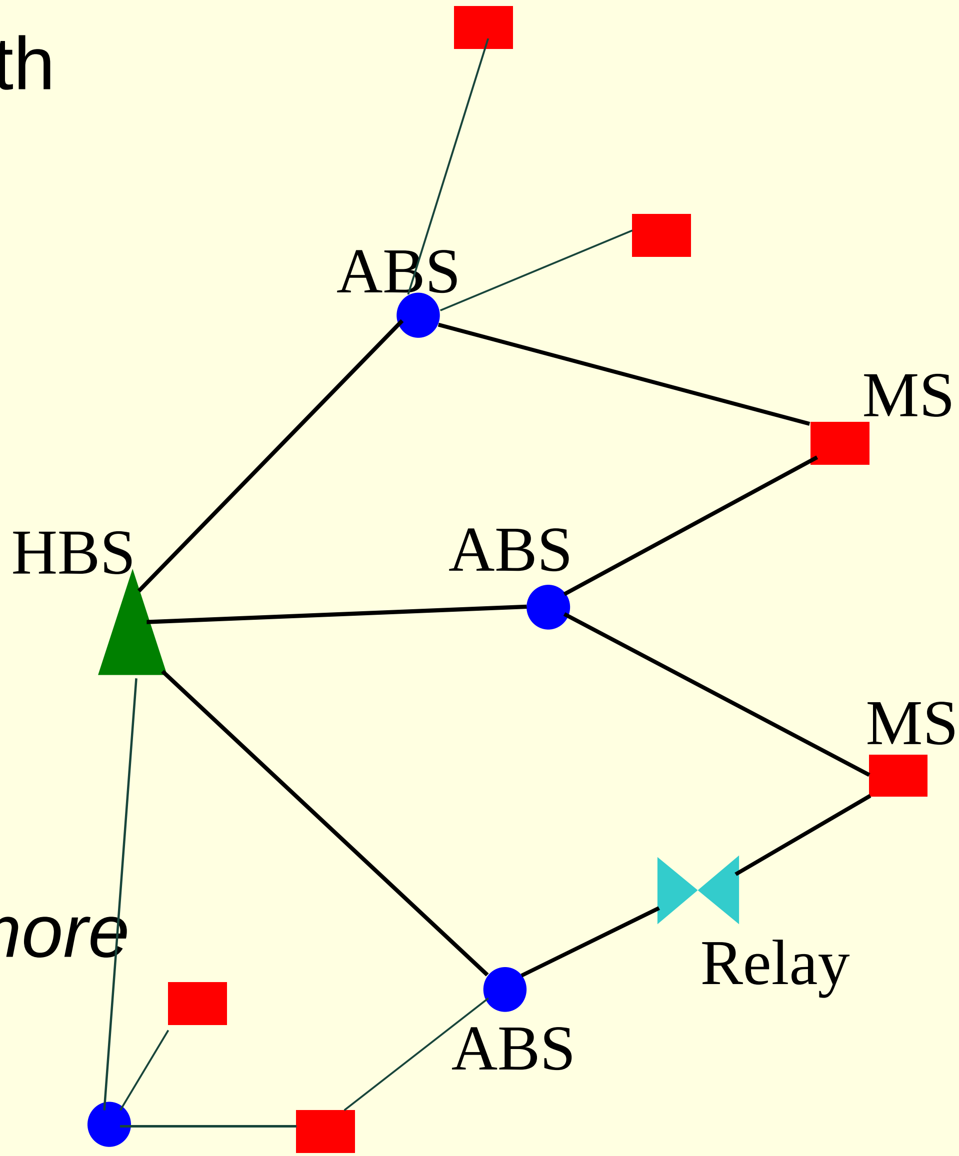
Possible architecture

- Hierarchical network with large Hub Base Station (HBS)
  - serving many small (cheap) Access Base Stations (ABS)
- Density means that mobiles (MS) can be served by two or more ABSs
- *Overall network looks more like a wireless mesh network*



