Fairness-aware Joint Routing and Scheduling in OFDMA-based Cellular Fixed-Relay Networks

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Outline

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- System Model
- The BS Algorithm for Joint Routing and Fair Scheduling
  - Mathematical Formulation of the Resource Allocation at the BS
  - The Low-complexity Iterative Algorithm
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- Conclusion

Background

- Orthogonal frequency division multiple access (OFDMA) and relaying are the envisioned technologies for the future broadband wireless communication networks (as in LTE-A, IEEE 802.16j and 802.16m)
- Aggressive channel reuse is required
- Efficient radio resource management (RRM) is crucial to exploit the opportunities offered by such networks
- Interference associated with aggressive channel reuse schemes could put cell edge users at a disadvantaged situation
- The conventional (opportunistic) scheduler will rarely serve users in such a bad channel condition;

  → defeats ubiquitous coverage

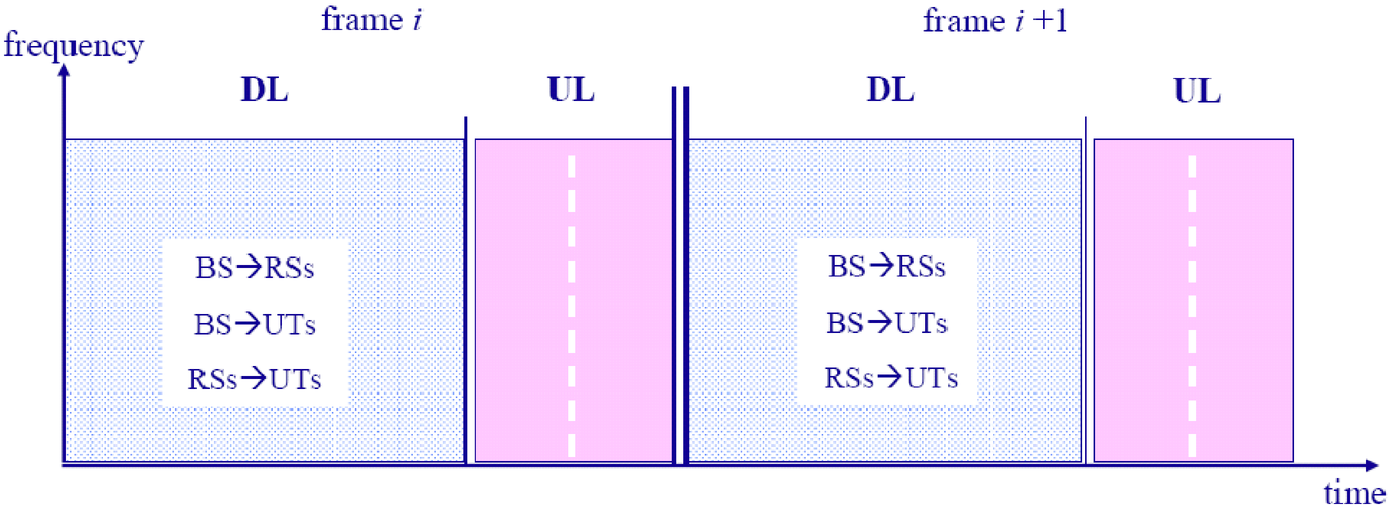
  → exposes the importance of fair algorithms
- Relays introduce more opportunities as well as new challenges such as routing

Background: Shortcomings in existing works

- ❑ Single-cell or single-relay scenarios are often considered to enable analysis
- ❑ Fairness is often not incorporated
- ❑ Resource partitioning is often considered to reduce inter-cell interference and the size of the optimization problem → suboptimal and requires planning
- ❑ Decoupled routing and scheduling for simplicity → suboptimal
- ❑ Full-queues assumption → traffic diversity is not exploited
- ❑ Load balancing (even distribution of subchannels among nodes) is either ignored or performed as a refinement process which affects the optimality of the allocation
- ❑ Over-simplified channel models
- ❑ Usually difficult to accommodate different service classes

System Model

- OFDMA-based cellular network in TDD mode
- Downlink scenario
- *K* users, *M* fixed digital relay stations (RSs) per
- OFDM subchannel is the basic allocation unit, *N* subchannels



- Any user terminal (UT) in a cell can be connected to any combination of nodes (generic ‘open’ routing)
  → Not restricted to a particular geographical deployment of relay stations
- In any cell, the serving BS and each of the *M* RSs have *K* user buffers

- Relays can receive and transmit different data concurrently on different orthogonal subchannels (quasi-full-duplex)
- User terminals can receive from multiple nodes (BS or RSs) simultaneously on different subchannels

System Model

- Fixed power allocation for BSs and RSs per subchannel
- Adaptive modulation is assumed (CR-QAM) so that on each subchannel the achievable Tx. rate is a function of the received SINR at destination node (user or relay) and the target BER as in [X.Qiu 1999]

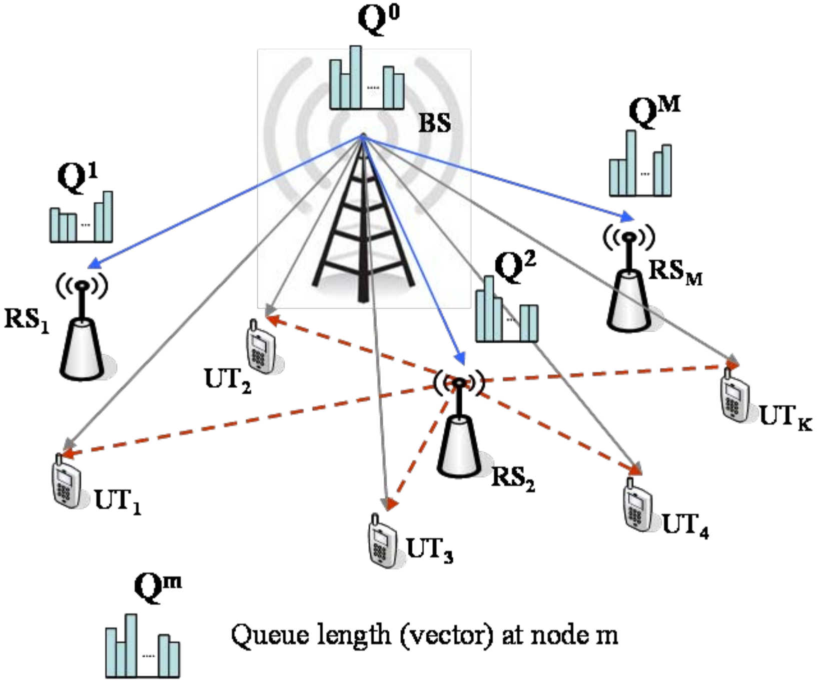
$$R_{org,dest,n} = W \log_2\left(1 + \frac{-1.5}{\ln(5.P_e)} SINR_{dest,n}\right)$$

- CSI is available at transmitter

Mathematical Formulation of the RRA at the BS

- Sum-demand (Sum-utility) maximization formulation
- The demand metric employed is proportional to the queue length at the source node and the achievable rate on its link to destination

- [Viswanathan 05]
  - A centralized joint scheduling and routing algorithm
  - Single-carrier CDMA relay network
  - Not applicable to multi-carrier networks



- We propose a novel formulation and a novel low complexity cell-level centralized algorithm for downlink OFDMA-based multi-cell fixed relay networks that
  - Maximizes total cell throughput
  - Achieves a high degree of fairness
  - Has a learning routing (relay-selection) strategy
  - Substantially improves cell-edge performance
  - Enables intra-cell load balancing

