Traffic Aware Interference Management for Flexible 5G Radio Access

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Outline

1. Objective, introduction and outline
   1.1 Network densification in 5G – challenges for interference management and potential solutions
   1.2 Dynamic and flexible TDD
   1.3 Overview of physical layer aspects of 3GPP New Radio (NR) in Rel-15

2. Traffic aware linear transceiver design
   2.1 System and queuing model & problem formulation
   2.2 Centralized joint space-frequency resource allocation (JSFRA) solution
   2.3 Joint UL/DL mode selection and transceiver design

3. Coordinated interference management in dense TDD based 5G networks
   3.1 Distributed transmission with Forward-Backward (F-B) training
   3.2 Direct beamformer estimation with over-the-air (OTA) F-B training
   3.3 Impact of limited pilot resources

4. OTA TX-RX training schemes in the context of 5G radio access
   4.1 Key technology components and procedures enabling dynamic TDD in NR
   4.2 Impact to frame structure design, UE operation
   4.3 Impact on reference signals, and control signaling
   4.4 Practical challenges
The Path to 5G: As Much Evolution As Revolution

(Source: ETRI graphic, from ITU-R IMT 2020 requirements)
5G Networks

- Heterogeneous 5G network
  - Macro cells with (massive) MIMO antenna arrays
  - Small cells and relays with (distributed) MIMO arrays with Dynamic/Flexible TDD – advanced interf. management
  - D2D communication with network coordination

Key requirements for 5G

Source: ITU, Samsung, Nokia, Ericsson, ...
MIMO Technologies in 5G

Advanced interference management

Massive MIMO

Hybrid analog-digital beamforming (especially in mm-wave frequencies)

Cloud-RAN

Source: Samsung

Source: www.profheath.org

Source: China Mobile

Source: www.profheath.org
Dynamic/Flexible TDD

- Significant load variation between adjacent cells
- Flexible UL/DL allocation provides large potential gains in spectral efficiency
- More challenging interference management

Figure: Flexible TDD frame structure

Dynamic/Flexible TDD

- Additional **UL-to-DL and DL-to-UL interference** associated with the dynamic TDD
- Interference mitigated by coordinated beamforming.
- More measurements and info exchange also at the terminal side
- Similar interference scenarios in underlay D2D transmission$^3$

Flexible TDD in 3GPP NR

Figure: New radio slot types agreed in 3GPP NR study item and the proposed switching slot structure. [A. Tölli, H. Ghauch, J. Kaleva, P. Komulainen, M. Bengtsson, M. Skoglund, M. Honig, E. Lähetkangas, E. Tiirola and K. Pajukoski, "Distributed Coordinated Transmission with Forward-Backward Training for 5G Radio Access", submitted to IEEE Communications Magazine, major revision, March 2018]

System Model & Problem Formulation

- OFDM system with $N$ sub-channels and $N_B$ BSs, $N_T$ TX antennas per BS
- $K$ users each with $N_R$ antennas

Goal: minimize the number of packets in BS queues via joint TX/RX design and resource allocation over spatial and frequency resources
Queueing Model

- Each user is associated with backlogged packets of size $Q_k$ packets.
- Queued packets $Q_k$ of each user follows dynamic equation at the $i$th instant as
  \[
  Q_k(i+1) = \left[ Q_k(i) - t_k(i) \right]^+ + \lambda_k(i) \tag{1}
  \]
  where $t_k = \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n}$ denotes the total number of transmitted packets corresponding to user $k$.
- $\lambda_k$ represents the fresh arrivals of user $k$ at BS $b_k$. 
JSFRA Formulation\textsuperscript{5}

- The optimization objective of (downlink) joint space-frequency resource allocation (JSFRA) to design transmit precoders is

\[
\text{minimize} \sum_{t_{l,k,n}} \left( \sum_{k \in U} a_k \left| Q_k - \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n} \right|^q \right)
\]

where \( a_k \) are arbitrary weights used to control the priorities

- Exponent \( q = 1, 2, \ldots, \infty \) plays different role based on the value it assumes

- Inherent maximum rate constraint: \( \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n} \leq Q_k \)

- Special cases (when \( Q_k > \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n} \forall k \)):
  - \( q = 1 \): Sum rate maximization
  - \( q = 2 \): Queue-Weighted Sum Rate Maximization (Q-WSRM)

JSFRA Formulation (MSE Reformulation)

The queue minimization problem can be solved by utilizing the relation between the MSE and the SINR as

$$\epsilon_{l,k,n} = (1 + \gamma_{l,k,n})^{-1}$$

Equivalence is valid only when the receivers are designed with the mean squared error (MSE) objective, i.e., using MMSE receivers

$$t_{l,k,n} = -\log_2(\epsilon_{l,k,n})$$

$$\epsilon_{l,k,n} = \mathbb{E}[(d_{l,k,n} - \hat{d}_{l,k,n})^2] = |1 - \mathbf{w}_{l,k,n}^H \mathbf{H}_{b_{k},k,n} \mathbf{m}_{l,k,n}|^2$$

$$+ \sum_{(j,i) \neq (l,k)} |\mathbf{w}_{l,k,n}^H \mathbf{H}_{b_{i},k,n} \mathbf{m}_{j,i,n}|^2 + \|\mathbf{w}_{l,k,n}\|^2 N_0$$
JSFRA Formulation (MSE Reformulation)

- **Queue minimization via MSE reformulation**

  \[
  \begin{align*}
  &\text{minimize} & & \|\tilde{v}\|_q \\
  &\text{subject to} & & t_{l,k,n} \leq -\log_2(\epsilon_{l,k,n}) \quad \forall l, k, n \\
  & & & \epsilon_{l,k,n} \geq |1 - w_{l,k,n}^H H_{b_k,k,n} m_{l,k,n}|^2 \\
  & & & + \sum_{(j,i)\neq(l,k)} |w_{l,k,n}^H H_{b_i,k,n} m_{j,i,n}|^2 + N_0 \quad \forall l, k, n \\
  & & & \sum_{n=1}^N \sum_{k\in\mathcal{U}_b} \sum_{l=1}^L \text{tr}(m_{l,k,n} m_{l,k,n}^H) \leq P_{\text{max}} \quad \forall b.
  \end{align*}
  \]

  where \(\tilde{v}_k \equiv \frac{1}{a_k} \left(Q_k - \sum_{n=1}^N \sum_{l=1}^L t_{l,k,n}\right)\)

- **The nonconvex (difference of convex) rate constraints are approximated via successive convex approximation (SCA) method**

- **Receive beamformers are designed by the MMSE receivers using the converged TX precoders**

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6The centralized formulation here is for the downlink only case.
Dynamic Traffic Scenario - Centralized Performance

Joint UL/DL Mode Selection and Transceiver Design for Dynamic TDD Systems

- OFDM system with $N$ sub-channels and $N_B$ BSs, $N_T$ TX antennas per BS
- $K$ users each with $N_R$ antennas

Goal: minimize the number of packets in BS/user queues via joint UL/DL cell mode selection, TX/RX design and resource allocation over spatial and frequency resources

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Objective

- Minimize the total number of backlogged packets in DL and UL

\[
\text{minimize } \sum_{k \in U} \alpha_k |v_k|^q + \beta_k |u_k|^q
\]

where \( \alpha_k, \beta_k \) are arbitrary priority weights and

\[
v_k = Q_k - t_k = Q_k - \sum_{n=1}^{N} \sum_{l=1}^{L} \log_2(1 + \gamma_{l,k,n})
\]

\[
u_k = \bar{Q}_k - \bar{t}_k = \bar{Q}_k - \sum_{n=1}^{N} \sum_{l=1}^{L} \log_2(1 + \bar{\gamma}_{l,k,n})
\]

- \( q = 1, 2, \ldots, \infty \) plays different role based on the value it assumes
  - Inherent maximum rate constraint:
    \[
    \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n} \leq Q_k
    \]
  - Special cases (when \( Q_k > \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n} \forall k \)):
    - \( q = 1 \): Sum rate maximization
    - \( q = 2 \): Queue-Weighted Sum Rate Maximization (Q-WSRM)

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Spatial Overloading in SINR

**DL SINR**

\[
\Gamma_{l,k,n} = \frac{\left| w_{l,k,n}^H H_{b_k,k,n} m_{l,k,n} \right|^2}{\hat{N}_0 + \sum_{i \in U \setminus \{k\}} \sum_{j=1}^L |w_{l,k,n}^H H_{b_i,k,n} m_{j,i,n}|^2 + \sum_{i \in U \setminus U_{b_k}} \sum_{j=1}^L |w_{l,k,n}^H \tilde{H}_{i,k,n} \tilde{m}_{j,i,n}|^2}
\]

