QUALCOMM CDMA TECHNOLOGIES

MIMO in (4G) cellular systems

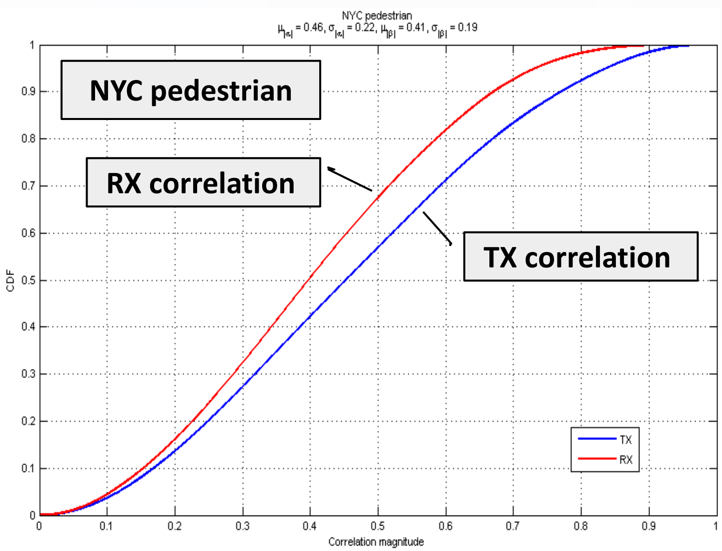
August 2014

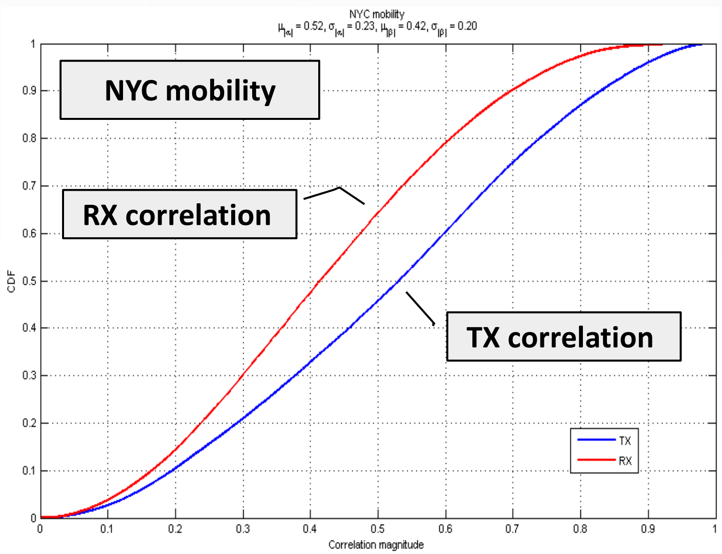
Outline

- MIMO in cellular: myths & truths
- MIMO techniques across 3GPP releases
- MIMO receivers: design & performance considerations
- Antenna management techniques
- Recent developments
- Lessons learned

MIMO in cellular: myths & truths (1/2)

- **Myth**: high antenna correlation precludes efficient MIMO
  - insufficient scattering in cellular environment
  - high correlation / low efficiency / blocking on user device form factor
- **Truth**: smartphone antennas allow for low correlation across bands
  - 4RX layout on a smartphone: corr ≈**0.2** / ≈**0.6** in high / low bands
    - 700MHz (top), 800-900MHz (bottom), 1.7-6GHz (both)

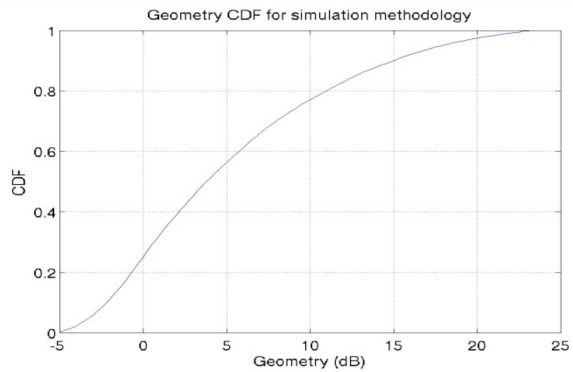




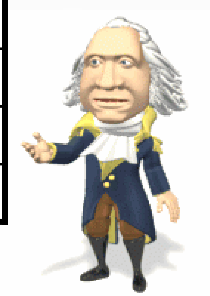
- **Truth**: signal strength well above thermal
  - >20dB in dense urban, >10dB (sub-)urban ≈90%

MIMO in cellular: myths & truths (2/2)