Mathematical Formulation of the RRA at the BS

- **Definition of the demand metric of RS$_m$ on subchannel n**

$$D_{n,m\rightarrow UT_k} = R_{m,k,n} Q_k^m$$

$$D_{n,m} = \max_k \{R_{m,k,n} Q_k^m\}$$

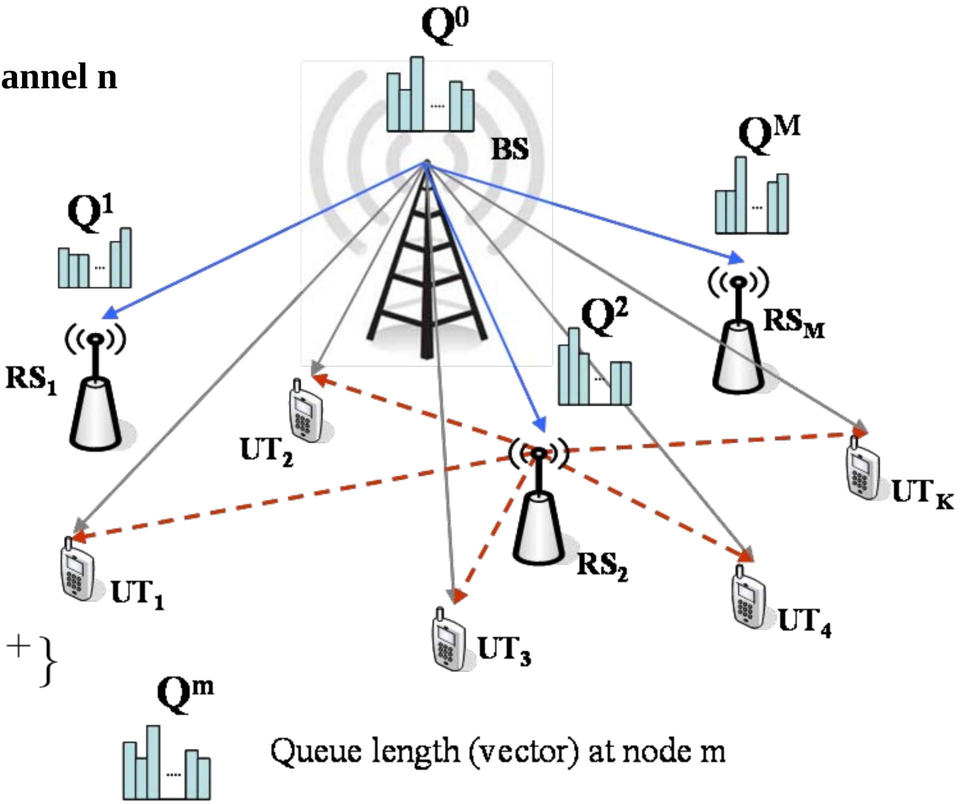
- **Definition of the demand metric of the BS on subchannel n**

$$D_{n,BS\rightarrow RS_m} = R_{0,m,n} \max_k \{(Q_k^0 - Q_k^m)^+\}$$

$$D_{n,0} = \max_j \{D_{n,BS\rightarrow j}\}$$

$j \in \mathcal{K} \cup \mathcal{M}$

The demand metric on BS-RS links incorporates the queues at the BS and those at the RS



Objective: Maximize the total cell throughput while maintaining fairness among users.

BILP Mathematical Formulation

$$\max_{\rho,\gamma} \left\{ \sum_{n=1}^{N} \sum_{m=0}^{M} \sum_{k=1}^{K} \rho_{m,k,n} R_{m,k,n} Q_k^m + \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{0,m,n} R_{0,m,n} \max_k \{ (Q_k^0 - Q_k^m)^+ \} \right\},$$

s.t.

$$\rho_{m,k,n} \in \{0,1\} \ \forall_{m,k,n}, \ \gamma_{0,m,n} \in \{0,1\} \ \forall_{m,n},$$

$$\sum_{m=0}^{M} \sum_{k=1}^{K} \rho_{m,k,n} + \sum_{m=1}^{M} \gamma_{0,m,n} \leq 1 \ \forall_n,$$

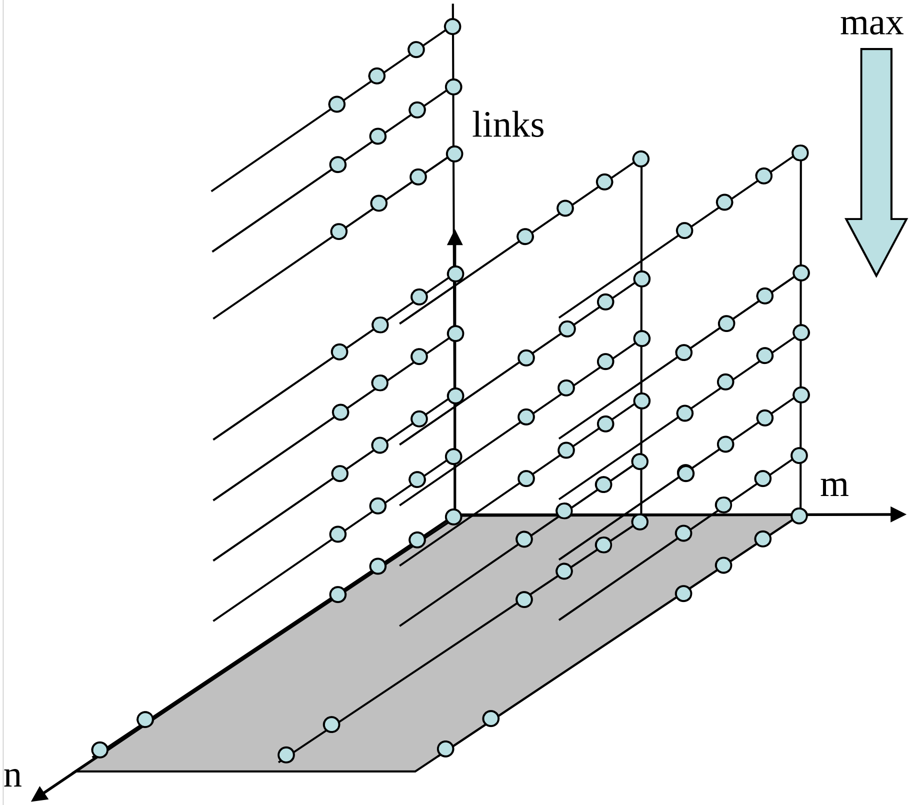
$$\sum_{n=1}^{N} \sum_{k=1}^{K} \rho_{0,k,n} + \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{0,m,n} \geq \mu,$$

$$\sum_{n=1}^{N} \sum_{k=1}^{K} \rho_{m,k,n} \geq \lfloor N/(M+1) \rfloor \quad \forall_{m \neq 0},$$

$$T \sum_{n=1}^{N} \left(\rho_{0,k,n} R_{0,k,n} + \sum_{m=1}^{M} \gamma_{0,m,n} R_{0,m,n} \kappa_k^m \right) \leq Q_k^0 \ \forall_k,$$

$$T \sum_{n=1}^{N} \rho_{m,k,n} R_{m,k,n} \leq Q_k^m \quad \forall_{m,k}, \ m \neq 0,$$

where $\kappa_k^m = \begin{cases} 1, & k = \arg\max_j \{Q_j^0 - Q_j^m\}^+ \\ 0 & \mathit{otherwise}. \end{cases}$



The Low-complexity Iterative Algorithm

1) For each unassigned subchannel, calculate the demand metric for each RS and the BS as defined earlier

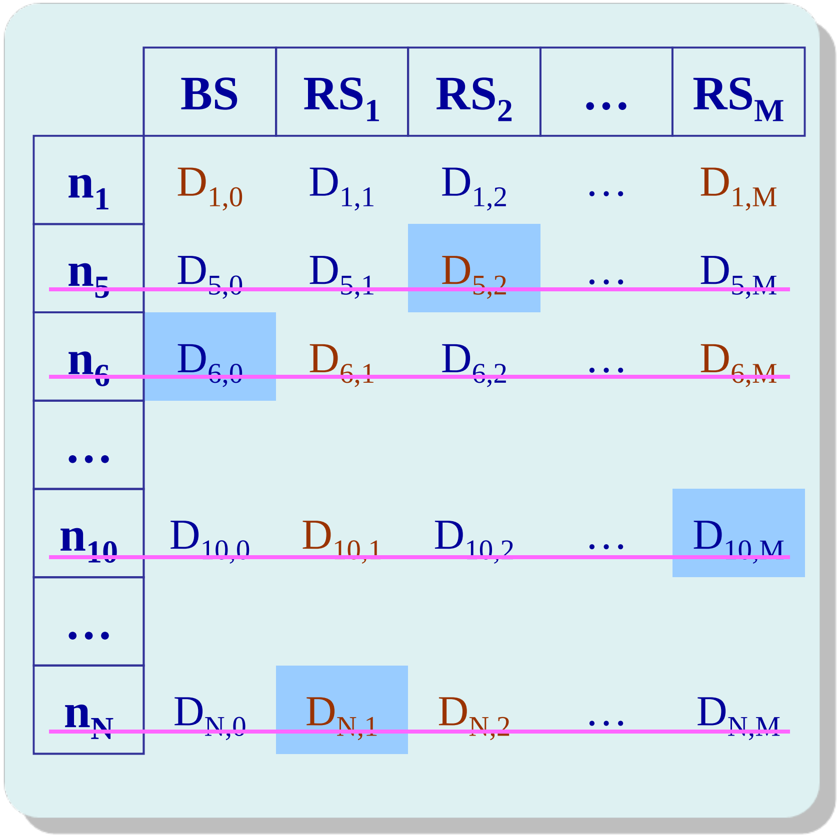
2) The algorithm solves a one-to-one optimization problem by applying the Hungarian Algorithm to the N-chunks by (M+1)-Tx nodes Demand matrix $[D_{n,m}]$