**UL SINR**

\[
\bar{\Gamma}_{l,k,n} = \frac{\left| \bar{w}_{l,k,n}^H H_{b_k,k,n}^T \bar{m}_{l,k,n} \right|^2}{\hat{N}_0 + \sum_{i \in U \setminus \{k\}} \sum_{j=1}^L |\bar{w}_{l,k,n}^H H_{b_k,i,n}^T \bar{m}_{j,i,n}|^2 + \sum_{i \in U \setminus U_{b_k}} \sum_{j=1}^L |\bar{w}_{l,k,n}^H \tilde{H}_{b_i,b_k,n} \bar{m}_{j,i,n}|^2}
\]

\(9\) Note that UL-DL and DL-UL interference terms in (9), and (10), respectively, include potential interference from all other-cell users. UL/DL mode selection per BS/user is handled separately via (relaxed) binary selection.
Queue Minimization with UL/DL Mode Selection

\[
\begin{align}
\text{min.} \quad & \|\tilde{v}\|_q + \|\tilde{u}\|_q \\
\text{s. t.} \quad & \gamma_{l,k,n} \leq \Gamma_{l,k,n} \quad \forall \ l, k, n \\
& \bar{\gamma}_{l,k,n} \leq \bar{\Gamma}_{l,k,n} \quad \forall \ l, k, n \\
& \sum_{n=1}^{N} \sum_{k \in \mathcal{U}_b} \sum_{l=1}^{L} \|m_{l,k,n}\|^2 \leq x_b P_{\text{max}} \quad \forall \ b \\
& \sum_{n=1}^{N} \sum_{l=1}^{L} \|\bar{m}_{l,k,n}\|^2 \leq \bar{x}_b P_{\text{UE max}} \quad \forall \ k \\
x_b + \bar{x}_b = 1 \quad \forall \ b, \quad x_b \in \{0, 1\}, \quad \bar{x}_b \in \{0, 1\}
\end{align}
\]

where \( \tilde{v}_k \equiv \frac{1}{a_k} (Q_k - \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n}) \) and \( t_{l,k,n} = \log(1 + \gamma_{l,k,n}) \)

- Nonconvex (difference of convex) SINR constraints, and integer UL/DL selection constraints
Approximation of the SINR Constraints

The DL SINR constraints in (11b) are relaxed as\(^\text{10}\) (UL similarly)

\[
\gamma_{l,k,n} \leq \frac{|w_{l,k,n}^H H_{b_k,k,n} m_{l,k,n}|^2}{\beta_{l,k,n}} = \frac{p_{l,k,n}^2 + q_{l,k,n}^2}{\beta_{l,k,n}} \quad (12)
\]

\[
\beta_{l,k,n} \geq \tilde{N}_0 + \sum_{i \in \mathcal{U} \setminus \{k\}} \sum_{j=1}^{L} |w_{l,k,n}^H H_{b_i,k,n} m_{j,i,n}|^2
+ \sum_{i \in \mathcal{U} \setminus \mathcal{U}_{b_k}} \sum_{j=1}^{L} |w_{l,k,n}^H \tilde{H}_{i,k,n} \tilde{m}_{j,i,n}|^2 \quad (13)
\]

where

\[p_{l,k,n} \triangleq \Re(w_{l,k,n}^H H_{b_k,k,n} m_{l,k,n}), \quad q_{l,k,n} \triangleq \Im(w_{l,k,n}^H H_{b_k,k,n} m_{l,k,n})\]

\textbf{Difference of convex constraint solved via successive convex (linear) approximation (SCA)}

Binary Relaxation

- Binary variables \( x_b, \bar{x}_b \in \{0, 1\} \) are replaced by continuous variables \( x_b, \bar{x}_b \in [0, 1], \forall b \)
- Problem (11) becomes convex (for fixed receivers, at any given linearization point of the SINR constraints)
- **Sparsity must be enforced!** → Use a regularization function\(^{11}\)

\[
\text{minimize} \quad \|\tilde{v}\|_q + \|\tilde{u}\|_q + \psi \sum_{t=1}^{N_B} (\log(x_b + \epsilon) + \log(\bar{x}_b + \epsilon)) \quad (14)
\]

successively linearized as

\[
\text{minimize} \quad \|\tilde{v}\|_q + \|\tilde{u}\|_q + \psi \sum_{b=1}^{N_B} \left( \frac{x_b - x_b^{(i)}}{x_b^{(i)} + \epsilon} + \frac{\bar{x}_b - \bar{x}_b^{(i)}}{\bar{x}_b^{(i)} + \epsilon} \right) \quad (15)
\]

Simulation Setup

1. slot allocation

- Red: Uplink
- Blue: Downlink

Figure: Final UL/DL allocation for a random drop of users and traffic states
Numerical Example

Figure: Average number of queued bits per user with varying packet arrival rates.

The mean arrival rate across all low and high rate demand users is 

$$(1 - \alpha)A + \alpha \beta A.$$
Open problems

- Decentralization, decoupling the problem
- Inter-carrier, inter-sector UL-DL interference
- Signalling, CSI acquisition
- Time-scale of changing UL/DL allocation?
- Impact of more practical traffic models
Distributed Solutions with Local CSI

Figure: Locally measured CSI.

Distributed Methods for fixed UL/DL allocation

- Overhead of the centralized design is large as the network size grows.
- Distributed approaches based on primal decomposition or ADMM can be used to reduce the signaling.

Precoder design by solving the KKT expressions of the JSFRA problem (5) via MSE reformulation.
Practical approach to design precoders with minimal backhaul usage.
KKT Expressions for (5)

Simple matrix or scalar expressions:

\[
\begin{align*}
\mathbf{m}_{l,k,n}^{(i)} &= \left( \sum_{x \in \mathcal{U}} \sum_{y=1}^{L} \alpha_{y,x,n}^{(i-1)} \mathbf{H}_{b_{k},x,n}^{H} \mathbf{w}_{y,x,n}^{(i-1)} \mathbf{H}_{b_{k},x,n}^{H} + \delta_{b} \mathbf{I}_{NT} \right)^{-1} \alpha_{l,k,n}^{(i-1)} \mathbf{H}_{b_{k},k,n}^{H} \mathbf{w}_{l,k,n}^{(i-1)} \\
\mathbf{w}_{l,k,n}^{(i)} &= \left( \sum_{x \in \mathcal{U}} \sum_{y=1}^{L} \mathbf{H}_{b_{x},k,n} \mathbf{m}_{y,x,n}^{(i)} \mathbf{m}_{y,x,n}^{H} \mathbf{H}_{b_{x},k,n}^{H} + N_{0} \mathbf{I}_{NR} \right)^{-1} \mathbf{H}_{b_{k},k,n} \mathbf{m}_{l,k,n}^{(i)} \\
\epsilon_{l,k,n}^{(i)} &= \left| 1 - \mathbf{w}_{l,k,n}^{H} \mathbf{H}_{b_{k},k,n} \mathbf{m}_{l,k,n}^{(i)} \right|^2 + \sum_{(x,y) \neq (l,k)} \left| \mathbf{w}_{l,k,n}^{H} \mathbf{H}_{b_{y},k,n} \mathbf{m}_{x,y,n}^{(i)} \right|^2 + \left\| \mathbf{w}_{l,k,n} \right\|^2 N_{0} \\
t_{l,k,n}^{(i)} &= - \log_{2}(\epsilon_{l,k,n}^{(i-1)}) - \frac{\epsilon_{l,k,n}^{(i)} - \epsilon_{l,k,n}^{(i-1)}}{\log(2) \epsilon_{l,k,n}^{(i-1)}} \\
\sigma_{l,k,n}^{(i)} &= \left[ \frac{a_{k} q}{\log(2)} \left( Q_{k} - \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n}^{(i)} \right)^{(q-1)} \right] + \\
\alpha_{l,k,n}^{(i)} &= \alpha_{l,k,n}^{(i-1)} + \rho^{(i)} \left( \frac{\sigma_{l,k,n}^{(i)}}{\epsilon_{l,k,n}^{(i)}} - \alpha_{l,k,n}^{(i-1)} \right)
\end{align*}
\]
Distributed Coordination via F-B Training

\[ T \text{ iterations} \]

Frame \( n \)

\[
\begin{array}{c}
\cdots \quad \text{BF} \quad \cdots \quad \text{BF} \\
\text{Data} \\
\end{array}
\]

Frame \( n+1 \)

\[
\begin{array}{c}
\cdots \\
\end{array}
\]

OTA Signaling

Processing

Backward (B) pilots

Forward (F) pilots

Backward link CSI estimation

TX beamformer computation

Forward link CSI estimation

RX beamformer computation

\textbf{Figure}: Simplified TDD frame structure with F-B training.
F-B training strategies with separate

- forward (F) phase demodulation (DM) pilots and
- backward (B) phase busy burst (BB) and channel sounding (CS) pilots.