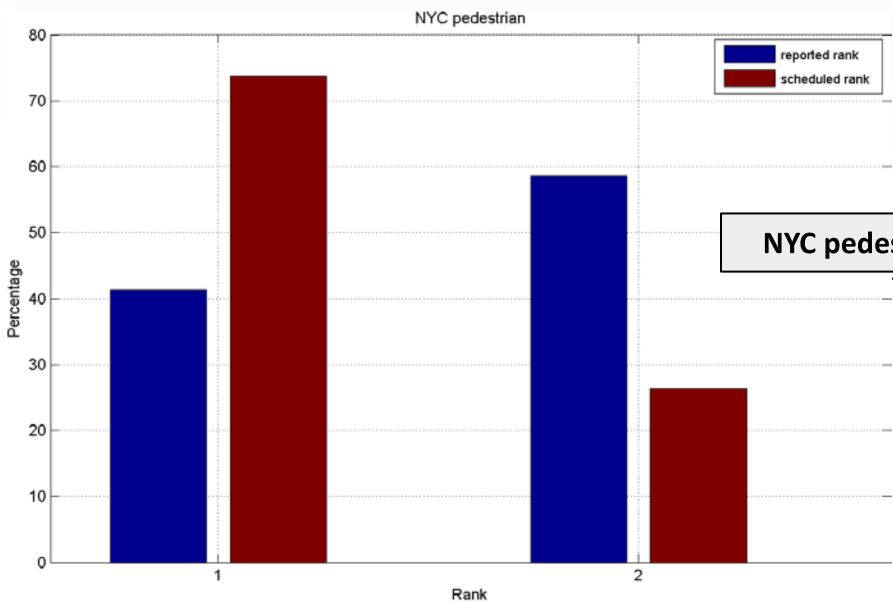
- **Myth:** operating CINRs too low to enable system level MIMO gains
  - 30% UEs below **0dB**, 60% UEs below **5dB**, 90% UEs below **20dB**

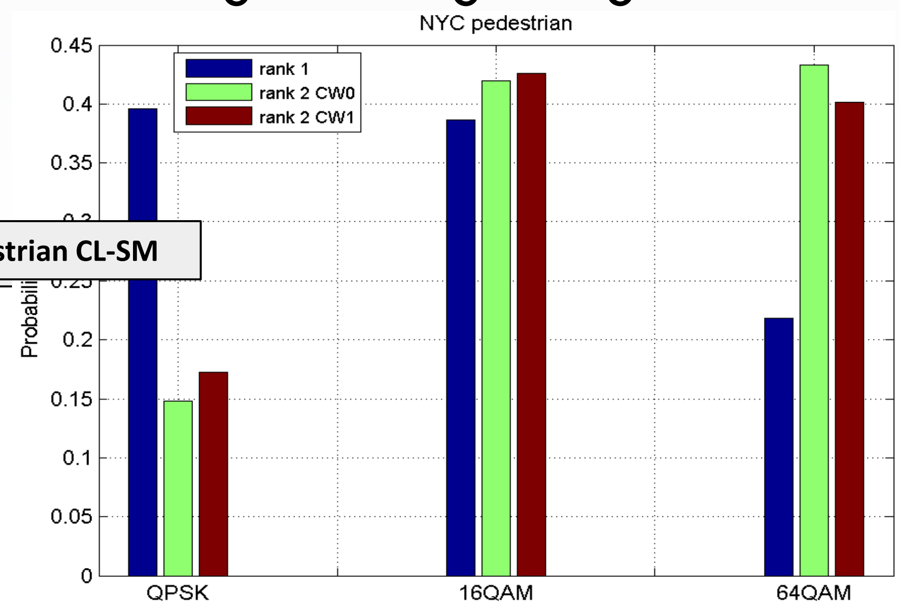


MIMO gain over SIMO	Equal grade of service			Equal bandwidth		
	2 x 2	2 x 4	4 x 4	2 x 2	2 x 4	4 x 4
ITU	1%	20%	18%	9%	36%	47%
SCM	-1%	5%	5%	5%	22%	32%



