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Physical layer network coding for 4G and beyond

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Outline

- The challenge of next generation wireless networks
- Next generation architectures
- Physical layer network coding
- Two-way relaying in hierarchical networks
- Conclusions

The dream

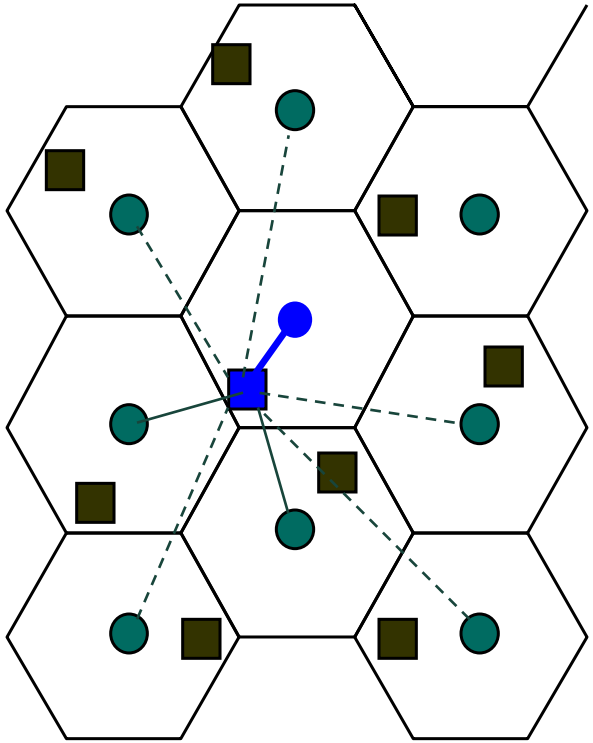
- To provide full Internet connectivity to **everyone**, **anywhere**
  - which means wirelessly
- Next generation wireless research has usually focussed on a ‘headline’ maximum data rate
  - but this will not be the rate most users experience, and probably is not the most important figure
  - In densely-populated cities a network for everyone must provide extremely high ***capacity densities***
- Various estimates of required capacity densities:
  - 1 Gbps/km^2, 10 Gbps/km^2, 25 Gbps/km^2…

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 1-2 orders of magnitude more!
  - 100$\times$ more bandwidth unlikely to be available
  - It is conjectured that Shannon bounds on link bandwidth efficiency are already close, but…

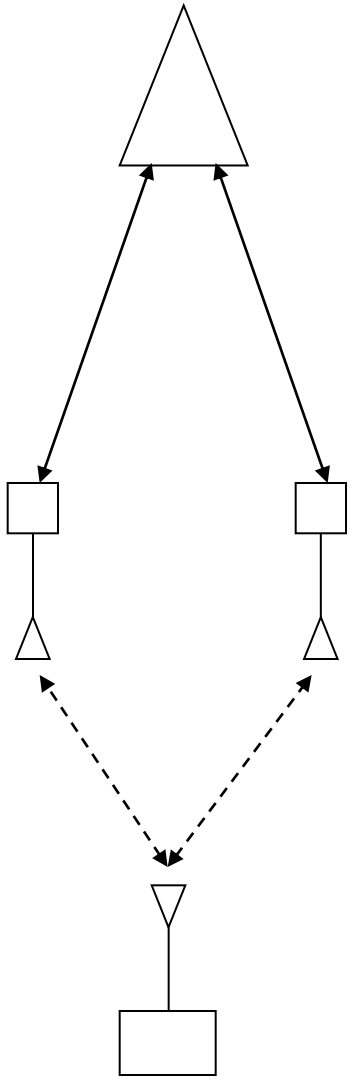
Network MIMO

- The major limiting factor for spectral efficiency is ***interference***
  - especially at cell edges
- A solution in principle is ***network MIMO***
- All BS antennas in all cells collaborate to serve all users
- The entire system then operates as a multi-user MIMO system with (on the downlink) $n_T \times n_C$ transmit and $n_R \times n_U \times n_C$ receive antennas
  - where n_C: no. of cooperating cells
    n_T: no. of TX antennas at BS
    n_R: no. of RX antennas at mobile
    n_U: no. of users
- In principle multiplexing gain approaches $\min(n_T \times n_C, n_R \times n_U \times n_C)$
- Interference is eliminated, since all signals are useful



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
- In addition accurate CSI required at all BSs