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A. Tölli et al, "Distributed Coordinated Transmission with Forward-Backward Training for 5G Radio Access", submitted to IEEE Communications Magazine, major revision Mar 2018
Decentralized Precoder Design - Strategy A

- Over-the-air (OTA) based iterative algorithm\(^{13}\) with Bi-directional training (BiT)\(^{14}\)

\[
m_{l,k,n}^{(i)} = \left( \sum_{x \in \mathcal{U}} \sum_{y=1}^{L} \alpha_{y,x,n}^{(i-1)} H_{b_k,x,n}^{H} w_{y,x,n}^{(i-1)} H_{b_k,x,n} + \delta_b I_{NT} \right)^{-1} \alpha_{l,k,n}^{(i-1)} H_{b_k,k,n}^{H} w_{l,k,n}^{(i-1)}
\]

\[
w_{l,k,n}^{(i)} = \left( \sum_{x \in \mathcal{U}} \sum_{y=1}^{L} H_{b_x,k,n} m_{y,x,n}^{(i)} m_{y,x,n}^{H(i)} H_{b_x,k,n} + N_0 I_{NR} \right)^{-1} H_{b_k,k,n} m_{l,k,n}^{(i)}
\]

- Transmit precoders \(m_{l,k,n}\) depend on \(H_{b_k,x,n}^{H} w_{y,x,n}\), i.e., effective uplink channel

- Receive beamformers \(w_{l,k,n}\) depend on \(H_{b_x,k,n} m_{y,x,n}\), i.e., effective downlink channel

- Can be measured locally at each node in TDD using precoded pilots

\(^{13}\)P. Komulainen, A. Tölli & M. Juntti, "Effective CSI Signaling and Decentralized Beam Coordination in TDD Multi-Cell MIMO Systems", IEEE Transactions on Signal Processing, vol. 61, no. 9, pp. 2204 – 2218, May 2013

Decentralized Precoder Design - Strategy B

- **To speed up the convergence**, the precoders of served users are updated assuming neighboring BSs transmit beamformers are fixed.

- **Inter-cell interference covariance at the served users** has to be known at the serving BS, \(i.e.,\)

\[
Z_{l,k,n} = \sum_{i \in \mathcal{U} \setminus \mathcal{U}_b} H_{b_i,i,n} m_{l,i,n}^H H_{b_i,i,n}^H + N_0 I_{N_R}.
\] (16)

- However, the inter-cell interference covariance knowledge is not required explicitly, effective whitened channel is enough.

- The whitening filter \(Q_{l,k,n}\) is given by \(Z_{l,k,n}^{-1} = Q_{l,k,n}^H Q_{l,k,n}\).

- Whitened channel is constructed at BS by transmitting (orthogonal) pilots precoded by the columns of \(Q_{l,k,n}\) from each user.
Decentralized Precoder Design - Strategy B

- Upon estimating the channel precoded with \( Q_{l,k,n} \), each BS can construct whitened channel as \( \tilde{H}_{b_k,k} = Q_{l,k,n} H_{b_k,k} \).

- The BS specific local iteration \( j \) to update transmit and receive beamformer is given as:

\[
\begin{align*}
\mathbf{m}_{l,k,n}^{(j)} &= \left( \sum_{x \in U_b} \sum_{y=1}^{L} \alpha^{(j-1)}_{y,x,n} \tilde{H}_{b_k,x,n}^{H} \mathbf{w}_{y,x,n}^{(j-1)} \tilde{H}_{b_k,x,n} \mathbf{w}_{y,x,n}^{H} \right)^{-1} \alpha^{(j-1)}_{l,k,n} \tilde{H}_{b_k,k,n} \mathbf{w}_{l,k,n}^{(j-1)} \\
\mathbf{w}_{l,k,n}^{(j)} &= \left( \sum_{x \in U_b} \sum_{y=1}^{L} \tilde{H}_{b_x,k,n} \mathbf{m}_{y,x,n}^{(j)} \tilde{H}_{b_x,k,n}^{H} \mathbf{m}_{y,x,n}^{H} \right)^{-1} \tilde{H}_{b_k,k,n} \mathbf{m}_{l,k,n}^{(j)}
\end{align*}
\]

- The above iterative procedure is performed until convergence or for predetermined number of updates - Strategy B.
Convergence Example for Sum Rate Maximation

Figure: Average convergence of the sum rate in the cell edge at 25 dB received SNR. Number of TX antennas $M = 4$, RX antennas $N = 2$, users per cell $K = 5$. [P. Komulainen, A. Tölli & M. Juntti, "Effective CSI Signaling and Decentralized Beam Coordination in TDD Multi-Cell MIMO Systems", IEEE Transactions on Signal Processing, vol. 61, no. 9, pp. 2204 – 2218, May 2013]
Signaling Requirement for OTA based Updates\textsuperscript{15} \textsuperscript{16}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{tdd-frame-structure.png}
\caption{TDD frame structure with Forward and two backward pilots.}
\end{figure}

\textsuperscript{15}P. Komulainen, A. Tölli & M. Juntti, Effective CSI Signaling and Decentralized Beam Coordination in TDD Multi-Cell MIMO Systems, IEEE Transactions on Signal Processing, vol. 61, no. 9, pp. 2204 – 2218, May 2013

Assumptions and Evaluation Model

- Every BS and user terminal uses orthogonal pilots in UL and DL over-the-air (OTA) signaling.
- For simplicity, pilot transmissions used to convey the equivalent channel information in one BiT iteration - consume $\eta$ resource share.\(^{17}\)
- Under this assumption, the effective rate by considering the signaling overhead is given as

$$\tilde{t}_{l,k,n} = (1 - I_{\max} \eta) \times t_{l,k,n} \quad (17)$$

- Total number of backlogged packets is evaluated as -

$$\chi = \sum_{k=1}^{K} [Q_k - \tilde{t}_k]^+$$

- In all simulations, we consider $\eta = 1\%$

\(^{17}\)In practice, the performance depends on the amount of available pilots and the size of coherence block.
Average Backlogged Packets - Distributed Design (DL Only)

Figure: Average backlogged packets for \( \{N, N_B, K, N_T, N_R\} = \{3, 2, 12, 4, 2\} \) evaluated over 250 slots with \( f_d T_s \approx 0.1 \) [G. Venkatraman, A. Tölli, M. Juntti & L-N. Tran "Queue Aware Precoder Design via OTA Training", in Proc. 2016 IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Edinburgh, UK, July 3–6, 2016]
OTA Signalling in Dynamic TDD\textsuperscript{18}

**Figure:** Interference at DL terminal

- **DL cell forward phase**
  - Users measure DL cell BS pilots and UL cell user pilots

- **DL cell backward phase**
  - BSs measure UL cell BS pilots and DL cell user pilots

\textsuperscript{18}P. Jayasinghe, A. Tölli & M. Latva-aho, Bi-directional Signaling Strategies for Dynamic TDD Networks in Proc. IEEE SPAWC 2015, Stockholm, Sweden, July, 2015
OTA Signalling in Dynamic TDD

UL cell forward phase
- BSs measure UL cell user pilots and DL cell BS pilots

UL cell backward phase
- Users measure DL cell user pilots and UL cell BS pilots

Figure: Interference at UL BS
Bi-directional F-B Training: Simulation Setup

19 omni-directional cells, 4-8 users/cell, 8 BS Antennas, 2 user antennas, 200m ISD, randomly selected UL/DL mode, \( P_{ul} = P_{dl}/\text{users} \)

\(^{19}\)P. Jayasinghe, A. Tlli, J. Kaleva & M. Latva-aho, "Bi-directional Beamformer Training for Dynamic TDD Networks", submitted to Transactions on Signal Processing, Minor Revision Aug 2018
**Figure:** Actual sum rate at SNR = 20 dB vs overhead for F-B beamformer training. WMMSE method = Strategy A and the 2nd method is from [J. Kaleva, A. Tölli & M. Juntti, "Decentralized Sum Rate Maximization with QoS Constraints for Interfering Broadcast Channel via Successive Convex Approximation", IEEE Transactions on Signal Processing, vol. 64, no. 11, pp. 2788–2802, June 2016.]
Figure: Actual sum rate at SNR = [5 20] dB vs overhead for F-B beamformer training. Strategy D is a heuristic scheme with single BF pilot.
Sum Rate with Distributed F-B Training (Strategy A)

Figure: Comparison of coordinated WSR beamformer design with respect to uncoordinated case with 5 F-B iterations, $K_i = 8$ & $M_i = 8$, $N_k = 2$. 
Impact of DL/UL Mode Selection Probability (Strategy A)

Figure: Dynamic TDD system performance with the DL cell probability at cell edge SNR = 20 dB, $K_i = 8$, $M_i = 8$, $N_k = 2$. 
Queue Minimization (Strategy A)

Figure: Total backlogged packets at the system after 1000 timeslots for each optimization objective with SNR = 20 dB, $K = 38$, $K_i = 2$, $M_i = 4$, $N_k = 2$. 