3) The algorithm virtually updates the affected user queues accordingly (entries shown in red)

$$Q_k^{m(i+1)} = \left(Q_k^{m(i)} - \lfloor R_m^{(i)} T \rfloor\right)^+$$

4) Eliminate assigned subchannels

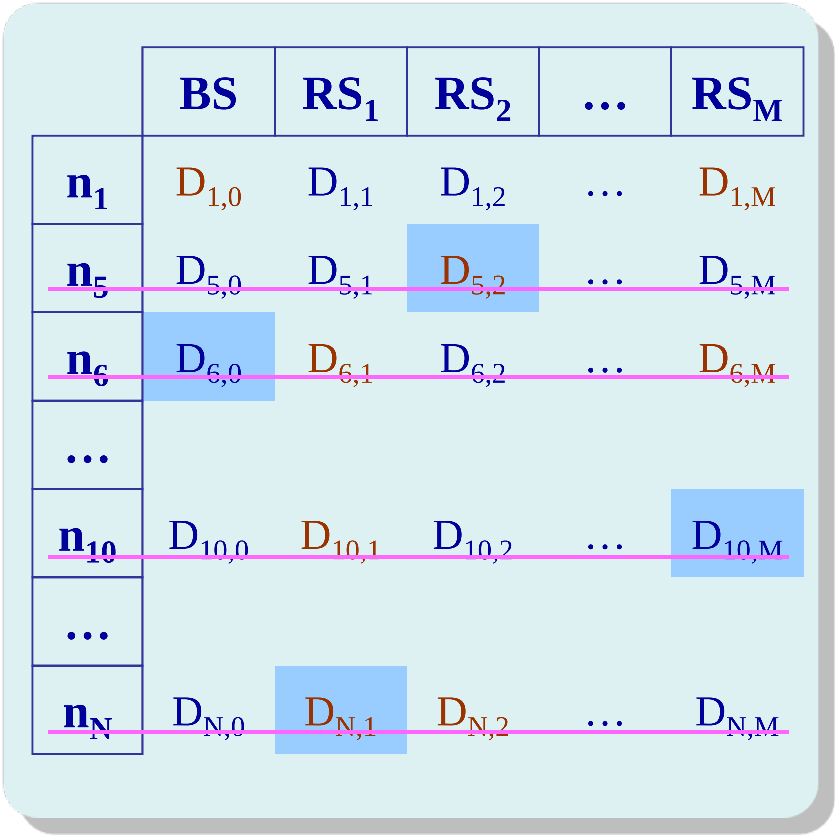
5) Repeat steps 1) to 4) until all the packets in user buffers are scheduled or the chunks are exhausted. The number of iteration is $\left\lceil \frac{N}{M+1} \right\rceil$



	BS	**RS_1**	**RS_2**	**…**	**RS_M**
n_1	$D_{1,0}$	$D_{1,1}$	$D_{1,2}$	…	$D_{1,M}$
~~**n_5**~~	~~$D_{5,0}$~~	~~$D_{5,1}$~~	~~$D_{5,2}$~~	~~…~~	~~$D_{5,M}$~~
~~**n_6**~~	~~$D_{6,0}$~~	~~$D_{6,1}$~~	~~$D_{6,2}$~~	~~…~~	~~$D_{6,M}$~~
…					
~~**n_{10}**~~	~~$D_{10,0}$~~	~~$D_{10,1}$~~	~~$D_{10,2}$~~	~~…~~	~~$D_{10,M}$~~
…					
~~**n_N**~~	~~$D_{N,0}$~~	~~$D_{N,1}$~~	~~$D_{N,2}$~~	~~…~~	~~$D_{N,M}$~~

Pseudo-code for the Iterative Algorithm

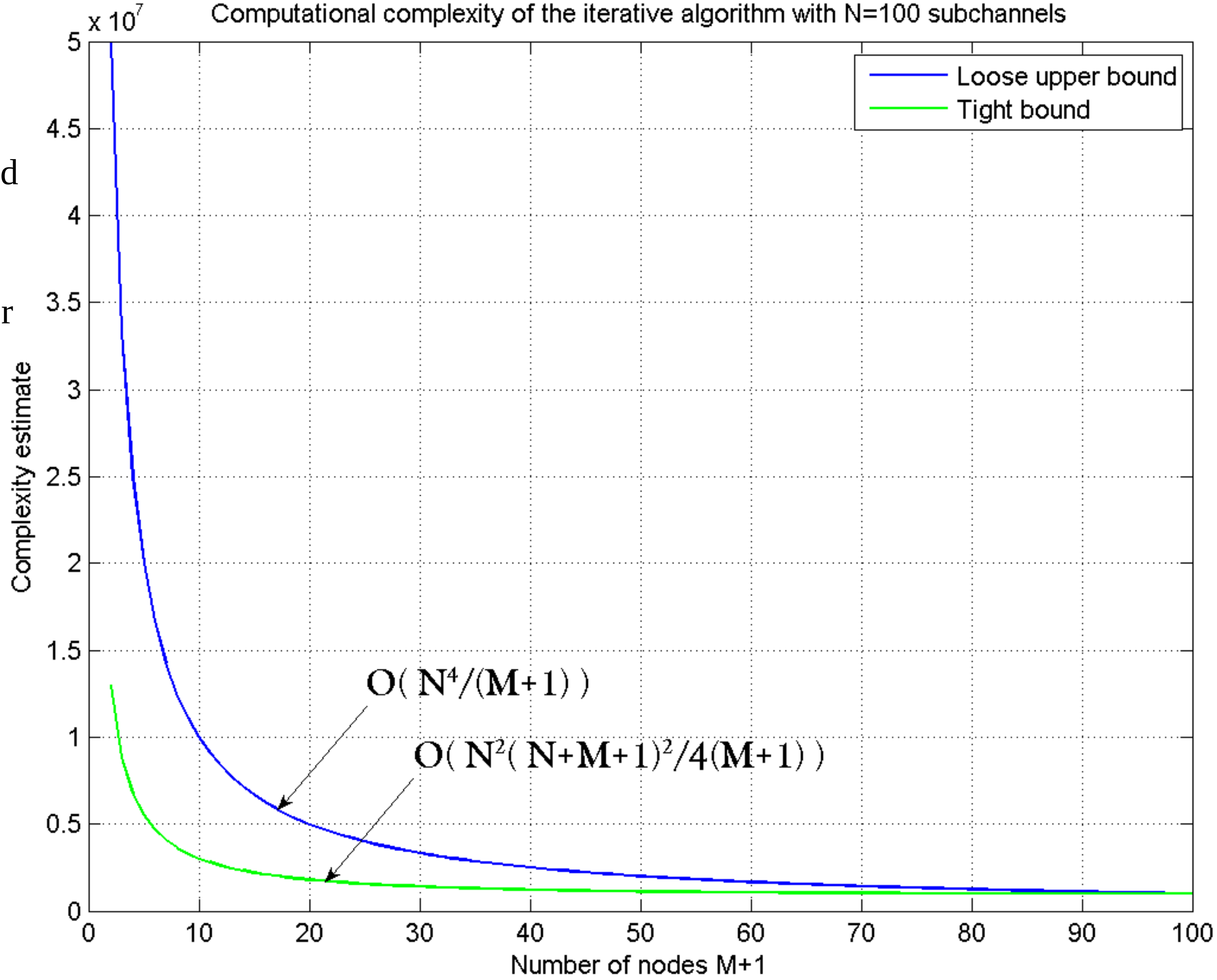
```
Initialization: $\mathcal{U} = \mathcal{N}$
while $\|\mathcal{U}\| \neq 0$ and $\sum \mathbf{Q^m} \neq \mathbf{0}$
  for each $n \in \mathcal{U}$
    for $m = 1$ to $M$
      $D_{n,m} = \max_k\{R_{m,k,n}\, Q_k^m\}$
      $\kappa_{n,m} = \arg\max_k\{R_{m,k,n}\, Q_k^m\}$

      $D_{n,0\to m} = R_{0,m,n} \max_k\{(Q_k^0 - Q_k^m)^+\}$
      $\kappa^m = \arg\max_k\{Q_k^0 - Q_k^m\}$
    end for
    $D_{n,0\to k} = R_{0,k,n} Q_k^0$
    $D_{n,0} = \max_j\{D_{n,0\to j}\}, \quad j \in \mathcal{K} \bigcup \mathcal{M}$
    $\kappa_{n,0} = \arg\max_j\{D_{n,0\to j}\}$
  end for

    % $\mathbf{D} = [D_{n,m}]$ is the demand matrix.
    $(\hat{\mathbf{n}}, \hat{\mathbf{m}}) \Longleftarrow$ Hungarian(D) % Vectors of indices
    $\mathcal{U} = \mathcal{U} - \{\hat{\mathbf{n}}\}, N_{assigned} = \|\hat{\mathbf{n}}\| = \|\hat{\mathbf{m}}\|$
    %$N_{assigned} \leq \min\{M + 1, \|\mathcal{U}\|\}$

  for $i = 1$ to $N_{assigned}$
    $\hat{n} = \hat{\mathbf{n}}(i)$, $\hat{m} = \hat{\mathbf{m}}(i)$, $\hat{r} = \kappa_{\hat{n},\hat{m}}$
      if $\hat{r} \in \mathcal{M}$ then
        $\hat{k} = \kappa^{\hat{r}}$,
        $Q_{\hat{k}}^0 = (Q_{\hat{k}}^0 - \lfloor R_{0,\hat{k},\hat{n}}\, T \rfloor)^+$
      else
        $Q_{\hat{k}}^{\hat{m}} = (Q_{\hat{k}}^{\hat{m}} - \lfloor R_{\hat{m},\hat{k},\hat{n}}\, T \rfloor)^+$
      end if
  end for
end while
```