Achieving capacity density

- Will probably need a combination of:
  - More spectrum
  - Network MIMO for improved bandwidth efficiency
  - **Increased BS density**
    - requires **low base station installation cost**,
    - and a **cost-effective *backhaul* network**
    - which also can support backhaul demands of network MIMO

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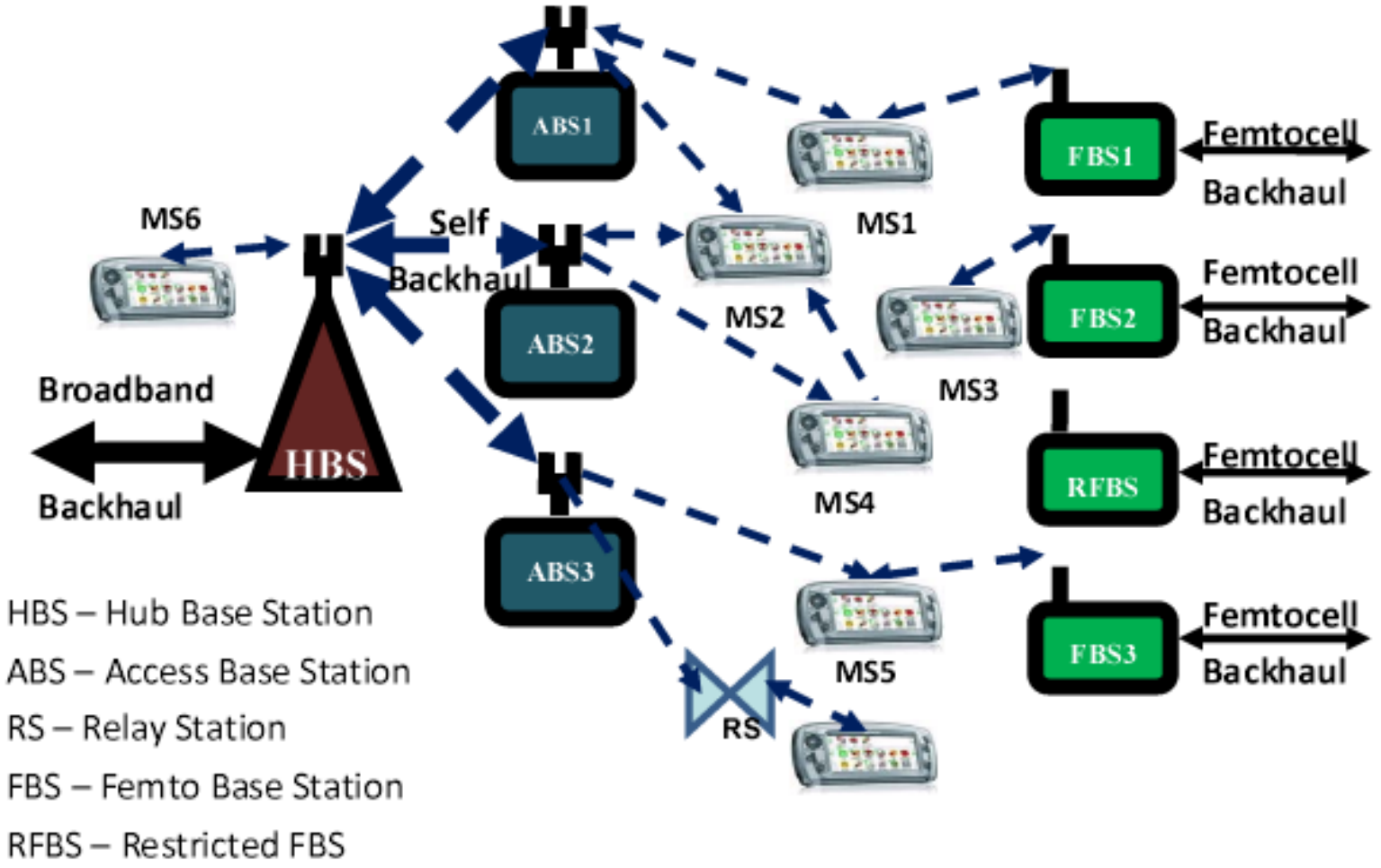
Wireless backhaul