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Impact of Non-orthogonal Pilots and Direct Filter Estimation

- Local CSI estimation requires (ideally) global knowledge of the pilot sequences.
- Leads (ideally) to global pilot resource allocation.
- The beamformers can be estimated directly as adaptive filters from the effective CSI.
  - All UL/DL pilots must then be transmitted synchronously across the cells.
  - For example, DL pilots are transmitted synchronously from the BSs to estimate the receiver beamformers.
  - Automatically suppresses both intra- and inter-cell interference, as well as the impact of overlapping pilots, in the MMSE sense, of the neighboring cell pilots.
- Reduces the pilot overhead in dense systems, relative to estimating CSI.
Consider a simplified multi-cell model. The received signal at UE 1 (not considering the inter-cell interference) is

\[ y_1 = H_1 x_1 b_1^H + H_1 x_2 b_2^H + N_1 \]  

(18)

where \( H_1 \) is the channel matrix, \( x_1, x_2 \) are the pilot precoders for UEs 1 and 2, \( b_1, b_2 \) are the pilot training sequences, and \( N_1 \sim \mathcal{CN}(0, \theta_1^2 I) \) is the estimation noise.
Stream Specific Beamformer Estimation (SSE)

Consider the optimal linear MMSE receiver:

\[ u_1 = \left( H_1 x_1 x_1^H H_1^H + H_1 x_2 x_2^H H_1^H + I \sigma_1^2 \right)^{-1} H_1 x_1 \]  \hspace{1cm} (19)

To construct (19), the UE needs to estimate the intended signal and interference. Namely,

\[ H_1 x_1 \approx y_1 b_1 = H_1 x_1 b_1^H b_1 + H_1 x_2 b_2^H b_1 + N_1 b_1 \]  \hspace{1cm} (20)

\[ H_1 x_2 \approx y_1 b_2 = H_1 x_2 b_2^H b_2 + H_1 x_1 b_1^H b_2 + N_1 b_2 \]

Assuming orthonormal pilots (\( b_1 \perp b_2 \) and \( \| b_k \| = 1 \)), we have

\[ y_1 b_1 b_1^H y_1^H + y_1 b_2 b_2^H y_1^H = H_1 x_1 x_1^H H_1^H + H_1 x_2 x_2^H H_1^H + 2 \Re \{ H_1 x_1 b_1^H N_1^H \} + 2 \Re \{ H_1 x_2 b_2^H N_1^H \} + N_1 b_1 b_1^H N_1^H + N_1 b_2 b_2^H N_1^H \]  \hspace{1cm} (21)

and the expected (statistical) covariance is

\[ \mathbb{E} \left[ y_1 b_1 b_1^H y_1^H + y_1 b_2 b_2^H y_1^H \right] = H_1 x_1 x_1^H H_1^H + H_1 x_2 x_2^H H_1^H + 2 \theta_1^2 I \]  \hspace{1cm} (22)
Direct Beamformer Estimation (DE)

The MMSE receiver optimization problem can be formulated as direct estimation of a receiver that minimizes the MSE between the received signal and pilot training sequence

$$\min_{\mathbf{u}_1} \| \mathbf{b}_1^H - \mathbf{u}_1^H \mathbf{y}_1 \|^2 = \min_{\mathbf{u}_1} \mathbf{b}_1^H \mathbf{b}_1 - \mathbf{u}_1^H \mathbf{y}_1 \mathbf{b}_1 - \mathbf{b}_1^H \mathbf{y}_1^H \mathbf{u}_1 + \mathbf{u}_1^H \mathbf{y}_1 \mathbf{y}_1^H \mathbf{u}_1$$

$$\mathbf{u}_1 = (\mathbf{y}_1 \mathbf{y}_1^H + \sigma_1^2)^{-1} \mathbf{y}_1 \mathbf{b}_1$$

(23)

The covariance matrix is given by

$$\mathbf{y}_1 \mathbf{y}_1^H = \mathbf{H}_1 \mathbf{x}_1 \mathbf{b}_1^H \mathbf{b}_1 \mathbf{x}_1^H \mathbf{H}_1^H + \mathbf{H}_1 \mathbf{x}_2 \mathbf{b}_2^H \mathbf{b}_2 \mathbf{x}_2^H \mathbf{H}_1^H + \mathbf{N}_1 \mathbf{N}_1^H + 2\Re\{\mathbf{H}_1 \mathbf{x}_1 \mathbf{b}_1^H \mathbf{b}_2 \mathbf{x}_2^H \mathbf{H}_1^H\} + 2\Re\{\mathbf{H}_1 \mathbf{x}_1 \mathbf{b}_1^H \mathbf{N}_1\} + 2\Re\{\mathbf{H}_1 \mathbf{x}_2 \mathbf{b}_2^H \mathbf{N}_1\}$$

(24)
Direct Beamformer Estimation (DE)

and matched filter (MF) part is

\[ y_1 b_1 = H_1 x_1 b_1^H b_1 + H_1 x_2 b_2^H b_1 + N_1 b_1 \]  

- UE only needs to know \( b_1 \) and the received signal \( y_1 \).
- Pilots can be overlapping (non-orthogonal).

With the same assumption as before, the (statistical) covariance matrix for DE is

\[ \mathbb{E} \left[ y_1 y_1^H \right] = H_1 x_1 x_1^H H_1^H + H_1 x_2 x_2^H H_1^H + \theta_1^2 I \]  

Asymptotically, the estimation noise is invariant to the number of UEs.
Detailed Model

- OTA F-B signaling architecture under imperfect conditions.
  - Pilot training sequence used by each user are not orthogonal.
  - Effective channels cannot be distinguished from the received information.

- The forward pilot iteration is used to send transmit precoder information \( m_{k,l}^{(a)} \).

- The receiver node estimate the MMSE receivers and user MSE weights using the received pilot information.

- Backward pilots are precoded with \( \sqrt{\omega_{k,l}^{(a)} u_{k,l}^{(a)}} \). At the same time RX transmits square-root of user specific weights \( \sqrt{\omega_{k,l}^{(a)}} \) send through feedback channel

- Both backward pilot information and feedback information are used to construct the transmit precoder.
Transmit Beamformer Estimation – Backward Phase

- Received precoded pilot training matrix at DL BS $b$ is

$$
R_b^{(dl)} = \sum_{\{i,j,l\} \in A_{dl}} \sqrt{\omega_i^{(dl)} H_{b,j}^{(dl)} H_{b,j}^H + \sum_{\{i,j,l\} \in A_{ul}} \sqrt{\omega_i^{(ul)} H_{b,i}^{(dl-ul)} H_{b,j}^H + N_b^{(dl)}}}
$$

where $b_{j,l} \in \mathbb{C}^S$ denote the pilot training sequence and $N_b^{(dl)} \in \mathbb{C}^{M_b \times S}$ is the estimation noise matrix, and $A_{dl}$ and $A_{ul}$ contain the stream indices of DL and UL cells, respectively.

- Similarly, received precoded pilot training matrix at UL user $k$ is

$$
R_k^{(ul)} = \sum_{\{i,j,l\} \in A_{ul}} \sqrt{\omega_i^{(ul)} H_{i,k}^{(ul)} H_{j,l}^H + \sum_{\{i,j,l\} \in A_{dl}} \sqrt{\omega_i^{(dl)} H_{j,k}^{(ul-dl)} H_{j,l}^H + N_k^{(ul)}}}
$$

where $N_k^{(ul)} \in \mathbb{C}^{N_k \times S}$ is the estimation noise matrix.