Some figures

- Assume HBS serves 1 km^2
- Assume total 40 MHz available
  - 20 MHz for MS-ABS (access links);
  - 20 MHz ABS-HBS (backhaul)
- Assume average 2 bits/s/Hz across cell
- Then capacity per ABS = 20×2 = 40 Mbit/s
- No. ABS per HBS = 1 Gbit/s / 40 Mbit/s = 25
- Area served by ABS = 1 km^2/25 = 40 000 m^2, or 200m square

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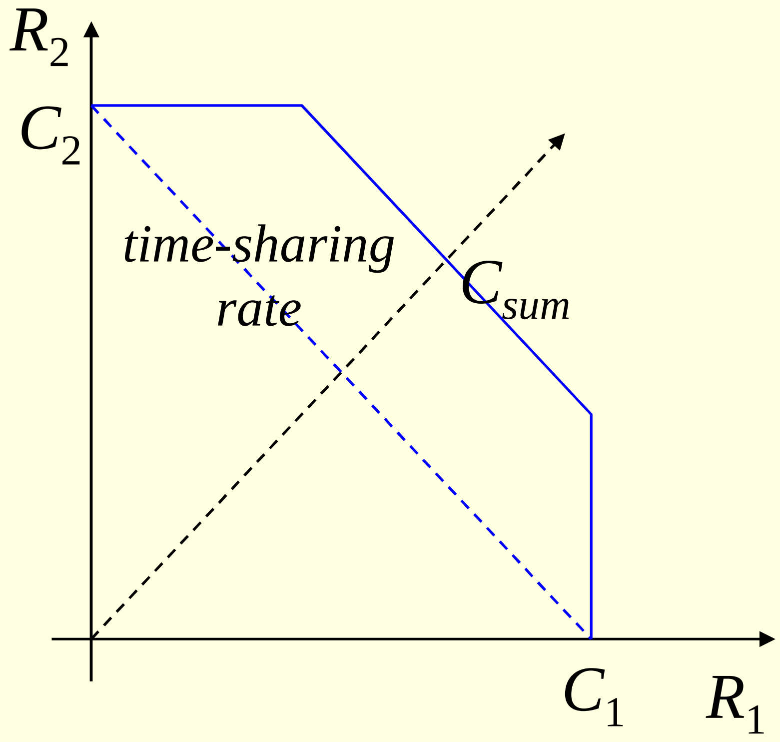
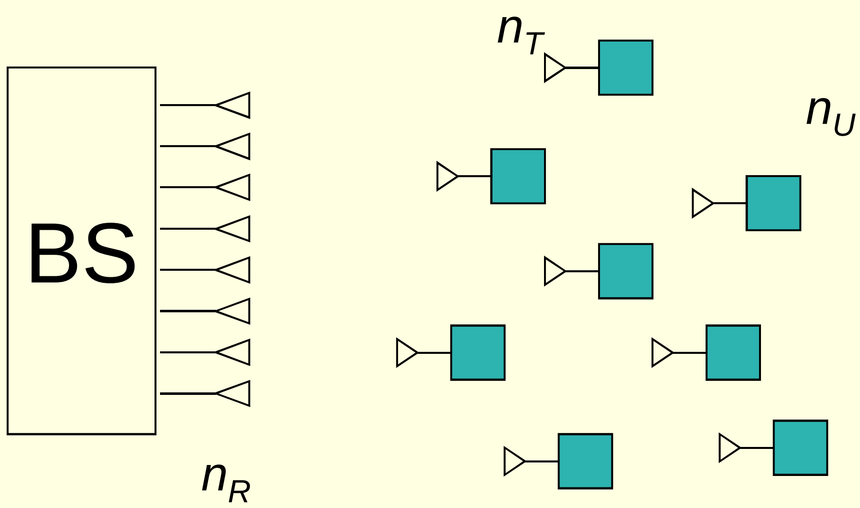
Information theoretic approach

- Optimum channel sharing involves **simultaneous transmission** by multiple users
  - as opposed to TDMA/FDMA ("time-sharing")
- Can define a ***capacity region***
  - a set of possible rates for each users
- Time-sharing is sub-optimal
- Capacity region achieved through
  - interference cancellation (uplink)
  - linear/non-linear precoding (downlink)