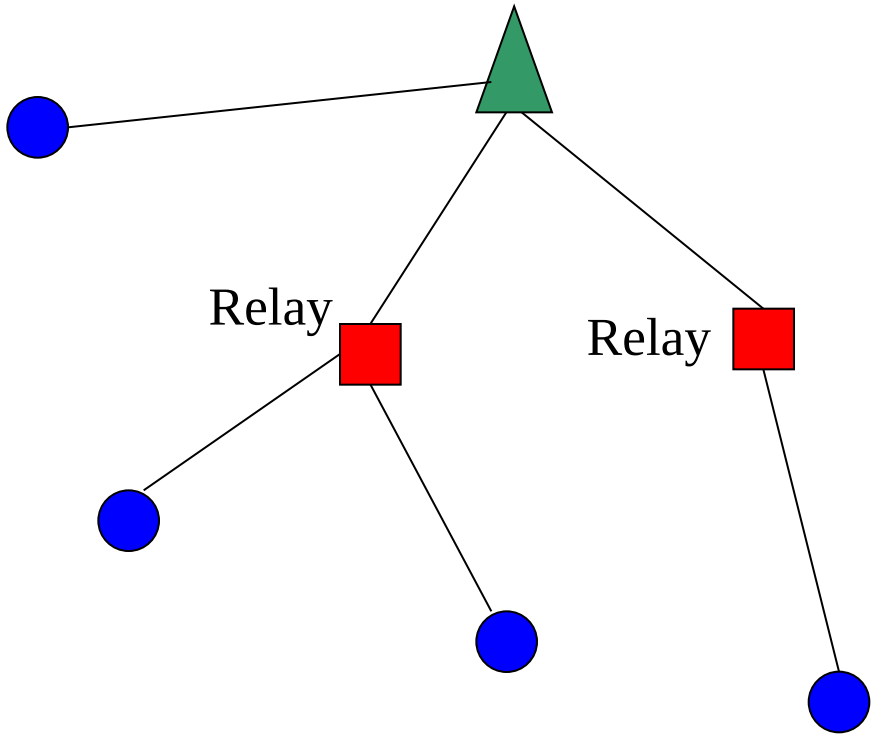
- Simple comparison with 4G proposals suggests we may need >10 BSs per km^2!
- We believe that the only cost-effective way to provide this must at least involve wireless backhaul
- However must allow for spectrum used by backhaul links
- Hence must minimise backhaul load
  - and network MIMO will tend to increase it significantly