- Transmit beamformers can be given in a closed form for both $(a) = (ul)$ and $(a) = (dl)$ as

$$
m_{k,l}^{(a)} = \left( R_r^{(a)} R_r^{(a)H} + I \nu_r^{(a)} \right)^{-1} \sqrt{\omega_k^{(a)} R_r^{(a)} b_{k,l}}
$$
Receive Beamformer and Weight Estimation – Forward Phase

The received pilot training matrix at DL user $k$ is

$$
T_{k}^{(dl)} = \sum_{\{i,j,l\} \in A_{dl}} H_{i,k}^{(dl)} m_{i,j,l}^{(dl)} b_{j,l} + \sum_{\{i,j,l\} \in A_{dl}} H_{j,k}^{(ul-dl)} m_{i,j,l}^{(ul)} b_{j,l} + N_{k}^{(dl)} \quad (30)
$$

Similarly, the received precoded pilot training matrix at UL BS $b$ is given by

$$
T_{b}^{(ul)} = \sum_{\{i,j,l\} \in A_{ul}} H_{b,j}^{(ul)} m_{i,j,l}^{(ul)} b_{j,l} + \sum_{\{i,j,l\} \in A_{dl}} H_{b,i}^{(dl-ul)} m_{i,j,l}^{(dl)} b_{j,l} + N_{b}^{(ul)} \quad (31)
$$

We can directly estimate the MMSE receivers $(a) = (ul)$ and $(a) = (dl)$ as

$$
u_{k,l}^{(a)} = \left( T_{r}^{(a)} T_{r}^{(a)H} + N_{0} I \right)^{-1} T_{r}^{(a)} b_{k,l} \quad (32)$$

and the corresponding MSE values as

$$
\epsilon_{k,l}^{(a)} = 1 - u_{k,l}^{(a)H} T_{r}^{(a)} b_{k,l} \quad (33)
$$
DE vs SSE

Define the ideal interference cov. matrix from (27) at DL BS $b$ as

$$
\Phi_{b}^{(dl)} = \sum_{\{i,j,l\} \in A_{dl}} \omega_{j,l}^{(dl)} H_{b,j}^{(dl)H} u_{j,l}^{(dl)} (H_{b,j}^{(dl)H} u_{j,l}^{(dl)})^H + \sum_{\{i,j,l\} \in A_{ul}} \omega_{j,l}^{(ul)} H_{b,i}^{(dl-ul)H} u_{j,l}^{(ul)} (H_{b,i}^{(dl-ul)H} u_{j,l}^{(ul)})^H.
$$

(34)

Similarly, (non-ideal) DE and SSE estimation matrices are given by

$$(\Phi_{b}^{(dl)})_{DE} = R_{b}^{(dl)} R_{b}^{(dl)H}$$

(35)

$$(\Phi_{b}^{(dl)})_{SSE} = \sum_{\{j,l\} \in A_{dl} \cup A_{ul}} R_{b}^{(dl)} b_{j,l} (R_{b}^{(dl)} b_{j,l})^H$$

(36)

It can be shown that

$$
E[|((\Phi_{b}^{(dl)})_{SSE} - \Phi_{b}|^2] = E[|((\Phi_{b}^{(dl)})_{DE} - \Phi_{b}|^2] + \bar{K}_{b} \bar{K}_{b}^H
$$

(37)

where $\bar{K}_{b}$ is an additional noise/contamination term.

DE is more resilient to pilot contamination
Pilot Decontamination by Pilot Allocation

- One way to mitigate pilot contamination from the system is use of intelligent **pilot allocation**.
- Simple (centralized) pilot allocation using path loss (RSSI) feedback.
- Define the utility function \( R_{P_i} \) for pilot \( i \in \{1, \ldots, N\} \) that shared with set of users \( P_i \subset U \) as,

\[
R_{P_i} = \sum_{k \in P_i} \log(1 + \sum_{j \in P_i/ \{k\}} I_j / S_k)
\]  

(38)

where \( S_k \) is the path gain between the user \( k \) and its serving BS \( b_k \), \( I_j \) is the path gain between the user \( j \) and adjacent BS \( b_k \).
- Then the unconstrained minimization problem which is used for the pilot allocation is given by

\[
\min_{P_i \forall i} \sum_{i=1}^{N} R_{P_i}
\]

(39)
**Figure:** Average Sum Rate vs. length of the training sequence

- Random pilots between cells
- Orthogonal intra-cell pilots
- 2 users per cell each with 2 stream
- $19 \times 2 \times 2 = 76$ pilots required for the fully orthogonal allocation
Figure: Average Sum Rate vs. length of the training sequence
Practical Challenges

- Aggregated scheduling block should be sufficiently long to allow for sufficient beamformer convergence and to avoid excessive overhead.
- Allocation in the nearby cells should be static during F-B training:
  - Trade-off between the channel coherence time and the size of the scheduling interval, as well as traffic burstiness.
- Basic NR bi-directional slot types defined in 3GPP cannot provide support for multiple Tx/Rx updates:
  - Additional switching slot in the beginning of the scheduling block could consist of a plurality of bi-directional F-B rounds.
  - May in practice be implemented via mini-slot structure.
- Terminals should start performing similar functions as BSs:
  - The UEs should be able to measure pilots, including the nearby users operating in reverse UL/DL mode to compute Tx/Rx beamformers.
- F-B training requires a dedicated PA/RF chain per antenna.
- Sufficient calibration of Tx/Rx RF chains both at BS and user side.
Conclusions

- Cross layer design of transmit and receive beamformers based on the number of residual packets was studied
  - An iterative solution is found by solving a series of convex subproblems
  - A practical approach via iterative computation of KKT expressions
  - Extensions of the proposed work in time-correlated fading scenario with limited information exchange

- Iterative OTA signalling methods can be used in Dynamic TDD and/or underlay D2D to handle the interference due to cross-user channels

- Pilot decontamination can be alleviated by DE

- Dynamic traffic aware cell mode (UL/DL) selection highly beneficial
On Physical Layer Aspects of 3GPP NR Rel-15

Juha Karjalainen and Antti Tölli


Special thanks to: F. Vook, M. Enescu, S. Hakola, E. Tiirola
References

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• [3] 3GPP, TR 38.913, “Study on Scenarios and Requirements for Next Generation Access Technologies”, v.1.0.0, Rel-14, 2017
• [5] 3GPP TS 38.211, “Physical channels and modulation”, 2018
• [6] 3GPP TS 38.213, “Physical layer procedures for control”, 2018
• [7] 3GPP TS 38.214, “Physical layer procedures for data”, 2018
• [8] 3GPP TR 38.874, “Study on integrated access and backhaul”, 2018
Background 3GPP Roadmap

- 3GPP features will be standardized in different **phases**, i.e. Rel-15 phase 1 and Phase-2
- To enable integration of later developed features, NR aims at **forward compatibility**

“3GPP activity towards IMT-2020”, G. Romano, www.3gpp.org
See further information on 3GPP NR standardization from 3GPP website: www.3gpp.org
Basics: Multi-Numerology (1)

- **Carrier Frequency range**: up to 52.6 GHz (phase 1 NR)
- **3GPP specification** supports **multiple OFDM numerologies** for connected mode and initial access, **sub-carrier spacing of 15*2^n kHz**
  - 15 kHz similar to LTE, good for wide area on traditional cellular bands
  - 30/60 kHz for dense-urban, lower latency and wider carrier BW
  - 60/120 kHz needed for high carrier frequency bands to combat phase noise
- Both FDD and TDD supported in NR
- NR supports 16 component carriers (CC) for carrier aggregation and dual connectivity (DC), bandwidth parts
- Initial access subcarrier spacings: 15, 30, 120 and 240 kHz

### OFDM numerologies for connected mode UE in 5G New Radio, Normal CP length

<table>
<thead>
<tr>
<th>Subcarrier spacing [kHz]</th>
<th>15</th>
<th>30</th>
<th>60</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol duration [us]</td>
<td>66.7</td>
<td>33.3</td>
<td>16.7</td>
<td>8.33</td>
</tr>
<tr>
<td>Nominal Normal CP [us]</td>
<td>4.7</td>
<td>2.3</td>
<td>1.2</td>
<td>0.59</td>
</tr>
<tr>
<td>Max BW [MHz]</td>
<td>5-50</td>
<td>5-100</td>
<td>10-400</td>
<td>50-400(*)</td>
</tr>
<tr>
<td>Max FFT size</td>
<td>2048</td>
<td>2048</td>
<td>2048</td>
<td>2048</td>
</tr>
<tr>
<td>Min scheduling interval (symbols)</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Min scheduling interval (slots)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Min scheduling interval (ms)</td>
<td>1</td>
<td>0.5</td>
<td>0.25</td>
<td>0.125</td>
</tr>
</tbody>
</table>

(*) Rel-15 supports up to 400 MHz bandwidth)

**Time-frequency scaling of LTE with scaling factor 2^n provides smooth implementation and good coexistence with LTE**
Basics: Multi-Numerology (2)

- **Forward compatible**: bandwidth parts, reduced always on signals
- **PRB(=12 sub-carriers)** corresponds to a scheduling unit in time and frequency
- The PRB size is **common** for **all numerologies**
  - Absolute duration and bandwidth of one PRB varies according to selected numberology
- NR supports **mixed numerology** based on FDM/TDM