- **Truth:** NWs operate at fractional loading resulting in high CINRs





NYC pedestrian CL-SM

LTE DL MIMO transmission modes

LTE Rel	TM	Description	Comments
8	1	Single antenna port aka SIMO	Applicable to cells configured w/ one CRS port, fairly uncommon across deployments
8	2	Transmit diversity	SFBC for 2 CRS ports, FSTD+SFBC for 4 CRS ports, rank 1 fallback for open/closed loop MIMO, used for DL control
8	3	Open loop spatial multiplexing	Large delay CDD (LD-CDD): (still) predominant MIMO TX mode across LTE NWs
8	4	Closed loop spatial multiplexing	Closed loop pre-coding, deployed initially by ALU only, getting increasing traction, increasing interest w/ 4 CRS
8	5	Multi-user MIMO	Poorly defined in terms of DEMOD (no reliable means of MU-MIMO detection) and CSF, not used in practice
8	6	Closed loop rank 1 precoding	Functionally equivalent to TM4 w/ codebook restriction to rank 1, not seen in practical deployments
8	7	Single stream beamforming	Mainly driven by 8TX TD-LTE deployments to support reciprocity based beamforming, no dedicated CSF
9	8	Dual stream beamforming	Extension of TM7 to two spatial streams, same purpose, somewhat better yet crippled CSF support
10	9	UE-RS based SU-/MU-MIMO	Provisions for DEMOD & CSF w/ increased number of TX antennas, up to 8 layers, introduction of dedicated RS for feedback (CSI-RS)
11	10	TM9 enhancements to support inter-cell coordination (CoMP)	Concepts of interference measurement sets and CSI processes, notions of RS co-location to handle timing / frequency and long term channel parameters

TM 1–6: DEMOD: CRS
CSF: CRS

TM 7–8: DEMOD: UE-RS
CSF: CRS

TM 9–10: DEMOD: UE-RS
CSF: CSI-RS

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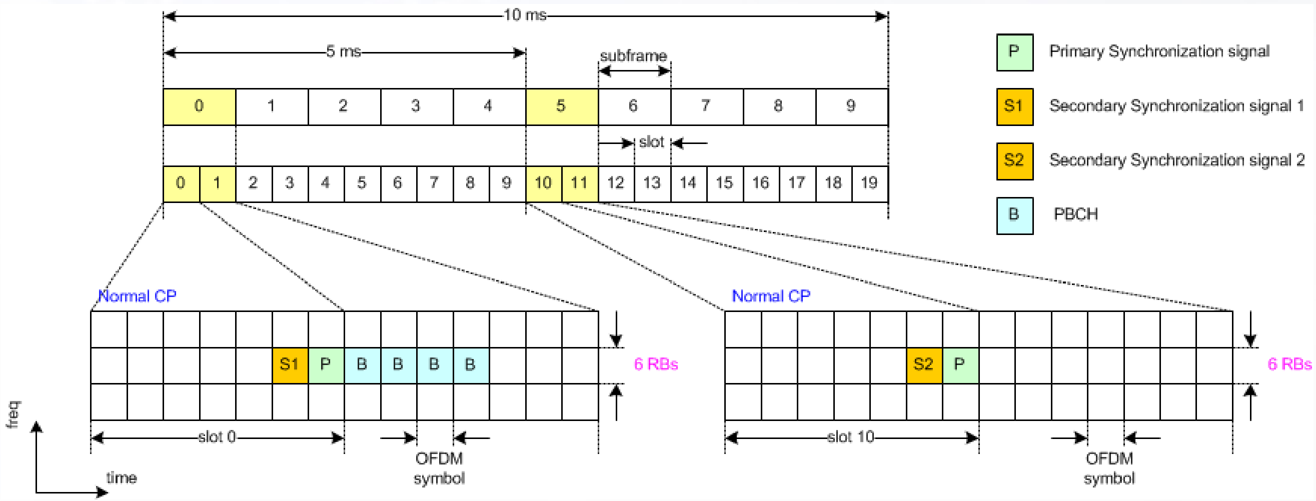
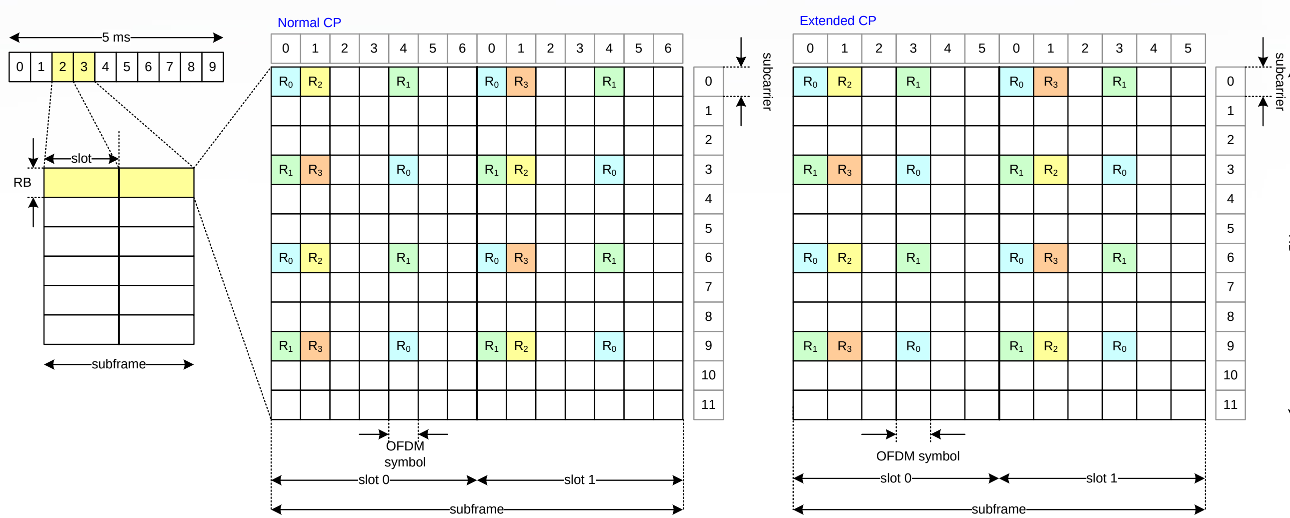
LTE radio frame numerology