BuNGee architecture



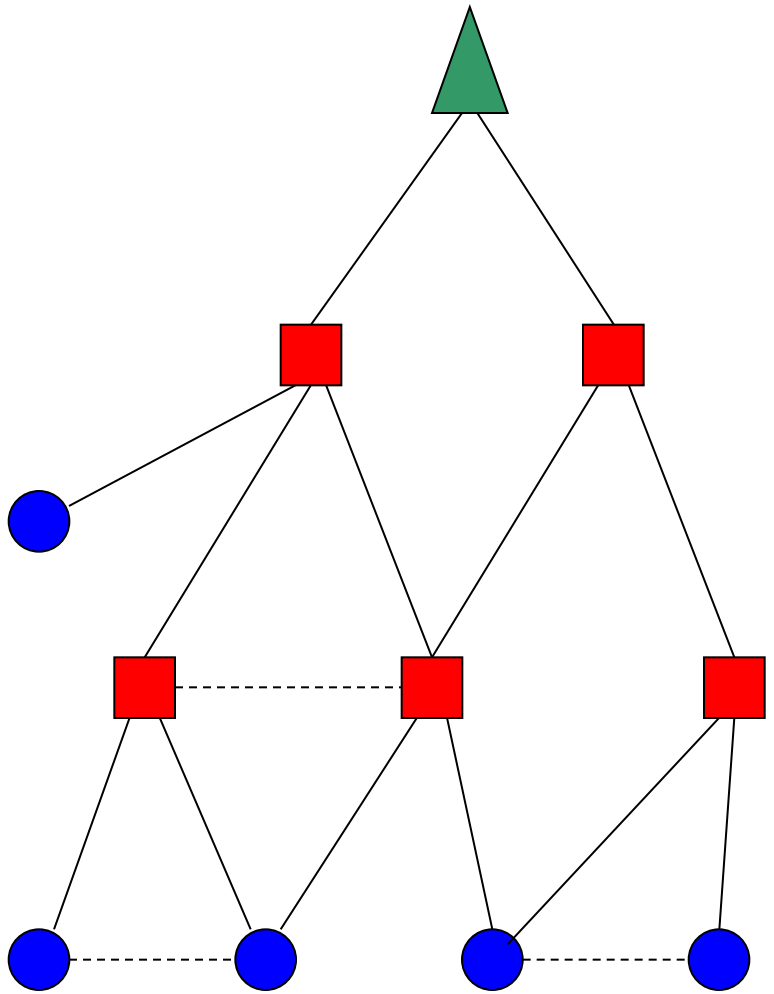
Wireless relaying

- Alternatively cell can be extended by adding fixed, or *infrastructure* relays
  - very similar architecture to wireless backhaul
  - with relays replacing ABSs
  - may allow direct connection of MSs to hub



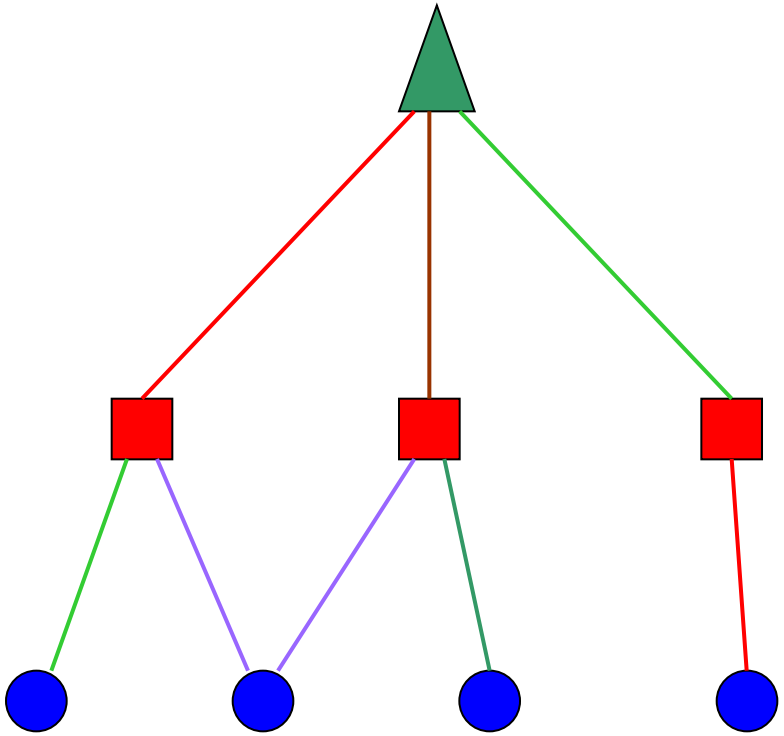
Hierarchical wireless network

- A generalised framework for network architectures involving wireless backhaul and/or relaying
- we might allow:
  - more than one layer of relays
  - direct connections between nodes on the same level
  - MSs to connect to different relay levels
- Similar to mesh network in structure



Limitations of in-band backhauling

- If we use wireless backhaul, we must account for bandwidth occupied
- Can we re-use the same spectrum in backhaul and access segments?
  - *in-band backhauling*
- Duplexing restrictions of ABSs usually prevent same resources being used in the two segments in the same place



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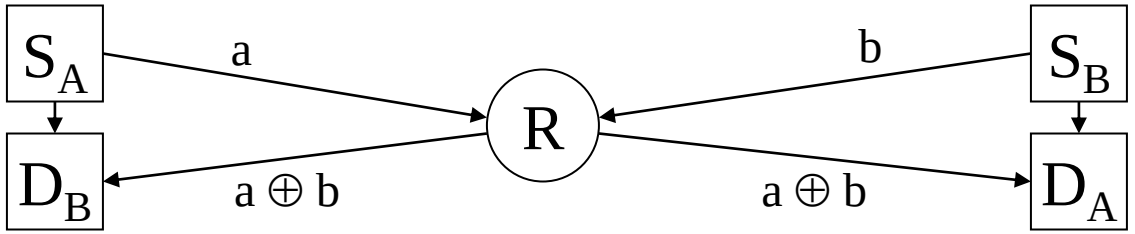
Network coding