Spectral utilization below and above 6GHz (*)

<table>
<thead>
<tr>
<th>SSC[kHz]</th>
<th>5MHz</th>
<th>10MHz</th>
<th>20MHz</th>
<th>50MHz</th>
<th>100 MHz</th>
<th>200 MHz</th>
<th>400 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 kHz</td>
<td>27</td>
<td>54</td>
<td>110</td>
<td>275</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30 kHz</td>
<td>13</td>
<td>27</td>
<td>54</td>
<td>137</td>
<td>275</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>60 kHz</td>
<td>-</td>
<td>13</td>
<td>27</td>
<td>68</td>
<td>137</td>
<td>275</td>
<td>-</td>
</tr>
<tr>
<td>120 kHz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>34</td>
<td>68</td>
<td>137</td>
<td>275</td>
</tr>
</tbody>
</table>

(*) All band options are not covered and PRB numbers are indicative

**Scalable PRB enables common control and reference signal desing for different numerologies**
Basics: Slot and Mini-Slot Structure

- **Radio Frame** (10 ms)
- **Subframe** (1 ms, defined by reference numberology 15KHz) provides absolute time reference independent from selected numerology.
- **Slot** is a basic scheduling interval. Minimum slot length is 14 OFDM symbols.
- **Slot aggregation** is supported.
- **Absolute slot length** (in terms of ms) varies according to the numerology.
- **Slot format indicator (SFO)** indicates symbol to either DL, UL or flexible (can indicate link direction over one or may slots) (dynamic via DCI or static or semi-static via RRC).
- **Low latency** requires short scheduling interval.
  - URLLC latency target with slot based scheduling can be achieved with 60 kHz SCS
  - A **Mini-slot** is needed to achieve low latency with 15 kHz SCS.

**Slot-based transmission**
- 60kHz SCS \( \rightarrow \) 0.250ms slot (14 OFDM symbols)
- Bi-directional slot \( \rightarrow \) low latency for control

**Mini-slot-based transmission**
- 15kHz SCS \( \rightarrow \) 0.071ms symbol duration
- No bi-directional mini-slot (gap overhead)

**NR is flexible in terms of adjusting the length of the scheduling interval**
**Target:** cell search & detection, coarse time and frequency synchronization, beam identification and minimum system information

- Both single and multi-beam operations supported (single port transmission)

**PSS, SSS:** coarse time & frequency synchronization, cell ID detection

**PBCH:** system information (e.g. SSB info (<6GHz: 3 bits w/ change of DRMS seq., >6GHz: 3 bits w/ change of DRMS seq + PBCH payload), SFN, PRACH res., etc.) (Polar codes used as channel code)

- Periodicities: 5, 10, 20, 40, 80 and 160ms

- In multi-beam operation SS-blocks grouped into SS-bursts
  - Max. Numb. SS-block within SS-burst sets L (gNB TX beams)
  - L=4: $f_c < 3$GHz
  - L=8: $3$GHz < $f_c < 6$GHz
  - L=64: $6$GHz < $f_c < 52.6$GHz
## Basics: 3GPP Evolution

### MIMO in 3GPP

<table>
<thead>
<tr>
<th>Release 8</th>
<th>Release 9</th>
<th>Release 10</th>
<th>Release 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 4x4MIMO</td>
<td>• 8TX TM8</td>
<td>• 8TX TM9</td>
<td>• Downlink CoMP (TM10)</td>
</tr>
<tr>
<td>• 4x2MIMO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• 8RX uplink</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Uplink CRAN</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Release 12</th>
<th>Release 13</th>
<th>Release 14</th>
<th>Release 15+</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Downlink eCoMP</td>
<td>• Massive MIMO 16TX</td>
<td>• Massive MIMO 32TX</td>
<td>• 5G / NR Massive MIMO 32TX+</td>
</tr>
<tr>
<td>• New 4TX codebook</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Basics: Downlink NR Rel-15 MIMO Framework

- Scalable and flexibly configurable framework
- Single Transmission Scheme (no transmission modes as in LTE)
- SU-MIMO: Up to 8 transmission layers per UE
- MU-MIMO: Up to 12 orthogonal DMRS (max. 4 layers per UE)
- Codeword-to-Layer Mapping
  - For 1 to 2-layer transmission: 1 codeword
  - For 3 and 4-layer transmission: 1 codeword
  - For 5 to 8-layer transmission: 2 codewords
    - For >4-layer transmission, each of the two CWs is mapped to at most 4 layers:
    - The 1st floor(L/2) layers \( \rightarrow \) CW0 and remaining layers \( \rightarrow \) CW1
### Basics: DL-MIMO Operation – Sub-6GHz

#### Single CSI-RS
- CSI-RS may or may not be beamformed
- Leverage codebook feedback
- Analogous to LTE Class A
- Process:
  - gNB transmit CSI-RS
  - UE computes RI/PMI/CQI
- Maximum of 32 ports in the CSI-RS (codebooks are defined for up to 32 ports)
- Typically intended for arrays having 32 TXRUs or less with no beam selection (no CRI)

#### Multiple CSI-RS
- Combines beam selection with codebook feedback (multiple beamformed CSI-RS with CRI feedback)
- Analogous to LTE Class B
- Process:
  - gNB transmits one or more CSI-RS, each in different “directions”
  - UE computes CRI/PMI/CQI
- Supports arrays having an arbitrary number of TXRUs
- Max 32 ports per CSI-RS

#### SRS-Based
- Intended for exploiting TDD reciprocity
- Similar to SRS-based operation in LTE
- Supports arrays having an arbitrary number of TXRUs.
- Process:
  - UE transmits SRS
  - Base computes TX weights

---

**Disclaimer:** NR-MIMO is flexible enough to support many variations on what is described on this slide
### Single Panel Array
- Combination of RF Beamforming and digital precoding at baseband
- RF Beamforming is typically 1RF BF weight vector per polarization: a single “Cross-Pol Beam”
- 2 TXRUs, Single User MIMO only
- Baseband Precoding Options:
  - None (rank 2 all the time)
  - CSI-RS based (RI/PMI/CQI)
  - SRS-based (RI/CQI)

### Multi-Panel Array
- Combination of RF beamforming and digital precoding at baseband
- RF Beamforming is typically 1RF BF weight vector per polarization per panel:
- One “Cross-Pol Beam” per sub-panel
- Number of TXRUs = 2 x # of panels
- Baseband Precoding Options:
  - CSI-RS based (RI/PMI/CQI)
  - SRS-based (RI/CQI)
- SU- and MU-MIMO (typically one UE per Cross-Pol Beam)
Basics: MIMO - Physical and Logical Array Configurations

- **8 columns**
  - (8,8,2) 128
  - 16 Ports: 1 Row of TXRUs
  - 32 Ports: 2 Rows of TXRUs

- **4 columns**
  - (8,4,2) 64
  - 16 Ports: 2 Rows of TXRUs
  - 32 Ports: 4 Rows of TXRUs

- **2 columns**
  - (8,2,2) 32
  - 16 Ports: 4 Rows of TXRUs
  - 32 Ports: 8 Rows of TXRUs
Basics: MIMO - Beam Management

- **Beam management** aims at align TX and RX beams both at gNB and UE (includes L1 and L2 procedures) for different physical channels/RSs and channels transmission
  - **DL**: PDCCH, PDSCH, TRS, CSI-RS, SSB
  - **UL**: PUCCH, PUSCH, SRS, PRACH
- Beam management distributed accross initial and connected mode operations (applicable above 6GHz)
- Beam management for DL and UL includes
  - **DL and UL beam “training”** procedures (P1-P3 & U1-U3)
  - **Beam recovery**: e.g. signal blockage re-establish failed control link between gNB and UE
  - **Beam Indication**: gNB provides beam indication info to enable UE to know which TX beam used for DL (UE can select its RX beam) and which TX beam used for UL (TX beam is align with RX beam at gNB)
  - **Beam measurements** (SSB and CSI-RS) and **reporting** e.g. different beam grouping schemes
Status of Dynamic TDD Cross-link Interference Mitigation in 3GPP NR Rel-15

- Study item of 3GPP NR Identified large amount different x-link interference mitigation techniques in TR 38. 802:
  - **Advanced receivers**: no restrictions UL/DL suppressed at the receiver by advanced receiver algorithm, e.g. MMSE-IRC
  - **Power control**: TRP-to-TRP interference can mitigated by UL TX power control
  - **Coordinated scheduling** among gNBs
  - **Sensing, etc.**