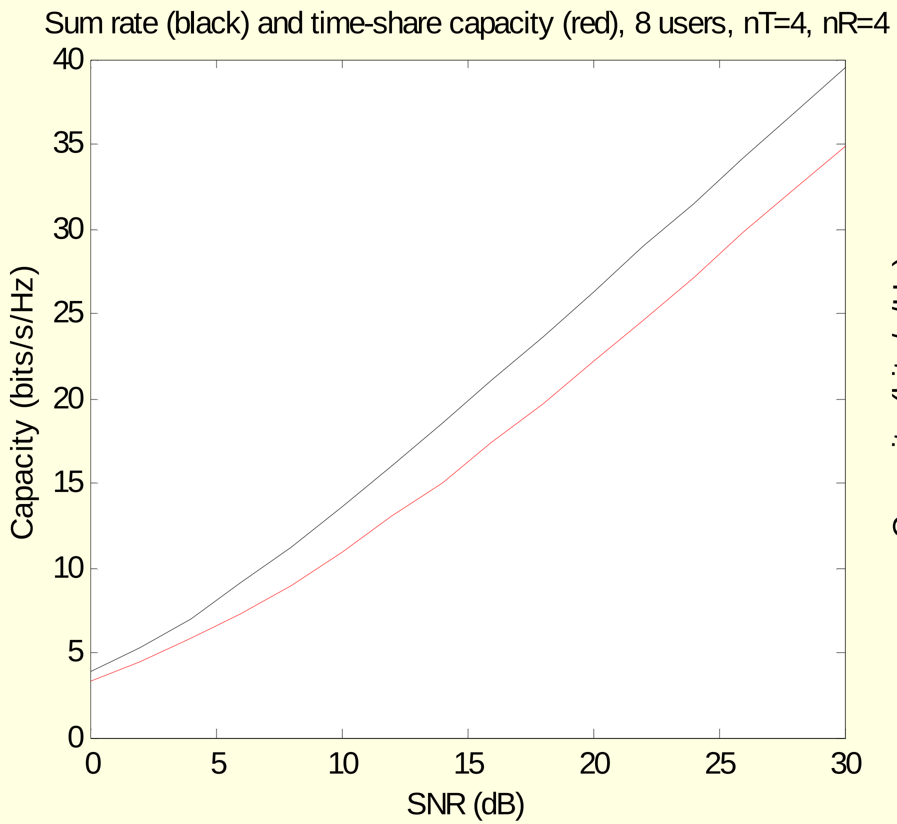


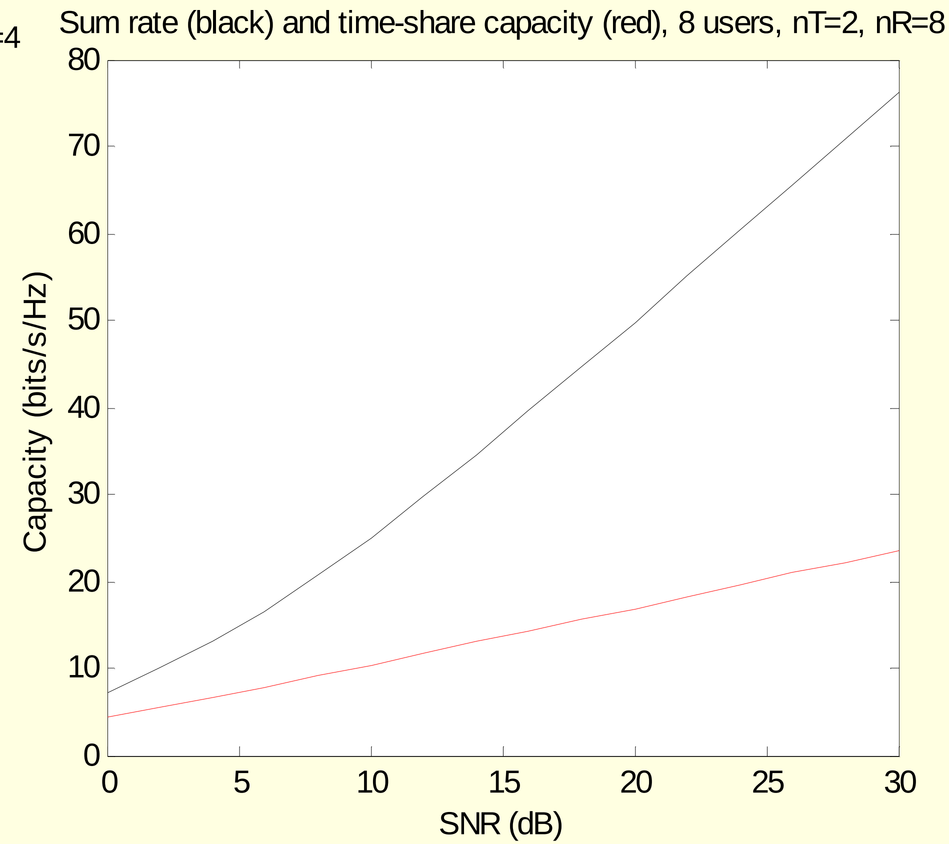
Multi-user MIMO

- Conventional TDMA/FDMA is equivalent to time-sharing
  - divides "headline" rate by no. of channels
- MU-MIMO allows several users to share same time slot/channel
- Users/BS can act as a single $n_T n_U \times n_R$ MIMO system