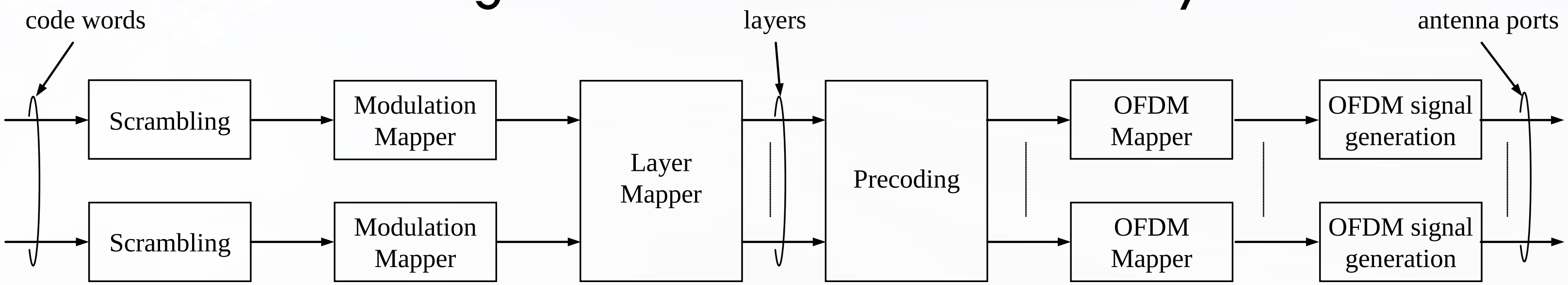


Common reference signals (CRS)



CRS based MIMO transmission (1/2)

- Concept of transport block (**TB**) aka codeword to layer mapping w/ maximum **2TB**s regardless of the number of layers



- **Open loop spatial multiplexing (LD-SDD)**: alternating precoders (4CRS) w/ permutation of precoder vectors across REs

$$y = \boldsymbol{W}(i)\boldsymbol{D}(i)\boldsymbol{U}\ x$$

2CRS: I_{2x2}
4CRS: cycles over 4 precoders

Number of layers υ	U	$D(i)$
1	$[1]$	$[1]$
2	$\begin{bmatrix} 1 & 1 \\ 1 & e^{-j2\pi/2} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & e^{-j2\pi i/2} \end{bmatrix}$
3	$\begin{bmatrix} 1 & 1 & 1 \\ 1 & e^{-j2\pi/3} & e^{-j4\pi/3} \\ 1 & e^{-j4\pi/3} & e^{-j8\pi/3} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-j2\pi i/3} & 0 \\ 0 & 0 & e^{-j4\pi i/3} \end{bmatrix}$
4	$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & e^{-j2\pi/4} & e^{-j4\pi/4} & e^{-j6\pi/4} \\ 1 & e^{-j4\pi/4} & e^{-j8\pi/4} & e^{-j12\pi/4} \\ 1 & e^{-j6\pi/4} & e^{-j12\pi/4} & e^{-j18\pi/4} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{-j2\pi i/4} & 0 & 0 \\ 0 & 0 & e^{-j4\pi i/4} & 0 \\ 0 & 0 & 0 & e^{-j6\pi i/4} \end{bmatrix}$

  - symmetric stream ⇨ virtual antenna mapping
  - designed to operate w/ common CQI across streams
  - ★ simplest & most prevalent MIMO transmission mode to date

CRS based MIMO transmission (2/2)