- NR Rel-15 RAN1 work related to cross-link interference (CLI) measurements and mitigation mechanisms have been de-prioritized beyond December 2017
  - Fully dynamic TDD supported in NR Rel-15 by dynamically assigning DL and UL transmission directions at least for data on a per-slot basis.
  - Introduce CLI measurements for UE-to-UE in Rel-15
  - Not to specify in Rel-15 TRP-to-TRP (DL-to-UL) cross-link interference measurement (vendor specific feature, i.e. scheduler)

- CLI mitigation techniques and requirement have not been specified → Rel-15 provides limited support for dynamic TDD operation
NR Rel-15 L1 Building Blocks for Cross-Link Interference (CLI) Mitigation

- Dynamic coordination of slot and frame structure (earlier slides)
  - With semi-static configuration CLI problems can be avoided → lack of flexibility and inefficient use of time and frequency resources
- NR DL & UL MIMO Framework (earlier slides)
- Network based interference avoidance mechanisms where CLI is measured and reported
- Rel-15 DL and UL reference signals
  - Enabling CLI measurements (intended and interfering signal(s))
    - DL & UL demodulation reference signals (DMRS)
    - DL Channel State Information reference signals (CSI-RS)
    - UL Sounding Reference Signals (SRS)
- Interference measurement resources
  - Channel State Information Interference Measurement (CSI-IM)
  - Non-Zero-Power (NZP)-CSI-RS
NR Rel-15 L1 Building Blocks for CLI Mitigation: Interference Measurement Resource Settings (1)

- **Rel-15** has been mainly built to support **DL-DL** interference measurements
- **Rel-15** supports **three** different **CSI** measurement settings to be higher layer configured for UE
  - **One** for *channel measurements*: one resource setting
    - **NZP CSI-RS** resource: DL CSI-aquisition, beam management, etc. (further details in up coming slides)
  - **Two** for *interference measurements*:
    - **CSI-IM** resource:
      - configurable "measurement window" enabling interference measurement
      - Number of CSI-RS resources equals to the number of CSI-IM resources
    - **NZP-CSI-RS** resource:
      - 1 resource set for channel and multiple sets for interference (max. 18 APs)

**Note**: NR Rel-15 does not provide support for specific CLI measurement resources. (To be further discussed in Rel-16)
NR Rel-15 supports **two** different interference measurement resources (targetted for DL-DL)

- **CSI-IM**: Flexibly configured resource for interference measurements
  - resource type: Periodic, semi-persistent, aperiodic
  - Resource set(s) including one or more CSI-IM resources
  - Resource supports **two CSI-IM RE-measurement patterns**
    - 2-2:
      - Sub-carrier locations: \{0, 2, 4, 6, 8, 10\}
      - Symbol positions: \{0, ...,12\}
    - 4-1:
      - Sub-carrier locations: \{0, 4, 8\}
      - Symbol positions: \{0, ...,13\}
  - Resources for channel and interference measurements are **spatially quasi-co-located** with each others (applicable above 6GHz)

- **NZP-CSI-RS**: UE assumes that each port configured corresponds interference layer

---

Example of UL-to-DL CLI measurement scenario on FR2 (above 6GHz)
NR Rel-15 L1 Building Blocks for CLI Mitigation: UL/DL Demodulation Reference Signal (DMRS) (1)

- **Target:**
  - Demodulation reference signal for
    - **PBCH** (broadcast), PDCCH (unicast)
    - **PDSCH** (unicast and broadcast/multicast) and PUSCH (unicast)
  - Support both **OFDM** (UL/DL) and **DFT-S OFDM** (UL)
  - Support **SU/-MU-MIMO** and **COMP**-type transmission

- **Resource configurations in frequency and time**
  - Slot and non-slot based (mini-slot,) both types, i.e. 1 & 2, supported
  - UE specifically configured
  - aperiodic/periodic/semi-persistent
  - Dynamic resource selection/activation
  - Number of APs and Allocation in time
    - Supported APs:
      - 1, 2, 3, 4, 6, 8, **12** (max. MU-MIMO)
      - Max. 4 Aps per UE
    - **Multi-Shot** DL DMRS w/ PDSCH (1-2 FL + 1-3 extra)
    - **Configurable** symbol locations:
      (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14) (with some restrictions due to multiplexing)
    - **1 extra:** w/ **1-symbol front-loaded** DMRS (3rd or 4th) one additional DMRS for PDSCH configured in **8th**, **10th** and **12th** symbol (just example)

- **2 extra:** w/ **1-symbol front-loaded** DMRS (3rd or 4th) in **(8th,12th)** or **(7th,12th)** symbol (just example)
- **3 extra:** w/ **1-symbol front-loaded** DMRS (3rd or 4th) in **6th,9th** and **12th** symbol (to support HST w/ low SCS) (just example)
  - For the **2-symbol front-load DMRS**, the 2-symbol additional DMRS symbol is configured in (just example)
    - **(9th,10th)** w/ PDSCH spanning to 10th or 11th or 12th symbol
    - **(11th,12th)** w/ PDSCH spanning to 13th or 14th symbol

- **UL DMRS:** UL and self-contained, mini-slot
  - FL DMRS (self.) located to 1st symbol

- **Numerology**
  - Rel-15 supports same numerology between PDSCH and DMRS
  - Rel-15 supports same numerology between PDCCH and DMRS

- **Multiplexing**
  - DMRS can be FDM:ed w/ PDSCH
  - DMRS can be FDM:ed w/ PUSCH (CP-OFDM)
  - DMRS can be TDM:ed w/ PUSCH (DFT-S-OFDM)
Potential RE locations for PDCCH and DMRS
Potential RE locations for DMRS AP1
Potential RE locations for DMRS AP2
Potential RE locations for DMRS AP3
Potential RE locations for DMRS AP4
Potential RE locations for CSI-RS APs 1-2
Potential RE locations for CSI-RS APs 3-4
Potential RE locations for CSI-RS APs 5-6
Potential RE locations for CSI-RS APs 7-8
Potential RE locations for PDSCH

Sequence:
- Resource specific, Pseudo-Noise (PN) (CP-OFDM) and Zadoff-Chu (DFT-S-OFDM)

Sequence initialization:

\[ c_{\text{init}} = \left(2^{17}(14n_s + l + 1)2^{n_{\text{SCID}}} + 1 + 2^{n_{\text{ID}}} + n_{\text{SCID}}\right) \mod 2^{31} \]

- where, \( n_s \) slot number and \( l \) OFDM symbol number within slot, \( n_{\text{SCID}} \{0,1\} \) related to scrambling ID and \( n_{\text{ID}} \{0,...,65535\} \) (10 + 6 fixed bits) higher layer configured parameter.

- UL and DL can be configured separately

1 PRB=12 RE

1 FL+1 extra

1 PRB=12 RE

1 FL+3 extra
NR Rel-15 L1 Building Blocks for CLI Mitigation: UL/DL DMRS (3)

- **RE patterns for PDSCH and PUSCH (CP-OFDM):**
  - Possible to configure two different RE configurations
  - >4 APs can be achieved by symbol aggregation

- **RE patterns for PUSCH (DFT-S-OFDM):**
  - **Comb-2**, 2 cyclic-shifts (up to 4 APs)
  - Sequence design: Zadoff-Chu

- **RE patterns for PBCH and PDCCH:**
  - **Broadcast (PBCH):**
    - Single AP
    - Sequence: Pseudo-Noise (reuse of LTE)
  - Single cast transmission (PDCCH)
    - Number of Aps: 1
    - User-specifically initialized
  - **Comb-4** (every 4th-RE)
    - DMRS FDM:ed w/ PBCH over 24 PRBs
    - DMRS FDM:ed w/ PDCCH over assigned PRBs/REGs

- **Broadcast/multi-cast PDSCH**
  - **Type-1**, up to 4 symbols
  - Single AP
  - Sequence: Pseudo-noise
  - **Comb-2**
NR Rel-15 L1 Building Blocks for CLI Mitigation: Channel State Information Reference Signal (CSI-RS) (1)

- **Design targets:**
  - **DL CSI acquisition** (CSI report) (Non-Zero power (NZP), and Zero power (ZP)),
  - **DL interference measurements:** CSI-IM resources
  - **DL Beam management** (beam reporting; L1-RSRP measurements) (NZP)
  - **DL Mobility RS** (handovers, RSRP measurements from neighboring cells)
  - **Time frequency tracking:** residual time-frequency tracking, Dopper spread, delay spread estimation

- **Configurations in frequency and time**
  - Full/partial band configurations supported
    - Resources on BWP w/ transmission BW equal or smaller than BWP
      - When TX BW smaller than BWP, CSI-RS spans contiguous RBs in the granularity of 4 RBs
  - Periodic, aperiodic and semi-persistent transmission
  - RE- Patterns
    - >10 different RE-patterns supported
    - Support for #Aps \(\{1,2,4,8,12,16,24,32\}\)
  - Symbol locations
    - **Multi-shot** up to 4 symbols per slot
    - **Configurable** symbol locations: \(\{1,2,3,4,5,6,7,8,9,10,11,12,13,14\}\) (with some restrictions due to multiplexing)