- Usually more BS than terminal antennas
  - multiplexing gain no longer limited by no. terminal antennas



Symmetric and asymmetric

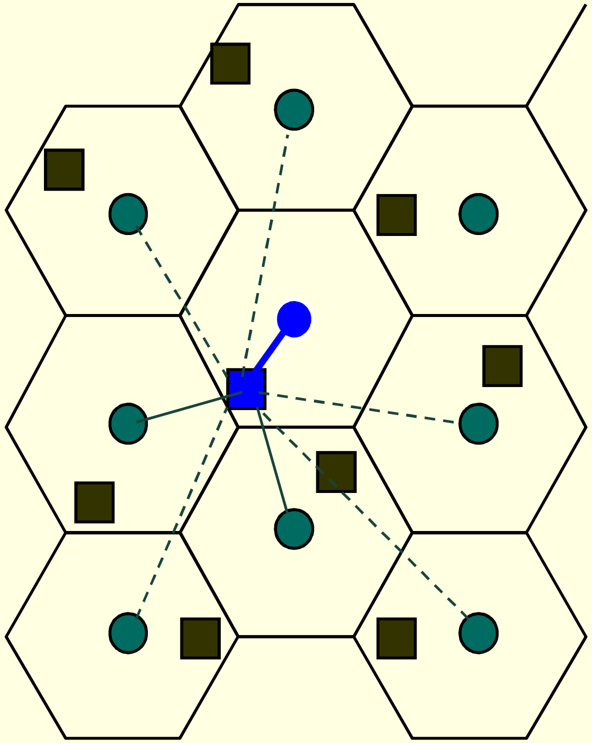




- Modest advantage when $n_T = n_R$ (symmetric links)
- Large advantage when $n_T \leq n_R$ (asymmetric links)
  - max. multiplexing gain becomes min(n_R, $n_T \times n_U$)