- **Closed loop spatial multiplexing:** precoded transmission w/ wideband or sub-band PMI application

$$y = \boldsymbol{W}(i)\ x$$

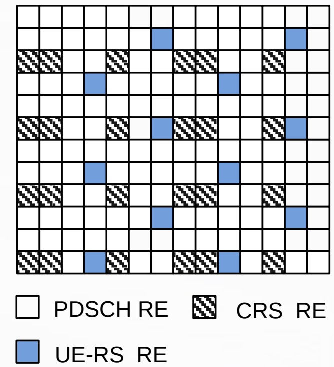
2CRS: 4 PMIs @ rank 1, 2 PMIs @ rank 2
4CRS: 16 PMIs @ rank 1, 2

Codebook index	Number of layers υ	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1&0\\0&1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\j&-j\end{bmatrix}$
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

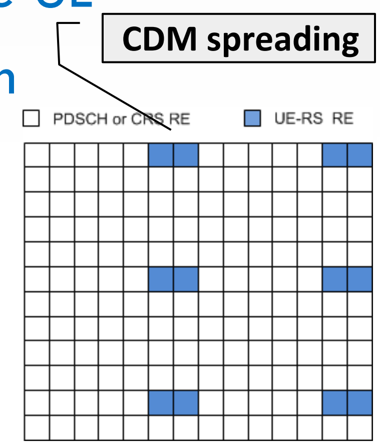
  - differentiated CQI values across streams: **enabled SIC receivers**
  - explicit wideband PMI or implicit sub-band PMI
  - ★ **less common but gaining traction, renewed interest w/ 4 CRS**
- **Closed loop rank-1 precoding:** special case of closed loop spatial multiplexing w/ rank 1 restriction
  - functionally achievable w/ TM4, not much practical value
- **Multi-user MIMO:** equivalent to closed loop rank-1 precoding w/ halved transmit power assumption built into UE feedback
  - lacks practical means to detect/handle MU interference, not used

UE-RS based MIMO transmission

- **Single stream beamforming**: channel reciprocity (TDD) to achieve "transparent" beamforming, tailored to large # antennas
  - UE specific RS (UE-RS) through same precoding as data
  - CSF from *transmit diversity*: CSF⇔DEMOD mismatch
  - relies on NW outer loop to recover beamforming gains
  - China (8TX) & limited deployments in Japan



- **Dual stream beamforming**: extends single stream beamforming
  - transparent MU-MIMO w/ detection & mitigation at the UE
  - CSF inherited from CRS modes: CSF⇔DEMOD mismatch
  - requires UL antenna switching feature to enable MIMO
    - Rel-8 TxDiv feature "mandated" along w/ TM8 support
  - recent deployments, predominantly in China



CSF for legacy DL MIMO

- UE feedback measurements based on CRS
  - constraints on NW spatial processing & mismatch for UE-RS modes
- Periodic feedback sent on UL control channel (PUCCH)
  - tradeoff between "constant" overhead & detail/accuracy
  - widely used across NWs
- Aperiodic feedback sent as scheduled UL upon NW request
  - on-demand feedback w/ DL scheduling activity
  - allowing for greater feedback detail/accuracy

		PMI feedback type		
		No	Wideband PMI	Subband PMI
CQI feedback type	Wideband CQI	Mode 1-0 TM 1,2,3,7	Mode 1-1 TM 4,5,6	Mode 1-2 TM 4,6
	UE selected sub-band CQI	Mode 2-0 TM 1,2,3,7	Mode 2-1 TM 4,5,6	Mode 2-2 TM 4,6
	NW selected sub-band CQI	Mode 3-0 TM 1,2,3,7	Mode 3-1 TM 4,5,6	N/A

Periodic (PUCCH) only | Aperiodic (PUSCH) only | Periodic (PUCCH) & aperiodic (PUSCH)

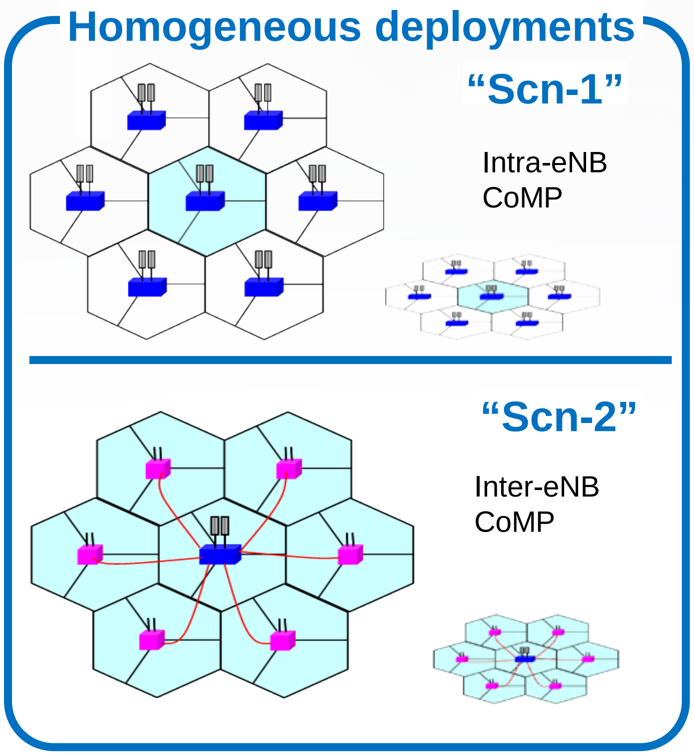
- Sub-band scheduling deployed w/ NW selected feedback