- **Periodicities:** 5, 10, 20, 40, 80, 160, 320, 640 slots

- **AP indexing:** within CDM group then across CDM groups

- **Sequence design:**
  - Use length-31 Gold sequence as in LTE
  - CSI-RS sequence initialization formula
    \[ c_{\text{init}} = (2^{10} \times (14n_s + l + 1)(2N_{ID} + 1)) + N_{ID} \mod 2^{31} , \]
    where \(n_s\) denotes slot index within a frame, and \(l\) is OFDM symbol index within a slot and \(N_{ID} \in \{0,1,\ldots,2^{10} - 1\}\) is UE specifically configured scrambling ID (with 10 bits)

- **Numerology**
  - Rel-15 supports same numerology between PDSCH and CSI-RS

- **Multiplexing**
  - w/ PDSCH (FDM w/ RM)
  - w/ DMRS
  - w/ SS-block (FDM not within same RBs w/ spatial QCL )
  - w/ PDCCCH (FDM not within same RBs w/ spatial QCL)
<table>
<thead>
<tr>
<th>APs (X)</th>
<th>Density [RE/PRB/Port]</th>
<th>N</th>
<th>(Y,Z)</th>
<th>CDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt;1, 1, 1/2</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1, 1/2</td>
<td>1</td>
<td>(2,1)</td>
<td>FD CDM-2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>(4,1)</td>
<td>FD CDM-4</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>(2,1)</td>
<td>FD CDM-2</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
<td>(2,2)</td>
<td>FD CDM-2, CDM4(FD2, TD2)</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1</td>
<td>(2,1)</td>
<td>FD CDM-2</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>2</td>
<td>(2,2)</td>
<td>CDM4(FD2, TD2)</td>
</tr>
<tr>
<td>16</td>
<td>1, 1/2</td>
<td>2</td>
<td>(2,2)</td>
<td>FD CDM-2, CDM4(FD2, TD2)</td>
</tr>
<tr>
<td>24</td>
<td>1, 1/2</td>
<td>4</td>
<td>(2,2)</td>
<td>FD CDM-2, CDM4(FD2, TD2)</td>
</tr>
<tr>
<td>32</td>
<td>1, 1/2</td>
<td>4</td>
<td>(2,2)</td>
<td>FD CDM-2, CDM4(FD2, TD2), CDM8(FD2, TD4)</td>
</tr>
</tbody>
</table>
NR Rel-15 L1 Building Blocks for CLI Mitigation: CSI-RS, Potential RE-Patterns for BM

- Number of APs: 1 - 2 (*)
- Support for both normal and extended CP (BM)

Frequency domain RE-patterns:

- $X=1(*)$, $N=1$, w/o CDM
- $X=2$, $N=1$, w/ CDM

$D=1$, $D=2$, $D=3$, $D=6$

1 PRB = 12 RE

OCC-2
NR Rel-15 L1 Building Blocks for CLI Mitigation: UL Sounding Reference Signal (SRS) (1)

- **Target:**
  - **UL CSI acquisition** covering freq. selective scheduling (MCS/CQI/RI) and CSI
  - **DL CSI acquisition** (e.g. non-codebook based transmission)
  - **UL beam management**
  - Support for both OFDM and DFT-S OFDM (UL)
  - Support for SU- and MU-MIMO transmission

- **Resource configurations in frequency and time**
  - Different groups for UL BM, DL/UL CSI acquisition
  - **User-specifically** configured including also configurable bandwidth (full/partial)
    - At least 4 PRB
  - **Periodic, semi-persistent and Aperiodic** transmissions supported
    - For aperiodic, UE can configured to transmit subset of all or all of resources w/o precoding or w/ same or different precoding
    - Support for 1, 2, 5, 10, 20, 40, 80, 160, 320, 640, 1280, 2560 periodicity w/ all SCSs
    - RE-patterns & allocation in time and frequency
    - SRS resource can be configured in the last 6 symbols in a slot
    - Supported #APs: **1, 2, 4** (for Rel-15 UEs)
    - **Comb-2** and **Comb-4 + cyclic shifts** (8, and 12)
    - **Multi-shot SRS:**
      - **1, 2, 4, adjacent OFDM symbols** within same slot (can mapped to last 6 six, if no PUSCH, whether SRS can be TX between PUSCH symbols)

- **Configurable frequency hopping**
  - Enables channel sounding of UE full bandwidth in narrow band SRS transmission
  - Intra/inter slot
  - Among CCs (one active in CC switching between active and inactive)

- **Antenna Switching**
  - To enable channel sounding for DL CSI acquisition (UE may have less TX RF-chains w.r.t RX RF-chains)
  - UE can use 1-4 TX APs for channel sounding
  - Inter and inter-slot switching

- **Numerology**
  - Rel-15 supports same numerology between PUSCH and SRS

- **Multiplexing**
  - SRS can be TDM:ed w/ PUSCH
  - SRS can be TDM:ed w/ PUCCH

- **Sequence**
  - User specifically configured
  - Zadoff-Chu (LTE based) initialized by sequence ID (10-bits)
  - Seq. length 272 PRB (max. BW in NR, in LTE 96 PRB)

- **UL precoder determination**
  - DCI CSI-RS resources to be used to calculate the precoder of the precoded SRS for aperiodic transmission
Based on UL measurements, gNB selects UE TX beam with SRI among configured resources and indicates SRI via DCI/MAC CE.
- **DL CSI acquisition** based on **UL SRS** sounding when $N_{rx} > N_{tx}$

- To enable UL TX antenna switching, higher layer parameter **SRS-SetUse** is set to ‘**Antenna Switching**’

- **Four** configurations supported depending on UE capability:
  - **Single SRS resource set** with **two SRS** resources in different symbols
    - Each resource consists of single or two SRS ports
    - SRS port of the second resource is associated with a different UE antenna port than the SRS port of the first resource SRS port of second
  - **Two SRS resource sets** with four **SRS resources** different symbols of **two different slots**
    - Each set configured with two SRS resources, or one set is configured with one SRS resource and the other set is configured with three SRS resources

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**NR Rel-15 L1 Building Blocks for CLI Mitigation: UL SRS for UE TX Antenna Switching (3)**

- **UE** w/ only **1 TX pane** at **same time**

- **No TX**

- **RX Panel#1**: SRS resource
- **RX Panel#2**: SRS resource
- **Set#3**: Antenna switching

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**an example of single SRS set w/single port resources**

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Agreed Study and Work Items Related to CLI in NR Rel-16

- two different SIs ongoing and two WIs to start related to CLI in NR Rel-16
Integrated Access and Backhaul (IAB) in NR Rel-16: CLI Aspects

- In ongoing 3GPP Rel-16 (RAN1 & RAN2), there is a study item to identify and evaluate potential solutions for efficient integrated access and backhaul for NR (will be capture in TR 38.874).
  - Including multi-hop backhaul
- As part of dynamic resource allocation between backhaul and access links, cross-link interference (CLI) measurement, coordination/management and mitigation between TRPs and UEs is studied.
  - Advanced receivers and transmitter coordination
- NR Rel-15 physical layer works as basis for physical layer of the IAB backhaul link
- IAB supports TDM, FDM, and SDM between access and backhaul links at an IAB-node, subject to a half-duplex constraint.
- For SDM / FDM scenario
  - TX: IAB node simultaneously transmit in DL (access UE and/or child IAB) and in UL (to parent IAB node)
  - RX: IAB node simultaneously receives in DL (transmission from parent node) and receives in UL (from access UE and/or child IAB node)

RP-170821: “Study on Integrated Access and Backhaul for NR”, AT&T, Qualcomm, Samsung
Integrated Access and Backhaul (IAB) in NR Rel-16: CLI Scenarios

- Cross-link interference mitigation techniques need to cover the following inter IAB node interference scenarios (*):
  - **Case 1**: Victim IAB node receives in **DL** in the backhaul link, interfering IAB node transmits in **UL** in the backhaul link.
  - **Case 2**: Victim IAB node receives in **DL** in the backhaul link, interfering IAB node transmits in **DL** in the access link.
  - **Case 3**: Victim IAB node receives in **UL** in the access link, interfering IAB node is transmitting in **UL** in the backhaul link.
  - **Case 4**: Victim IAB node receives in **UL** in the access link, interfering IAB node transmits in **DL** in the access link.

(*) RAN1-#93, Busan, Korea, RAN1 chairman's notes