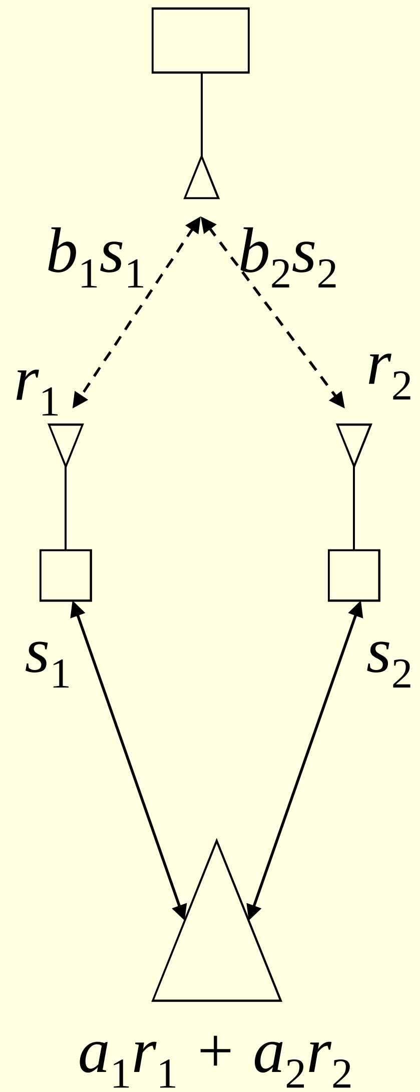
Network MIMO

- Allow multiple base stations to cooperate to transmit to a given mobile
  - or to receive from that mobile
- Then there is in principle no CCI!
  - since all received signals are exploited as signals
- The entire system then operates as a multi-user MIMO system with $n_T \times n_U \times n_C$ transmit and $n_R \times n_C$ receive antennas
  - where n_C is the number of cooperating cells
  - in principle multiplexing gain approaches $\min(n_R \times n_C,\ n_T \times n_U \times n_C)$



Backhaul capacity requirements

- On the downlink, if two BSs cooperate to communicate with an MS, that MS's data should be sent to both
  - could double backhaul requirements
- On the uplink, neither may be able to decode the MS without the signal from the other
  - hence analogue signal may need to be transmitted over the backhaul in high precision
  - may increase backhaul requirements by several times
- Need to ensure backhaul links are efficiently used



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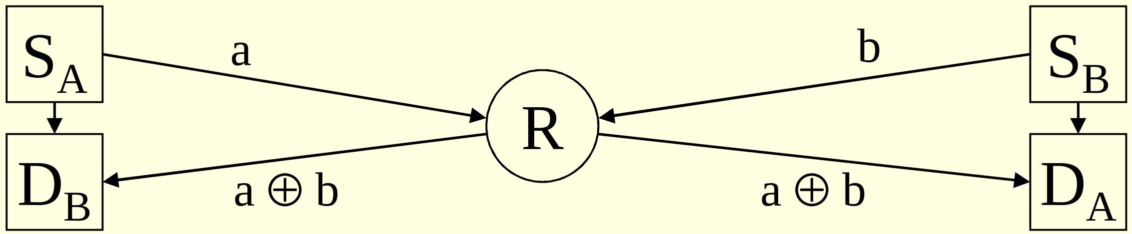
Network Coding: the 2WRC

- A network node applies a joint coding function to two (or more) incoming data streams

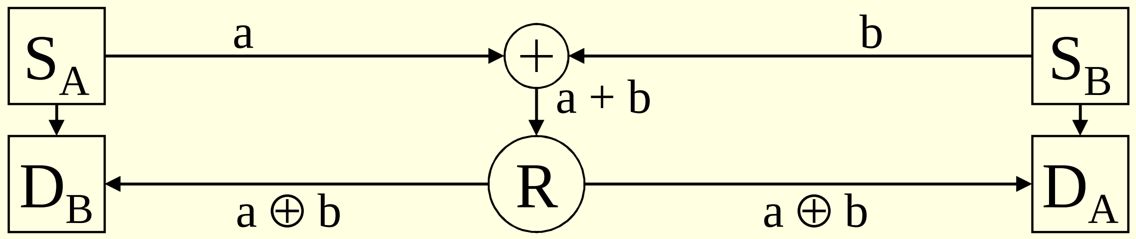


- Simple example: the two-way relay channel (2WRC)
  - allows a relay to support transmissions in two directions at once
- Relay broadcasts XOR combination of two incoming streams
- Each destination can then reconstruct data intended for it by XOR combination with the data it transmitted

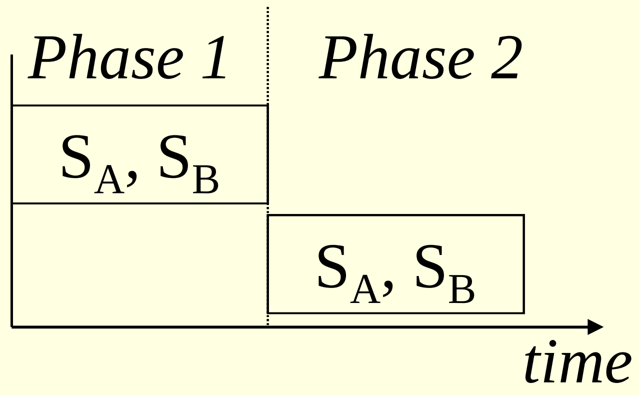
Physical layer network coding (PLNC)