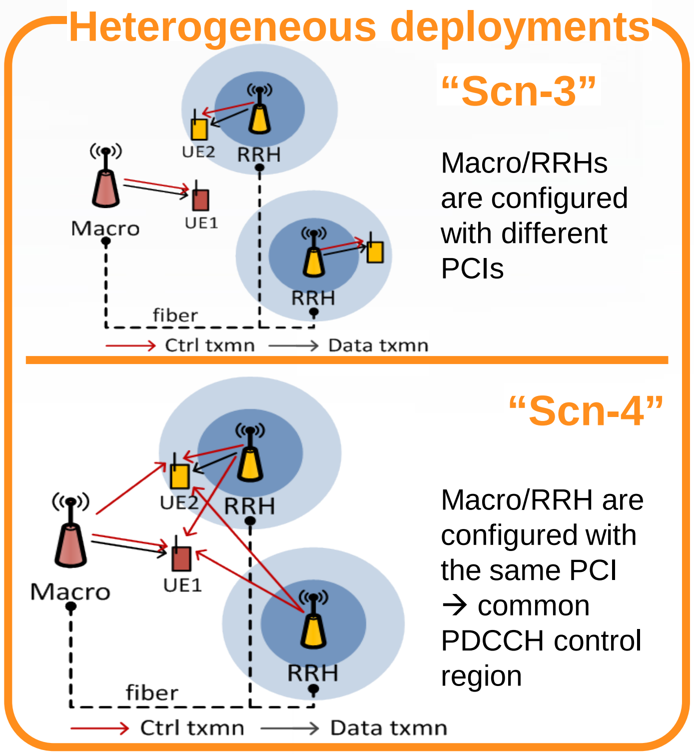
Advanced DL MIMO design principles

- Fundamental change in RS design & use principles
  - TX antenna dimension ≠ spatial multiplexing dimension
  - CSI estimation accuracy ≠ demodulation estimation accuracy
  - enable NW spatial processing "transparent" to the UE
  - ★ **convergence towards UE-RS based demodulation design**
  - ★ **concept of "dedicated" CSI-RS in Rel-10 (TM9)**
- Precoding framework to accommodate "practical" configurations
  - hierarchical codebooks for commercial 8TX configurations
  - separation into wideband & sub-band spatial feedback
- Scaling to higher MIMO order & SU-MIMO support
  - primarily extension of UE-RS design
- Towards a better inter-cell coordination
  - ★ **notions of interference measurement resources (IMR) & CSI process**

DL CoMP framework

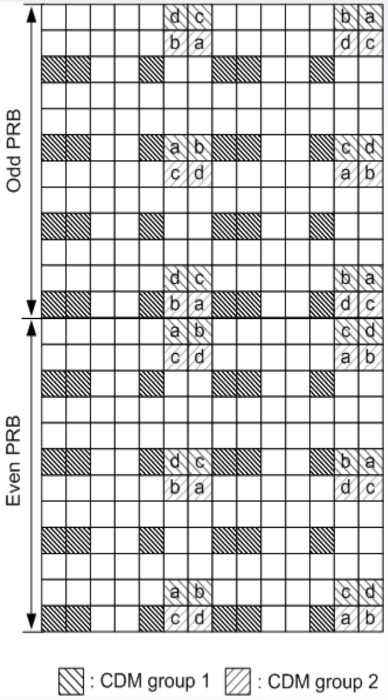
- CoMP CSI enhancements
  - CSI feedback related to various/multiple transmission points
  - introduce the notion of interference hypotheses
- CoMP CSI enhancements
  - virtual cell ID & quasi-colocation of reference signals



