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

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Dynamic 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**


2. 3GPP TSG RAN WG1, "Study on scenarios and requirements for next generation access technologies TR 38.913," 3rd Generation Partnership Project 3GPP, www.3gpp.org, 2016
Dynamic TDD

Figure: UL-DL/DL-UL interference in Dynamic 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

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System Model & Problem Formulation

1. slot allocation
   - Uplink
   - Downlink

- 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 uplink (UL) / downlink (DL) cell mode selection, TX/RX design and resource allocation over spatial and frequency resources
Queueing Model

- Each user is associated with backlogged packets of size $Q_k$.
- Queued DL (UL) packets $Q_k$ ($\bar{Q}_k$) of each user follows dynamic equation at the $i$th instant as

$$Q_k(i + 1) = \left[ Q_k(i) - t_k(i) \right]^+ + \lambda_k(i) \quad (1)$$

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 $b_k$.
- Separate user specific queues for UL and DL traffic.
Objective

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

\[
\min_{t_k, \bar{t}_k} \sum_{k \in U} \alpha_k |v_k|^q + \beta_k |u_k|^q 
\]  

(2)

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

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

(3)

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

(4)

- \(q = 1, 2, \ldots, \infty\) 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\(^5\)

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

\((5)\)

### UL SINR

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

\((6)\)

\(^5\)Note that UL-DL and DL-UL interference terms in (5), and (6), 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

\[
\begin{align*}
\text{min.} & \quad \| \tilde{\mathbf{v}} \|_q + \| \tilde{\mathbf{u}} \|_q \quad (7a) \\
\text{s. t.} & \quad \gamma_{l,k,n} \leq \Gamma_{l,k,n} \quad \forall \ l, k, n \quad (7b) \\
& \quad \tilde{\gamma}_{l,k,n} \leq \tilde{\Gamma}_{l,k,n} \quad \forall \ l, k, n \quad (7c) \\
& \quad \sum_{n=1}^{N} \sum_{k \in \mathcal{U}_b} \sum_{l=1}^{L} \| \mathbf{m}_{l,k,n} \|_2^2 \leq x_b P_{\text{max}} \quad \forall \ b \quad (7d) \\
& \quad \sum_{n=1}^{N} \sum_{l=1}^{L} \| \bar{\mathbf{m}}_{l,k,n} \|_2^2 \leq \bar{x}_{b_k} P_{\text{max}}^{\text{UE}} \quad \forall \ k \quad (7e) \\
& \quad x_b + \bar{x}_b = 1 \quad \forall \ b, \quad x_b \in \{0, 1\}, \quad \bar{x}_b \in \{0, 1\} \quad (7f)
\end{align*}
\]

where \( \tilde{v}_k \triangleq \frac{1}{a_k^q} (Q_k - \sum_{n=1}^{N} \sum_{l=1}^{L} t_{l,k,n}) \) 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 (7b) are relaxed as\(^6\) (UL similarly)

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

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

\[
+ \sum_{i \in \mathcal{U}\setminus\mathcal{U}_{b_k}} \sum_{j=1}^L |w_{l,k,n}^H \tilde{H}_{i,k,n} \tilde{m}_{j,i,n}|^2
\]

where

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

- 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 (7) becomes convex (for fixed receivers, at any given linearization point of the SINR constraints)

- **Sparsity must be enforced!** → Use a regularization function

  \[
  \min \| \tilde{v} \|_q + \| \tilde{u} \|_q + \psi \sum_{t=1}^{N_B} (\log(x_b + \epsilon) + \log(\bar{x}_b + \epsilon)) \quad (10)
  \]

  successively linearized as

  \[
  \min \| \tilde{v} \|_q + \| \tilde{u} \|_q + \psi \sum_{b=1}^{N_B} \left( \frac{x_b - x_b^{(i)}}{x_b^{(i)} + \epsilon} + \frac{\bar{x}_b - \bar{x}_b^{(i)}}{\bar{x}_b^{(i)} + \epsilon} \right) \quad (11)
  \]

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Simulation Setup

1. slot allocation

- **Uplink**
- **Downlink**

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

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Numerical Example

![Graph showing average queue backlog (bits) vs. arrival rate (A).]

**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 \((1 - \alpha)A + \alpha\beta A\).
Next Steps

- 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