	BS	**RS_1**	**RS_2**	**…**	**RS_M**
n_1	$D_{1,0}$	$D_{1,1}$	$D_{1,2}$	…	$D_{1,M}$
~~**n_5**~~	~~$D_{5,0}$~~	~~$D_{5,1}$~~	~~$D_{5,2}$~~	~~…~~	~~$D_{5,M}$~~
~~**n_6**~~	~~$D_{6,0}$~~	~~$D_{6,1}$~~	~~$D_{6,2}$~~	~~…~~	~~$D_{6,M}$~~
…					
~~**n_{10}**~~	~~$D_{10,0}$~~	~~$D_{10,1}$~~	~~$D_{10,2}$~~	~~…~~	~~$D_{10,M}$~~
…					
~~**n_N**~~	~~$D_{N,0}$~~	~~$D_{N,1}$~~	~~$D_{N,2}$~~	~~…~~	~~$D_{N,M}$~~

Computational Complexity

- The brute-force solution of the optimal BILP is NP-hard **$O((K(M+1))^N)$**
- The complexity estimate for the proposed iterative algorithm is polynomial in time
- Unlike the majority of formulations, the computational complexity decreases as the number of nodes increases, for moderate number of UTs



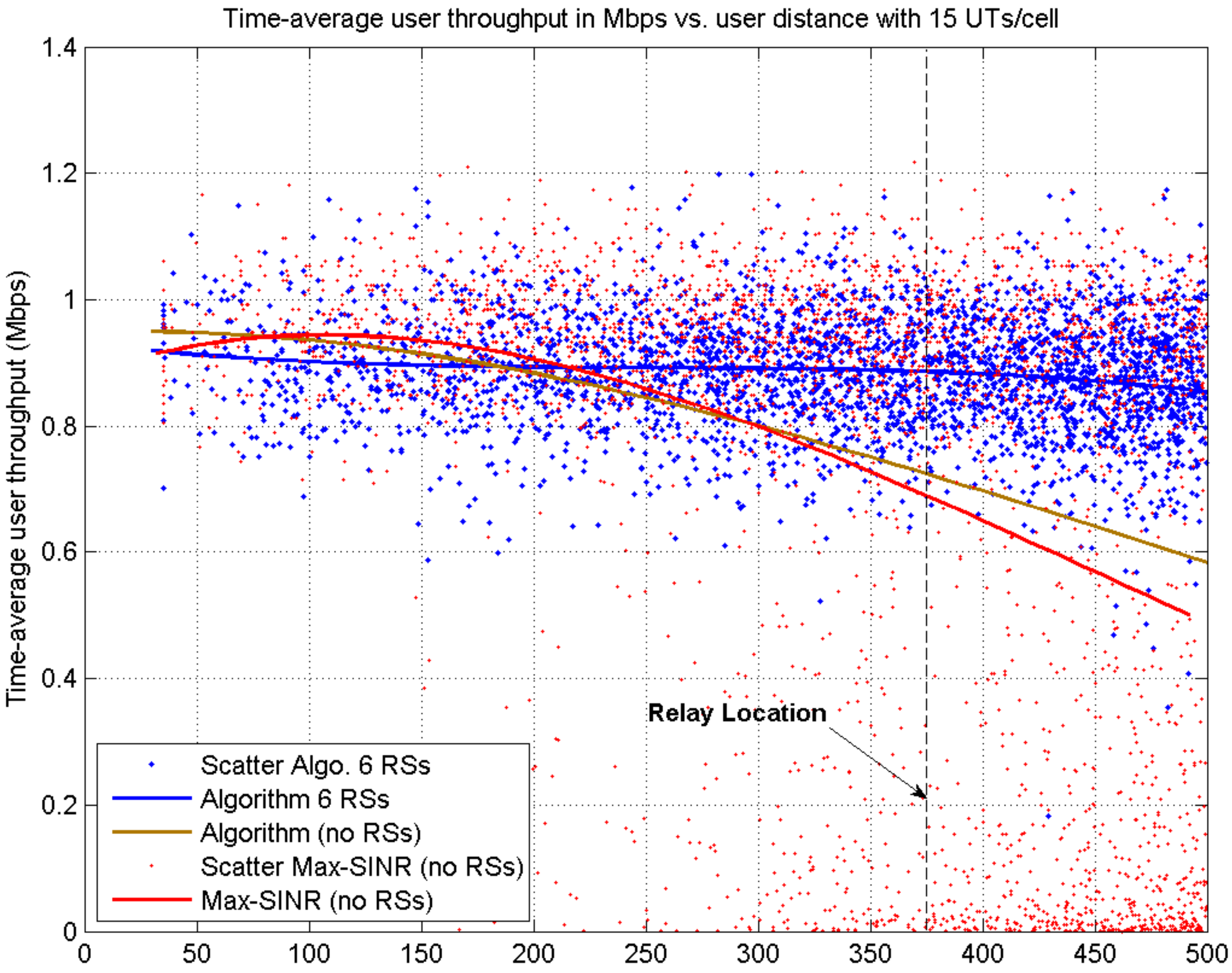
Simulation Parameters

Parameter	Value
BS-BS distance	1 Km
RS distance from BS	0.65 x cell radius
User min. close-in distance to BS	35 m
BS Tx. antenna gain	15 dB
RS Tx. antenna gain	10 dB
RS Rx. antenna θ_{3dB}	20 deg
UT Rx. antenna gain	0 dB
Shadowing st. dev. on user and interference links	8.9 dB
Shadowing st. dev. on BS-RS links	4 dB
Rician K-factor for BS-RS links	10 dB
Carrier frequency	2.5 GHz
User mobility	20 Km/hr (0-90)
BS-RS links max. Doppler spread	4 Hz
Power delay profile taps LOS (WINNER C2)	8 taps
Power delay profile taps NLOS (WiMax Forum)	6 taps