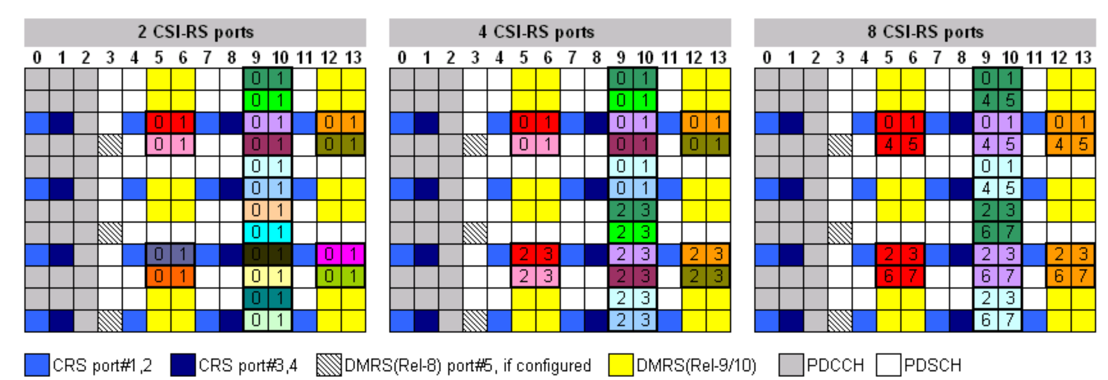


Advanced DL MIMO reference signals

- UE-RS to accommodate up to 8 MIMO streams
  - unified UE-RS pattern structure scalable w/ MIMO rank
  - high rank ports added through time domain CDM
    - trade overhead for less tolerance w.r.t. mobility
- CSI-RS to accommodate up to 8 TX ports
  - configurable duty cycle: 5,10,20,40,80ms
  - 1 in 12 tones: ≈5us delay spread resolution



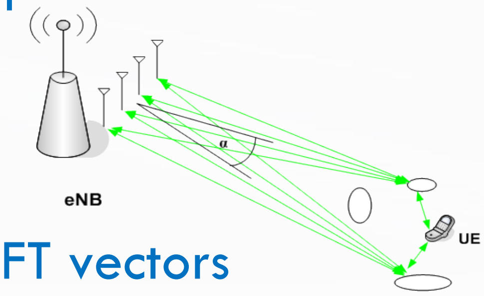
$$S = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix} = [a\ b\ c\ d]$$



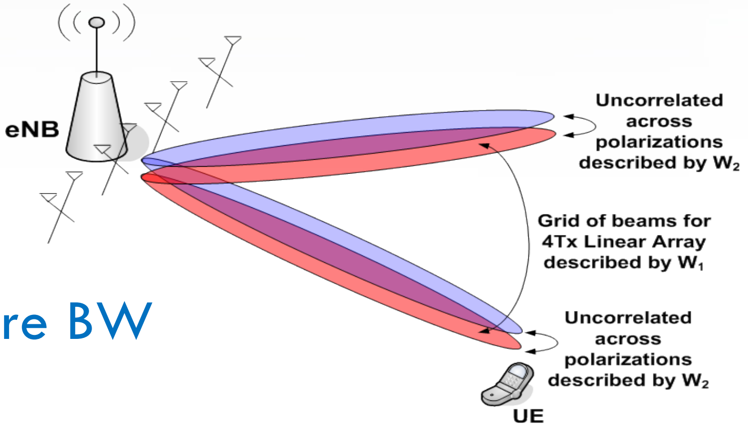
- CSI process: a combination of CSI-RS and IMR
  - IMRs used to measure interference under different (CoMP) hypotheses
  - mix & match of TX channel & interference scenarios in UE reports

Codebook design considerations

- Dual codebook structure to match antenna correlation patterns
  - relatively high correlation between co-polarized TX antennas
  - relatively low correlation between x-polarized antenna sets
  - scattering mostly around UE ⇨ low RX correlation



- 8 CSI-RS precoders follow Kronecker structure
  - W_1 - grid of beams within co-pol antennas: 4x1 DFT vectors
  - W_2 - 2x2 co-phasing matrices following legacy design principle
  - extended to 4TX in Rel-12



- Feedback overhead reduction
  - W_1 : single reported value across the entire BW
  - W_2 : sub-band PMI reporting enabled

UL MIMO in LTE

- Traffic: closed loop spatial multiplexing w/ up to four streams
  - addition of CDM across DM-RS symbols to increase RS dimension
  - precoding codebook design following DL design principles
    - addition of “hot-bit” precoders to enable TX antenna selection
    - constraints to preserve SC-FDMA waveform
- Control: open loop transmit diversity
  - orthogonal resources allocated for two transmit ports
  - antenna virtualization for >2 transmit ports
- To date no commercial deployments supporting UL MIMO