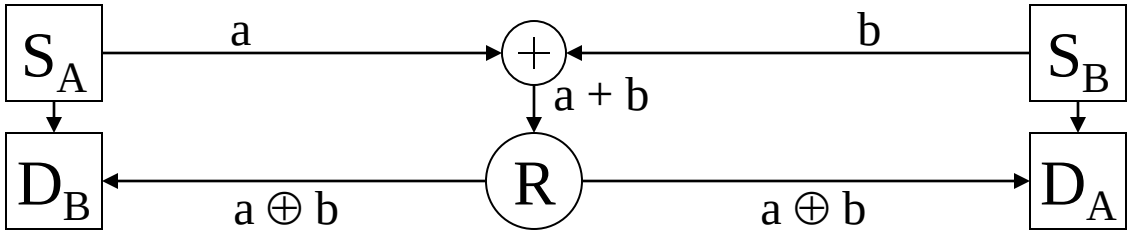
- A network node applies a joint coding function to two (or more) incoming data streams
  - instead of simply switching between them
- Simplest application – the two way relay channel (TWRC)
  - allows a relay to support transmissions in two directions at once
  - Relay sneds XOR combination of two incoming streams to both destinations
  - Each destination can then reconstruct data intended for it by XOR combination with the data it transmitted



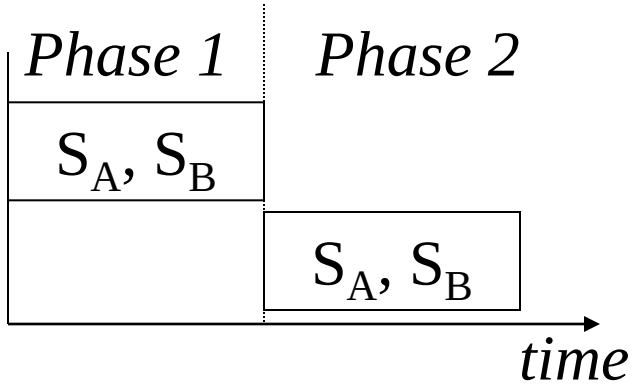
Physical layer network coding (PLNC)

- 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

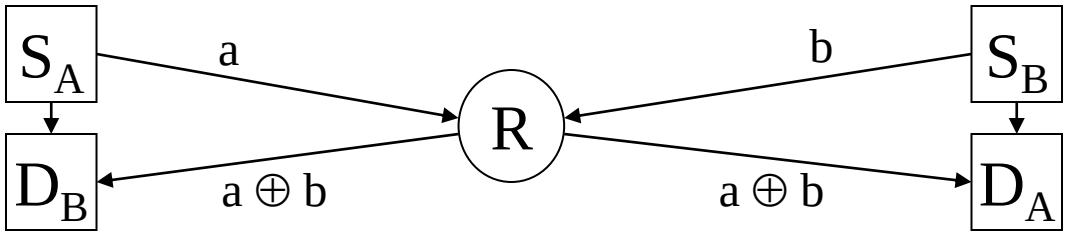


- System operates in two phases
  - Phase 1: sources transmit simultaneously
  - Phase 2: relay transmits
- Assume both sources transmit BPSK
  - {+1, -1} ⇔ {1, 0}