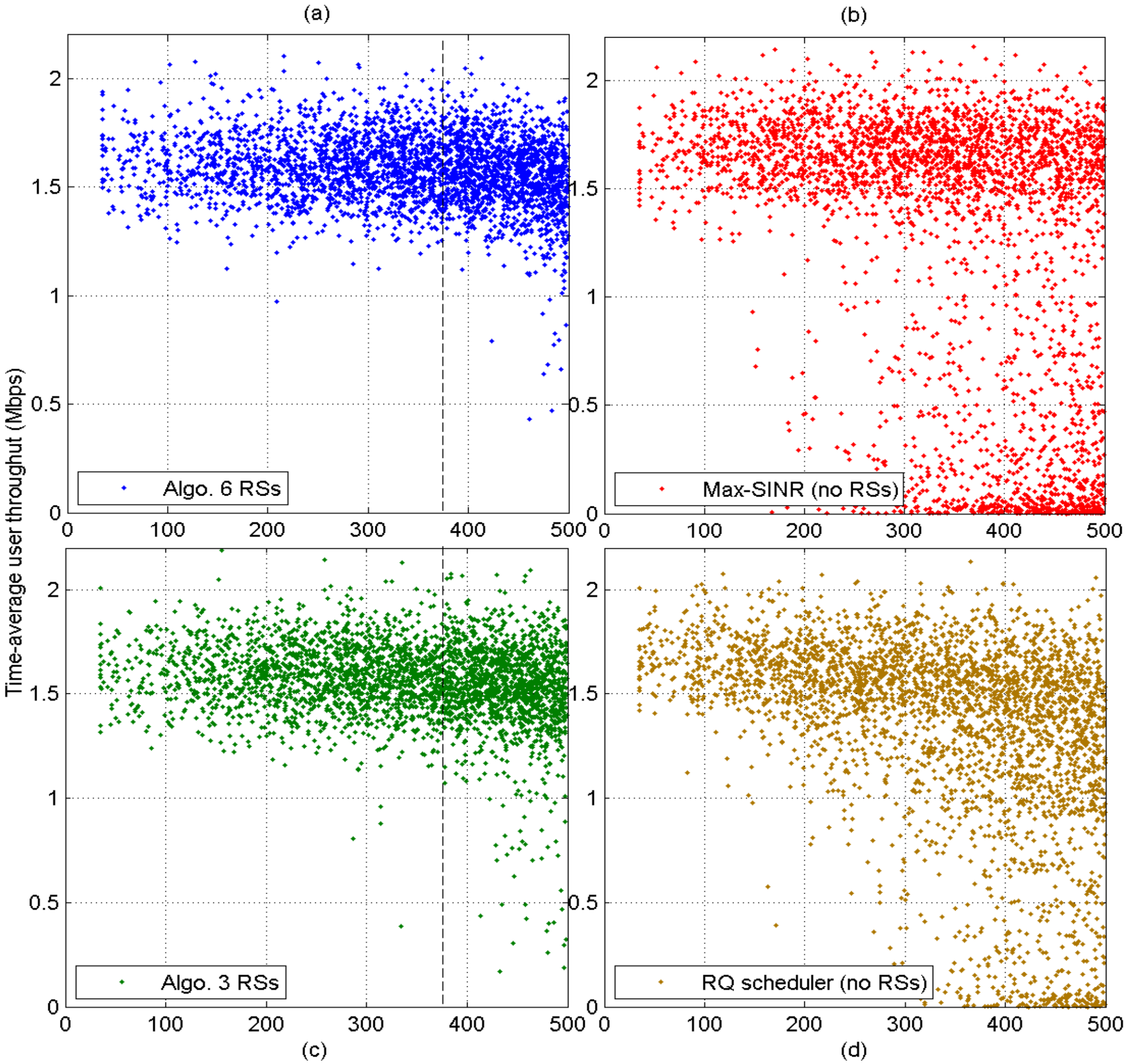
Simulation Parameters

Channel sampling time = TDD frame length	2 msec
Downlink : Uplink ratio	2:1
DL Tx. time in OFDM data symbols	11 symbols
OFDM subcarrier bandwidth	10.9375 KHz
OFDM symbol duration	102.86 usec
Subchannel width	18 subcarriers
Total bandwidth	20 MHz
Number of subchannels	102
CR-QAM target BER	10^{-3}
Noise power density at Rx. nodes	-174 dBm/Hz
BS total Tx. power	46 dBm
RS total Tx. power	37 dBm