DL (MIMO) receiver design

- Early MIMO performance specifications assume LMMSE
  - competitive analysis focused on low/moderate mobility
  - MIMO focus: single cell, low correlation, moderate CINR (≤30dB)
- Interference nulling receivers
  - multi-cell evaluation framework defined in RAN4
  - **Rel-11**: interference rejection combining (LMMSE-IRC) RX category
- Growing interest in MIMO performance under adverse conditions
  - competitive analysis looks at wide range of mobility / delay spread / antenna correlation: **EPA/EVA5L/H, EVA/ETU70L/H, ETU300L**
    - delays spreads up to **5us**, TX & RX correlation up to **0.9**
  - attention to **30-40dB** CINR raising the bar for RF: I/Q mismatch, IPN
- Advanced UE categories further tighten performance requirements
  - **Rel-12**: reduced complexity ML (R-ML) receiver as baseline
  - performance requirements based on 4RX chain availability upcoming

RX antenna management techniques

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- Antenna selection attracts attention since early days of MIMO
  - cost & power effective way to improve performance & coverage
  - … however little traction in WWAN industry for ≈10 years
    - real estate & layout considerations don't appeal to OEMs
    - cost & insertion loss of extra components
- Feature evolution of portable devices antenna sharing
  - Wi-Fi integration ⇨ cross-tech antenna sharing
  - LTA carrier aggregation (CA) requires additional RX chains: facilitates antenna selection or combining
- ★ **Cross-tech antenna sharing framework**
  - system-wide optimization of antenna assignment
  - one tech only active (LTE or WiFi),
  - different QoS (VoLTE w/ data on WiFi)
  - LTE backhaul (MiFi)

RX antenna selection field results

- Throughput analysis w/ 2TX/cell and up to 4RX at the UE
  - two cross-polarized TX antennas at eNodeB @ 2.17GHz
  - smart-phone & laptop form factors, no hand blocking
  - mix of indoor / outdoor measurements
- Gains w/ adaptive 2 out of 4 selection
  - instantaneous: ≈**15%** median & ≈**30%** (10%) tail
  - 100ms delay: ≈**15%** median & ≈**20%** (10%) tail
  - 500ms delay: ≈**12%** median & ≈**20%** (10%) tail
  - **fixing primary antenna retains most of the gain**
- Selection or combining?
  - either option is available for CA capable UEs
    - UE CA capability will often exceeds the need in most scenarios
  - combining across multiple RX chains incurs substantial power penalty
  - ★ **smart antenna selection & receiver switching algorithms**

Towards higher order MIMO

- Currently 2TX deployments dominate worldwide
  - TDD: 8TX antennas in China, yet configured w/ 2CRS
  - FDD: 4CRS trial NW in Europe (TMO), SKT pioneered commercial 4CRS
    - major commercial rollout of 4TX/4CRS NWs expected later this year
- What to expect w/ 4CRS?
  - UE-RS modes are designed to better scale w/ number of TX
  - however TM9(10) are not yet commercially available
  - 4 CRS deployments … long term of transitional?

Scenario	Test	2x2	4x2
Near cell 10MHz	DL FTP (Mbps)	32.7	33.4
	UL FTP (Mbps)	10.1	10.1
Cell edge 10MHz	DL FTP (Mbps)	3.59	6.63
	UL FTP (Mbps)	0.21	0.9

- Higher order spatial multiplexing … yet to be seen

New areas in DL MIMO

- Network assisted interference cancellation
  - Rel-12: signaling framework to convey neighbor cell parameters to UEs in order to facilitate RS and/or data interference cancellation
    - neighbor (virtual) cell IDs, CRS & MBSFN configuration, TM restriction
  - Rel-13: consider extending the same for (intra-cell) MU-MIMO
- Higher order modulation schemes
  - 256QAM coming in Rel-12
- Non-orthogonal multiple access (NOMA)
  - advanced MIMO transmission techniques e.g. superposition / DPC
- MMW MIMO aka massive MIMO

4G MIMO: lessons learned (1/2)

- Avoid/minimize pilot pollution in a broadband wireless design
  - broadband data networks are partially loaded
  - wideband/continuous/scattered pilots generate interference floor
  - high cost of pilot interference mitigation
  - makes heterogeneous deployments intractable
  - pilot collisions undermines utility of channel feedback
  - ★ **much RAN4 work over past few years focused on "mitigating" the impact of common pilots (CRS) designed in Rel-8**
- Pay attention to channel state feedback design
  - data networks tend to operate in low PHY BLER regime
  - accurate feedback is critical to highlight (advanced) receiver gains
  - inaccurate CQI partly mitigated by NW rate control loops … much harder to fix incorrect rank

4G MIMO: lessons learned (2/2)

- Design MAC w/ practical traffic behavior in mind
  - cellular systems have been mostly designed/evaluated under “full buffer” model
  - better performance can be achieved w/ advanced coordination techniques