- In a wireless network, we do not have discrete, non-interfering paths
  - except by using TDMA or FDMA
- Signals:
  - are broadcast to all nodes within range
  - combine additively in signal space
- However it is still possible to extract a joint information stream equivalent to XOR combination

PLNC for 2WRC

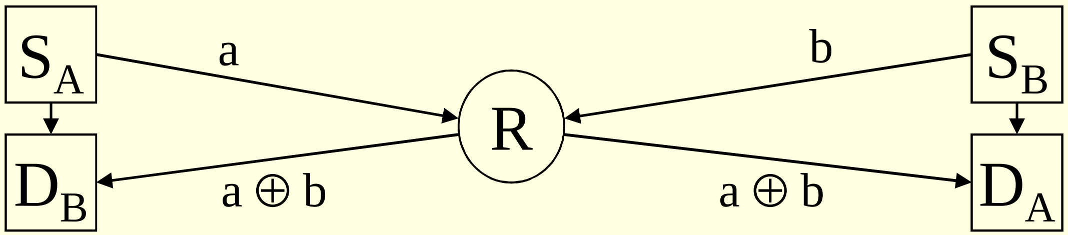


- System operates in two phases
  - Phase 1: sources transmit simultaneously
  - Phase 2: relay transmits
- Assume both sources transmit BPSK
  - {+1, -1} ⇔ {1, 0}

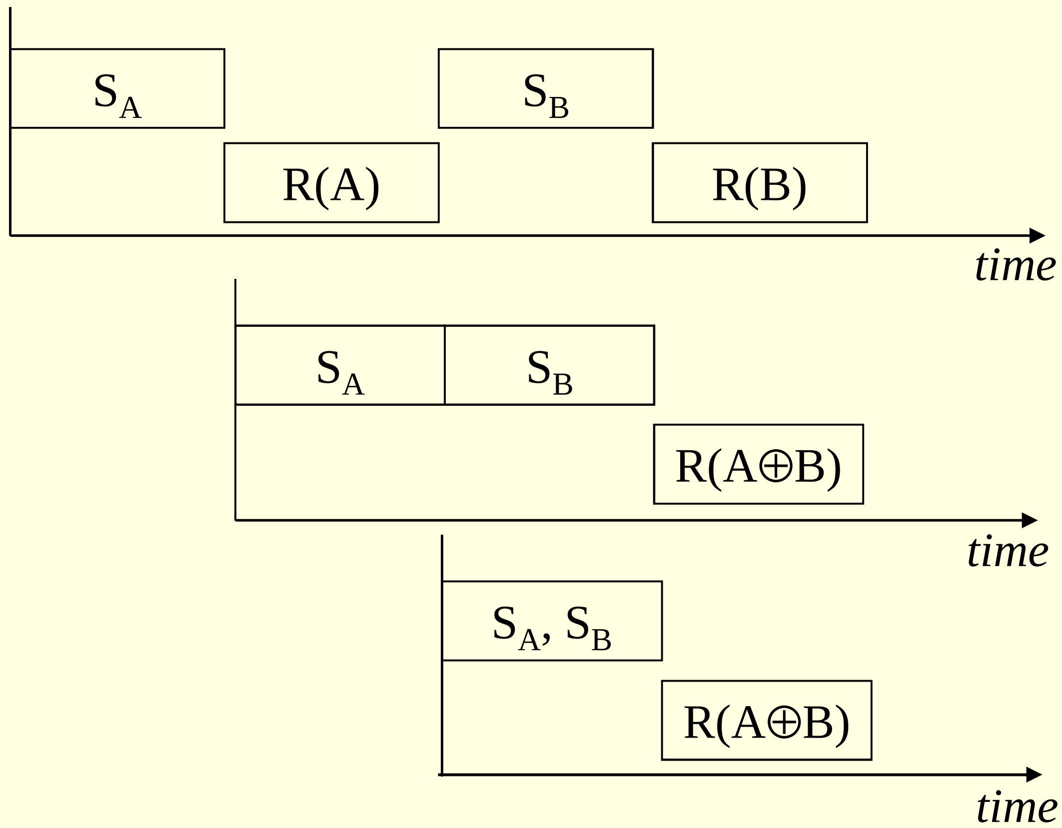


a	b	a+b	$a \oplus b$
0	0	-2	0
0	1	0	1
1	0	0	1
1	1	+2	0

For comparison



- Without network coding
- Network layer network coding
- Physical layer network coding