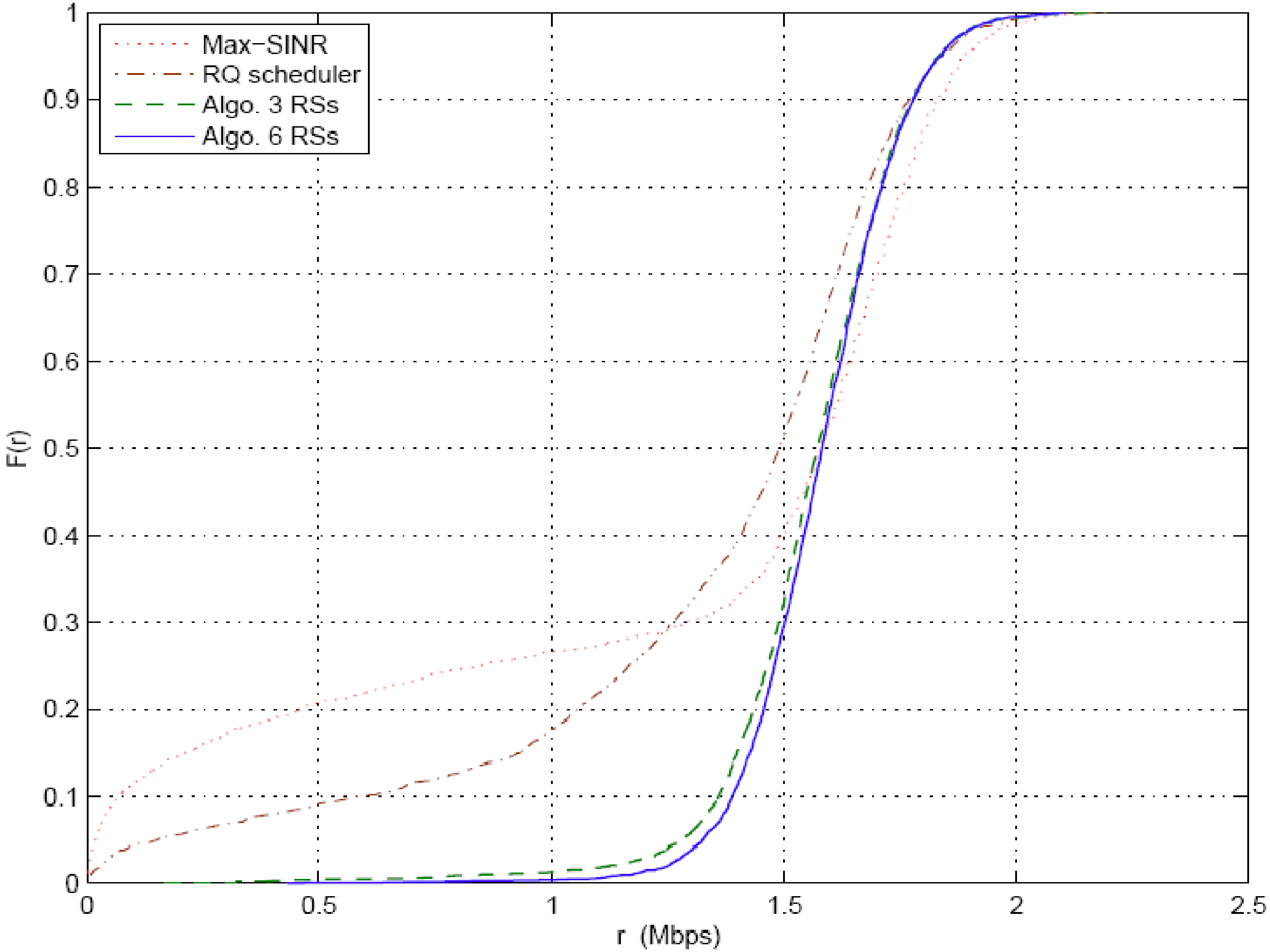
Simulation Results: User throughput



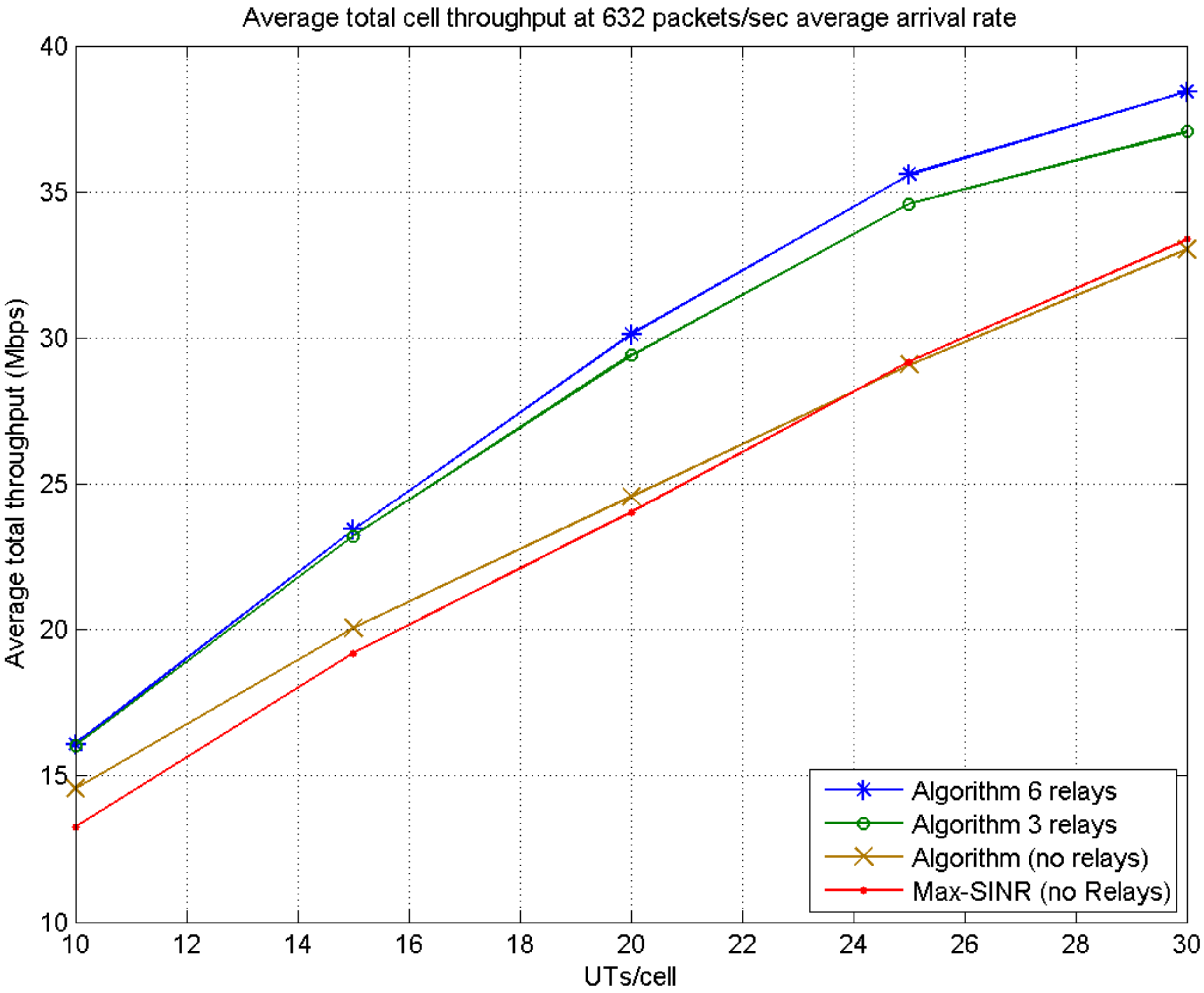
Simulation Results: User throughput with 15 UTs/cell



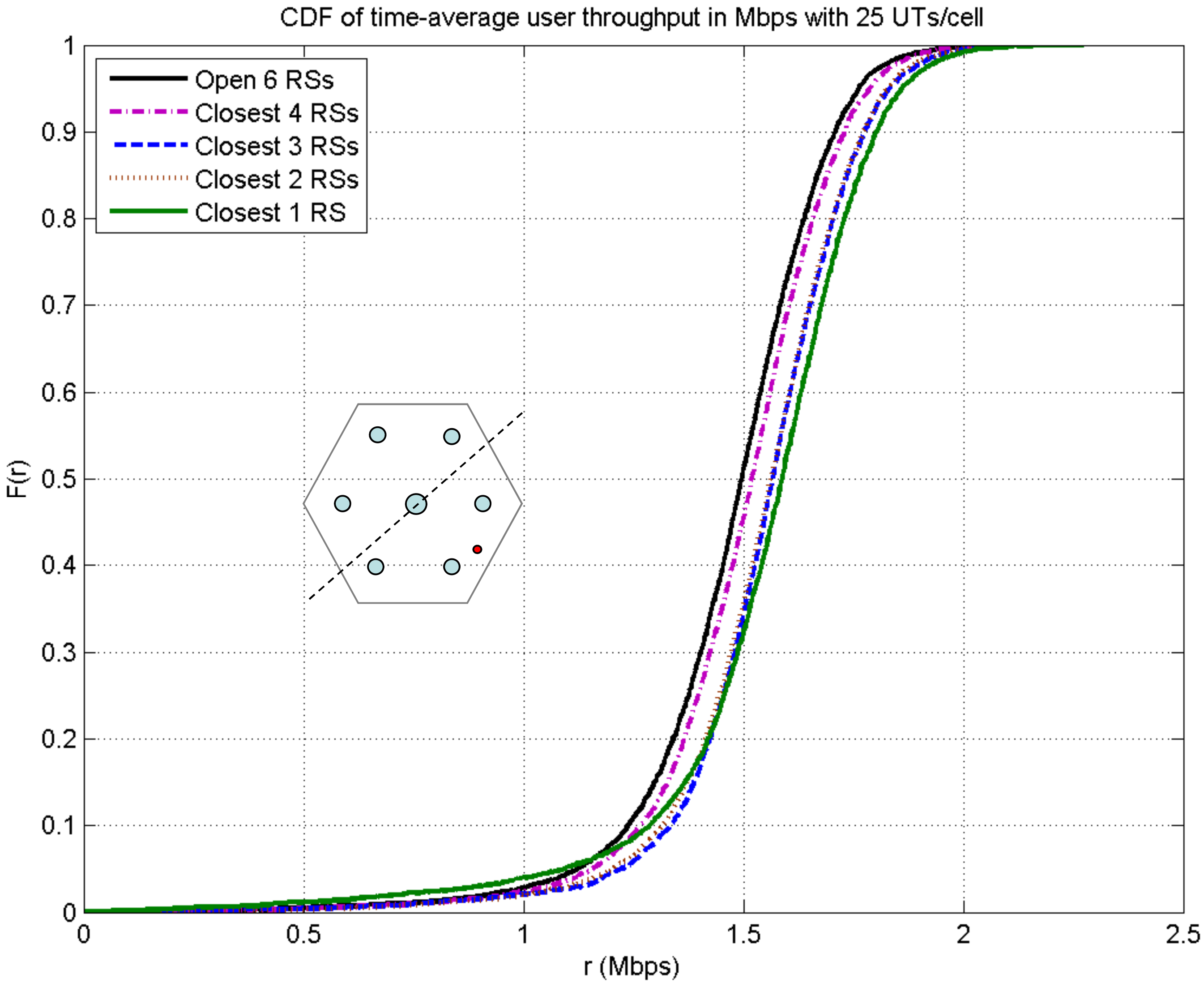
Simulation Results: CDF of time-average user throughput in Mbps with 25 UTs/cell



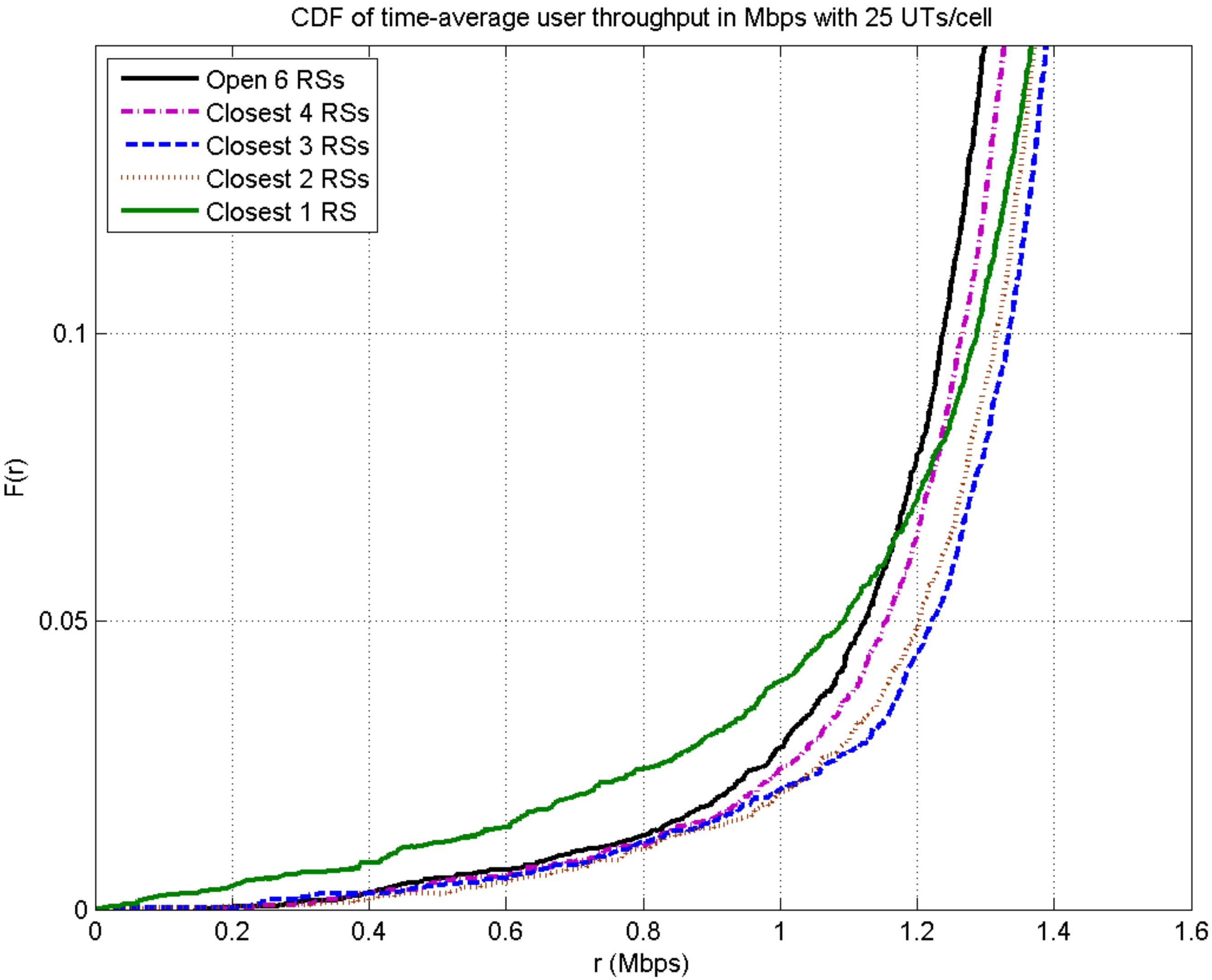
Simulation Results: Average total cell throughput