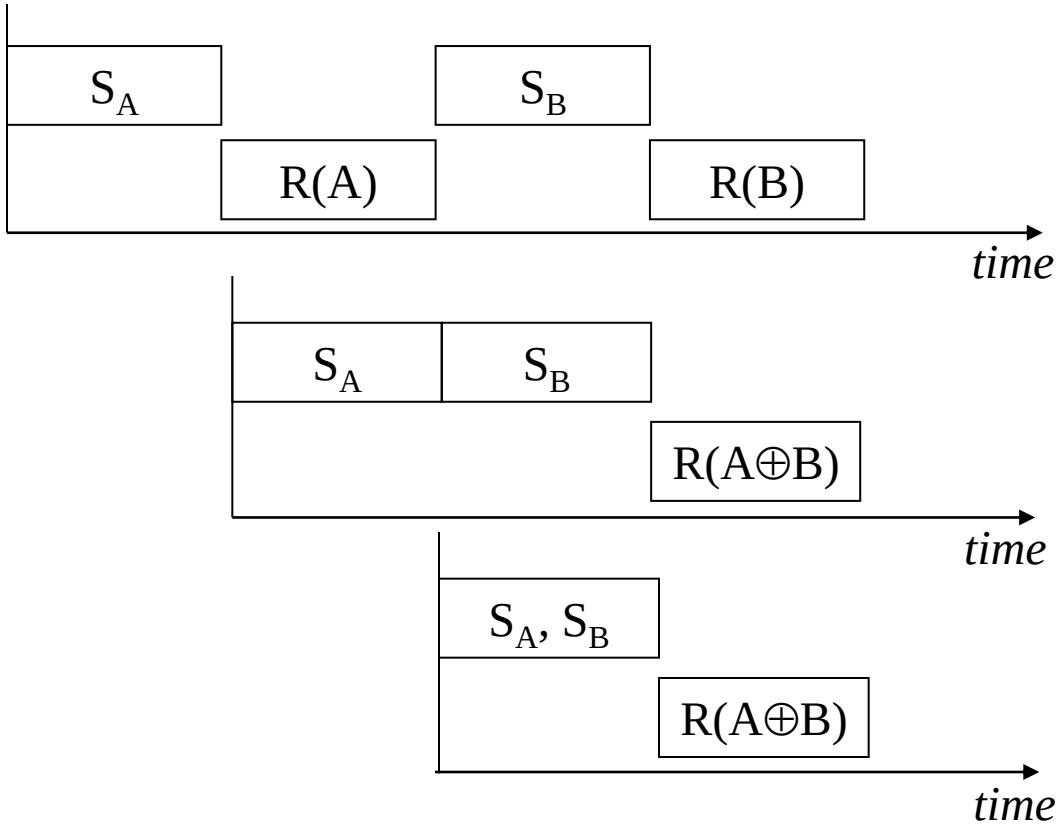


a	b	a+b	a ⊕ b
0	0	-2	0
0	1	0	1
1	0	0	1
1	1	+2	0

For comparison



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



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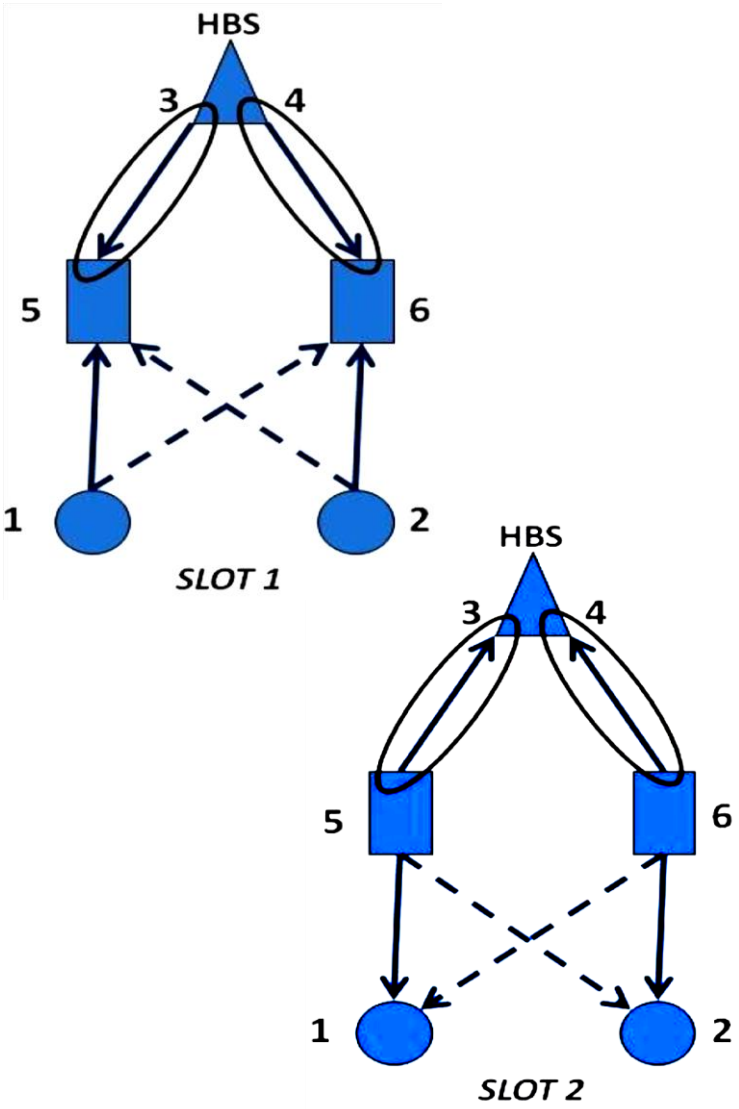
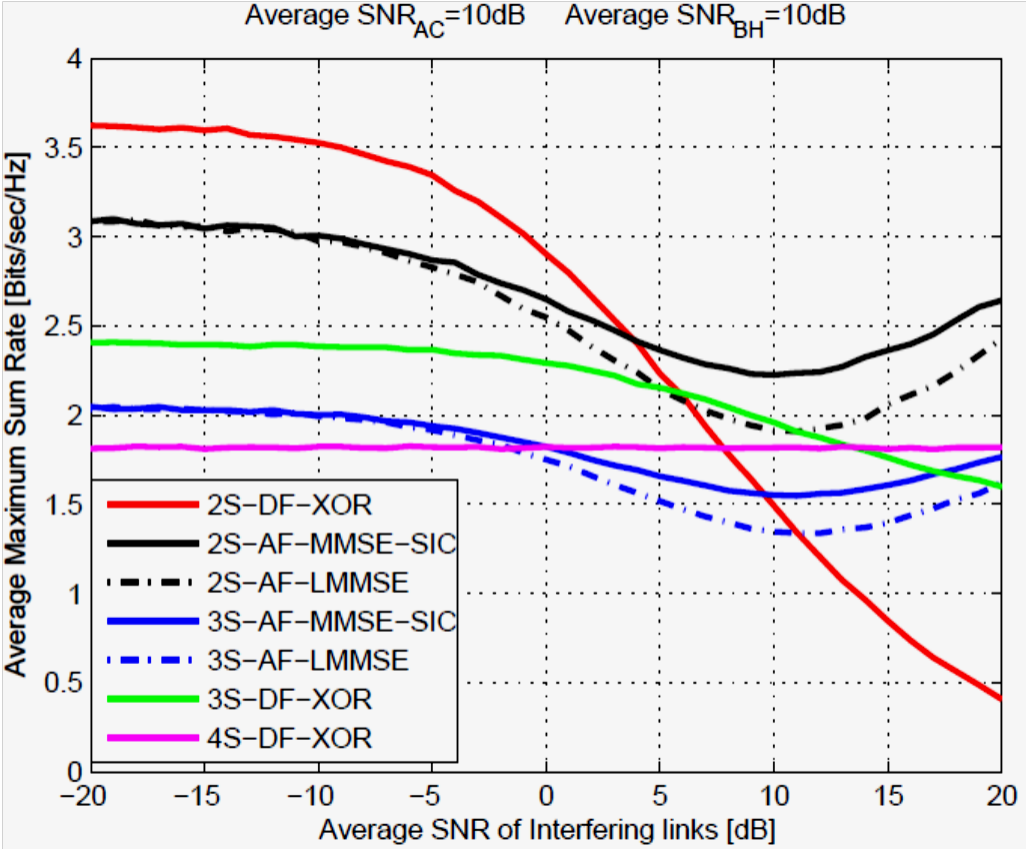
Two-way relaying in hierarchical wireless network

- Duplexing constraints can be alleviated using 2-way relaying
  - allows access and backhaul resource to be shared at each RBS
  - however neighbouring RBSs and corresponding MSs may interfere
- We have analysed this considering a simple scenario
- Assume 2 RBSs share resources over 2 slots
  - i.e. both RBSs and MSs transmit simultaneously on same channel
  - consider amplify-and-forward and network coded decode-and-forward relaying



Capacity results

- Plot resulting capacity against strength of interfering links
  - for small interference DF is better
  - for large interference AF capacity increases again
  - both MSs can exploit both ABSs
    - exploits a form of network MIMO
  - Generally 2 slots are better than three or four



Conclusions (1)

- Next generation wireless networks will be required to handle much larger *capacity densities*
- MIMO techniques can greatly increase link capacity
  - but still seriously affected by interference in cellular networks
- **Multi-user MIMO** can greatly increase capacities
  - especially for asymmetric systems
- **Network MIMO** can further increase capacity
  - and also largely eliminate interference
  - however increases backhaul load

Conclusions (2)

- **Physical Layer Network Coding** can better exploit backhaul capacity
  - by allowing backhaul links to be shared
  - by exploiting correlation of signals travelling by different routes
  - by overcoming duplexing constraints on spectrum sharing
- All these techniques will be essential elements of next generation networks!