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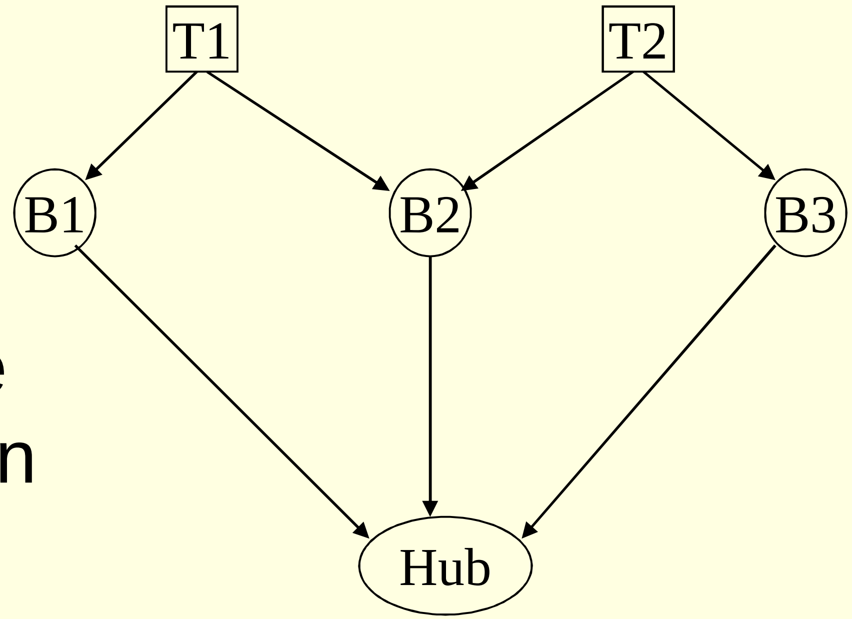
PLNC in network MIMO



- Example:
  - 2 terminals connected to hub via 3 BS
- B2 can use PLNC, to share its link with the hub between two terminals
- It can use distributed compression via *Slepian-Wolf coding*,
  - exploiting correlation of the data with B1 and B3
- Reduces backhaul load

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Objectives

- **To identify candidate scenarios for analysis**
  - **including simplified topologies relevant to next generation networks with wireless backhaul**
- **To identify information theoretic results relevant to those scenarios**
- **Hence dimension the potential gains available, in terms of user capacity *versus* cost**
- **To identify and begin development of practical schemes to approach these gains**

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Programme for exchange visit(s)

- Seminars to exchange expertise and prior work on both sides
- Discussions to identify candidate scenarios for the application of PLNC in 4G networks
- Identify relevant information theoretic results
- Apply results obtained to scenarios identified, to estimate gains available from use of PLNC
- Discuss possible practical methods to implement PLNC in these cases
- Plan future work in both institutions, including:
  - papers to be published,
  - funding to be sought,
  - follow-up exchange visits

Personnel involved

- University of York
  - Prof. Alister Burr
  - Dr Agisilaos Papadogiannis
- Shanghai Jiao Tong University
  - Prof. Meixia Tao

Collaborations

- FP7 Project BuNGee (Beyond Next Generation mobile broadband)
  - coordinated by Alvarion
- Prof. Tadashi Matsumoto, JAIST Kanazawa/CWC Oulu
- Prof. Jan Sykora, Czech Technical University in Prague
- EPSRC project on “Delay Tolerant Distributed Space Time Block Coding”
  - Prof. Fuchun Zheng, University of Reading
  - Dr Mike Fitch, BT Labs