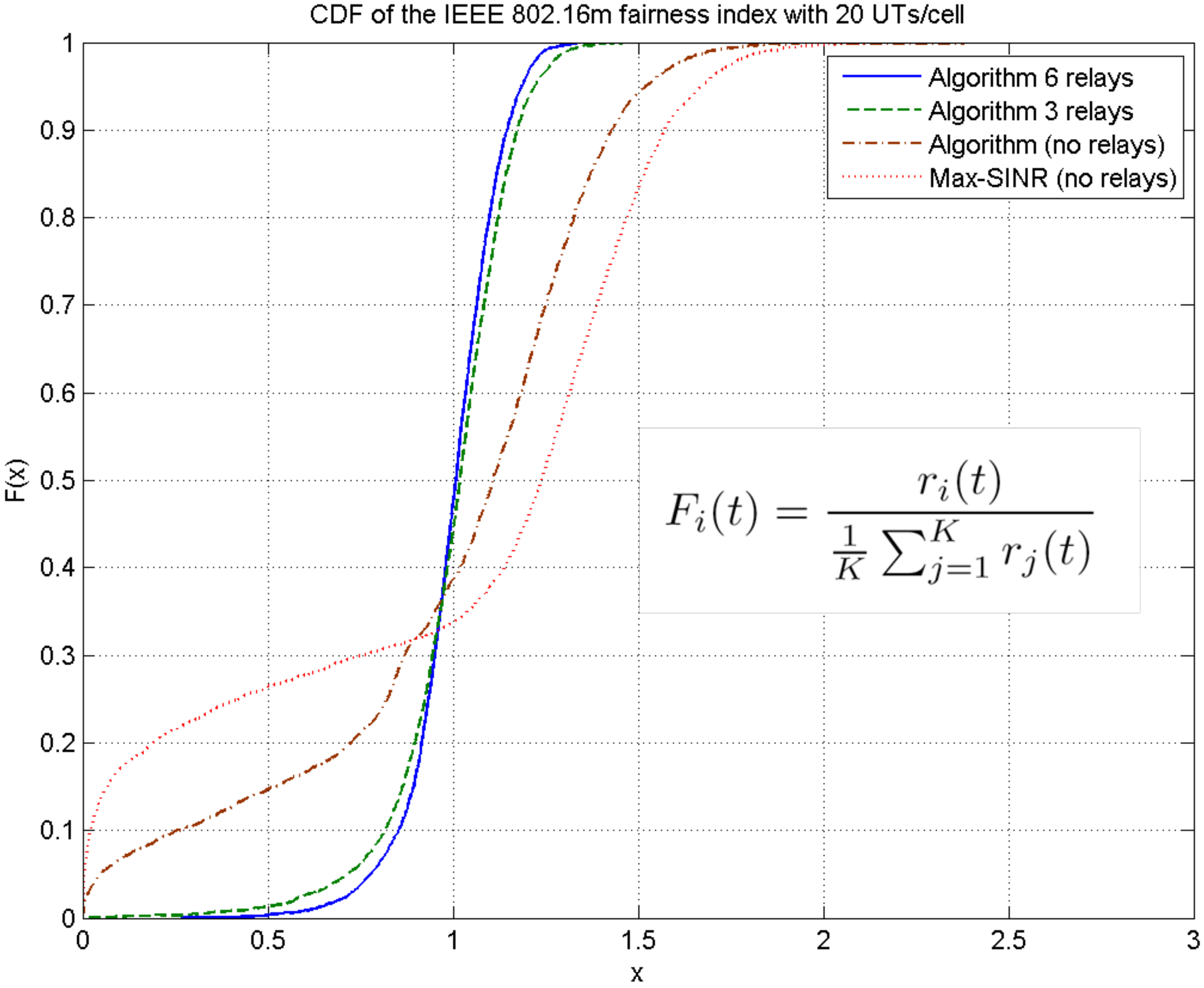
Simulation Results: Open routing vs. constrained routing (a proof of concept)



Simulation Results: Open routing vs. constrained routing (lower tail)

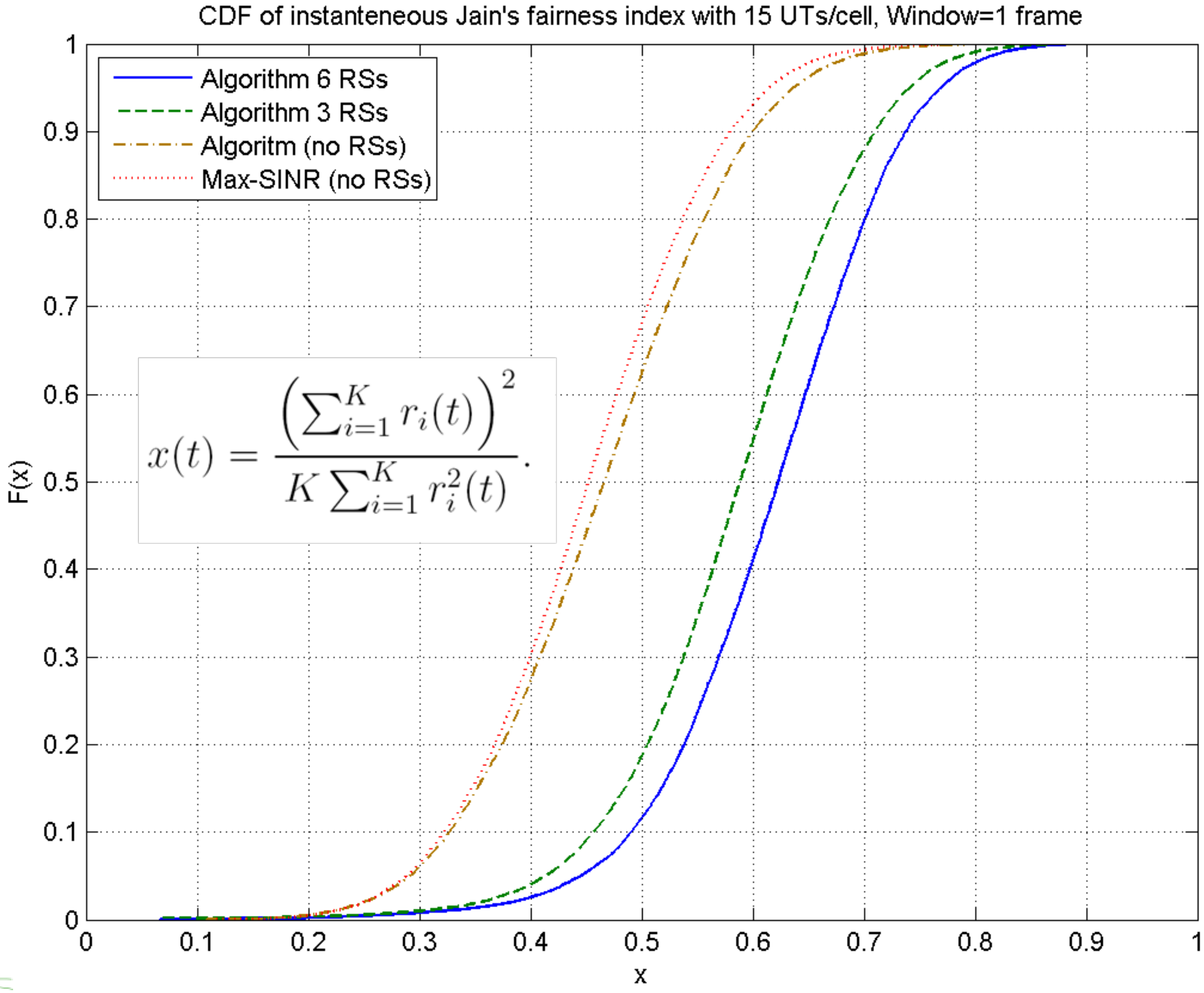


Simulation Results: User fairness



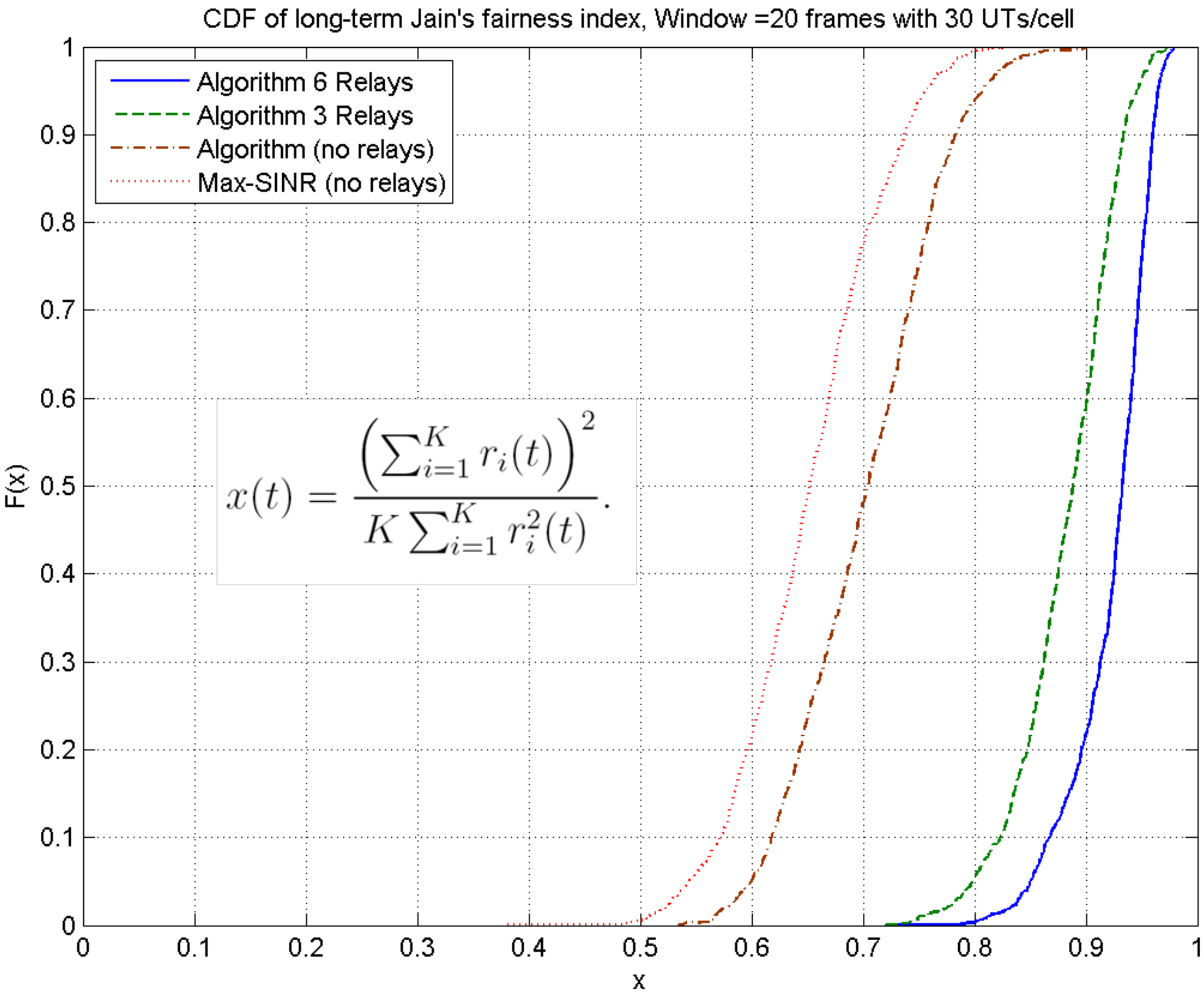
$$F_i(t) = \frac{r_i(t)}{\frac{1}{K}\sum_{j=1}^{K} r_j(t)}$$

Simulation Results: User fairness



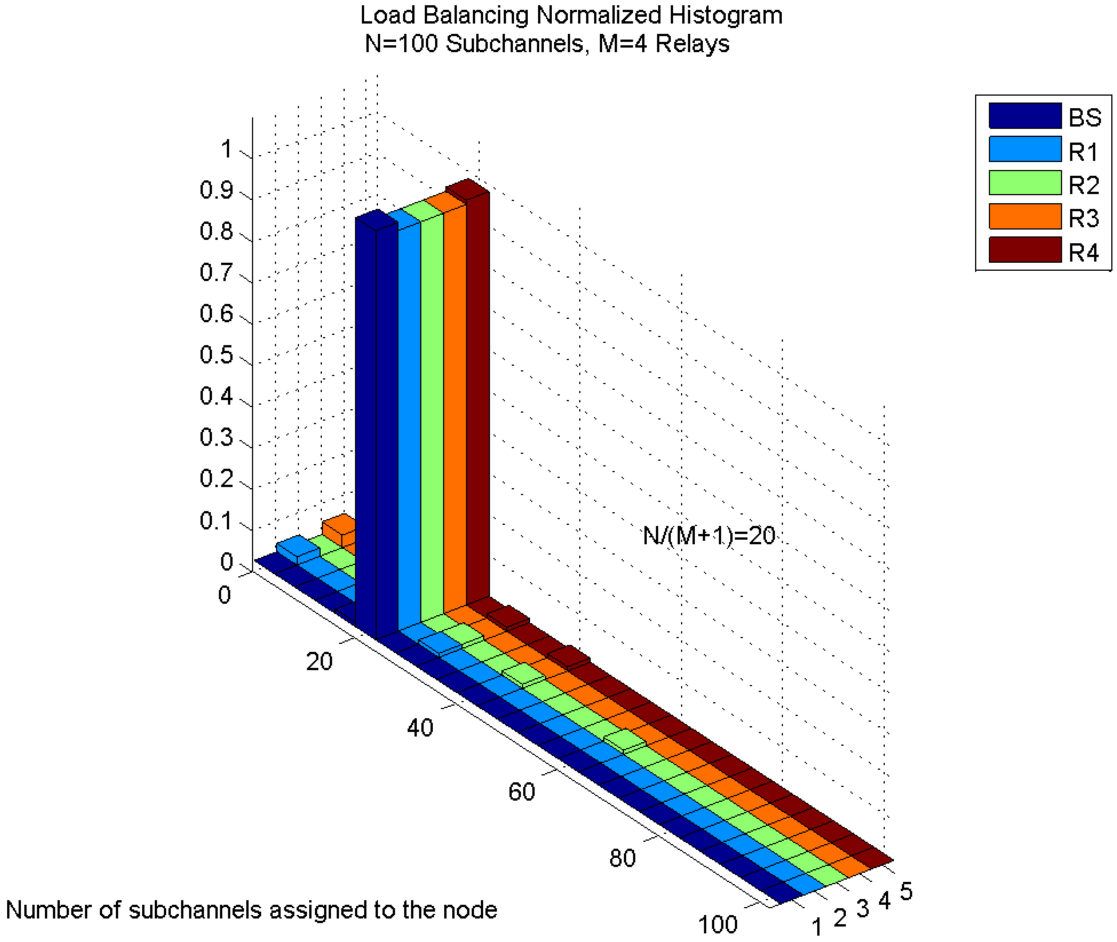
$$x(t)=\frac{\left(\sum_{i=1}^{K} r_i(t)\right)^2}{K\sum_{i=1}^{K} r_i^2(t)}.$$

Simulation Results: User fairness



$$x(t) = \frac{\left(\sum_{i=1}^{K} r_i(t)\right)^2}{K \sum_{i=1}^{K} r_i^2(t)}.$$

Simulation Results: Load balancing



Conclusion

- A novel fairness-aware joint routing and scheduling algorithm is proposed for OFDMA-based cellular relay networks
- The algorithm ensures short- as well as long-term fairness among users, including cell-edge users
- The fairness is achieved with minimal impact on the overall network throughput
- The algorithm exploits the opportunities in OFDM sub-carriers, channel dynamism, and queue and traffic diversities.
- Simulation results prove the learning ability and the efficiency of the routing strategy which dynamically converges to better routes, even under the challenging uniform relay deployment examined
- The inherent load-balancing feature works independently from the traffic load at adjacent BSs and results as well in spatial spreading of the co-channel interference across the network