

Interference-Aware Real-Time Flow Scheduling for Wireless Sensor Networks

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Motivation

- Challenges in real-time wireless sensor networks
 - **predictable:** real-time + reliability
 - **dynamic environments:** interference, unreliable links
 - **scalability:** support large networks
- **RFS: real-time flow scheduling**



RFS vs. WirelessHART

- **Wireless interference**
 - prevent interference [WirelessHART]
 - **interference aware [RFS]**
- **Wireless channels**
 - **single channel [RFS]**
 - multiple channels [WirelessHART]
- **Scalability**
 - centralized [WirelessHART]
 - **two-level [RFS]**

Real-time flows

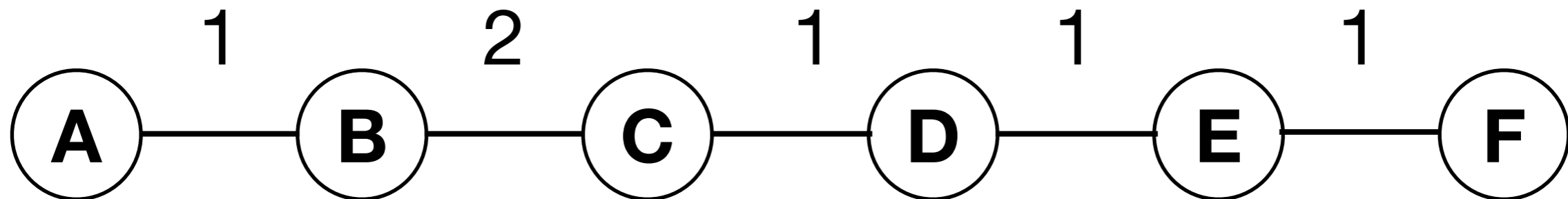
- Established between arbitrary end-points
- Flow instances are released periodically
- Timing properties (period, deadline, phase)
- Precedence constraints due to hop-by-hop forwarding
- Links are unreliable => retransmissions

Our approach

- **Planner: construction of plan when route is established**
 - all instances of a flow are executed according to the same plan
 - accounts for **precedence constraints** + **unreliable links**
- **Scheduler: run-time execution of concurrent flows**
 - dynamically schedules multiple concurrent flows
 - handles **interference** + **prioritization**
- ***This setup allows for a clean separation of concerns!***

Plans

- **Link estimator** provides #retransmission needed for reliability
- **Plans:** constructed when routes are established
 - precedence constraints enforced
 - links transmit sufficient times to deliver packets with high likelihood



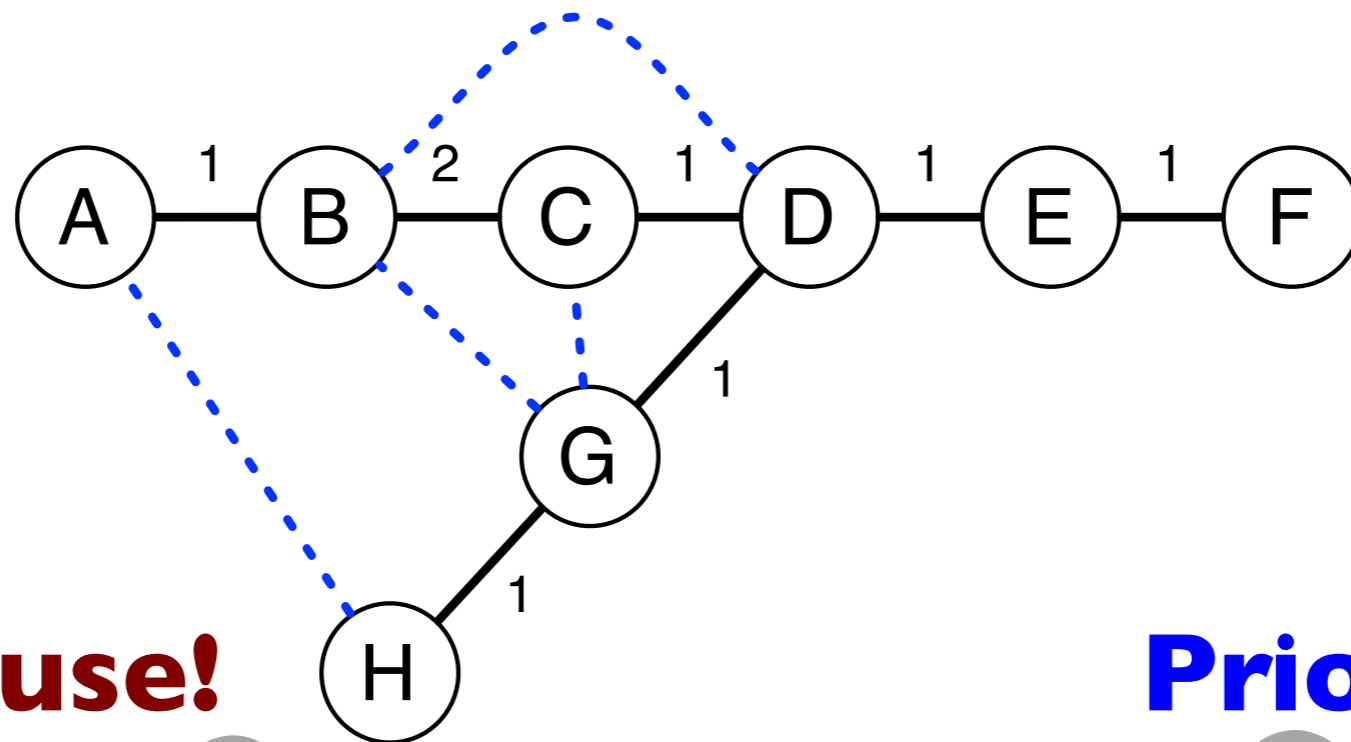
Plan: (AB) (BC) (BC) (CD) (DE) (EF)

Generic interference model

- **Different approaches to modeling and estimating interference.**
 - graph
 - Signal to Noise plus Interference Ratio (SNIR)
- **Decouple real-time scheduling and specific interference models**
 - scheduler works with interference estimator via a generic interface
- **Generic model**
 - **conflict** between two transmissions => cannot occur simultaneously
 - mapping from graph and SNIR threshold models
 - new interference models and estimators may be easily incorporated

Scheduler

- consider flows in decreasing order of priority
- execute the next transmission of a flow if it does not conflict with the transmissions of higher priority flows scheduled in the current slot



Spatial reuse!

Prioritization!

| Slot | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------------|----|----|----|----|----|----|----|----|---|
| F ₁ | | AB | BC | BC | CD | DE | EF | | |
| F ₂ | FE | ED | | | | | DG | GH | |

Schedulability analysis

- **Response-time analysis for flows with arbitrary interference**
 - static priorities
 - deadlines \leq periods
- **Response time of flow l is:**

$$R_l = L_l + \sum_{h \in hp(l)} \left\lceil \frac{R_l}{P_h} \right\rceil \cdot I(l, h)$$

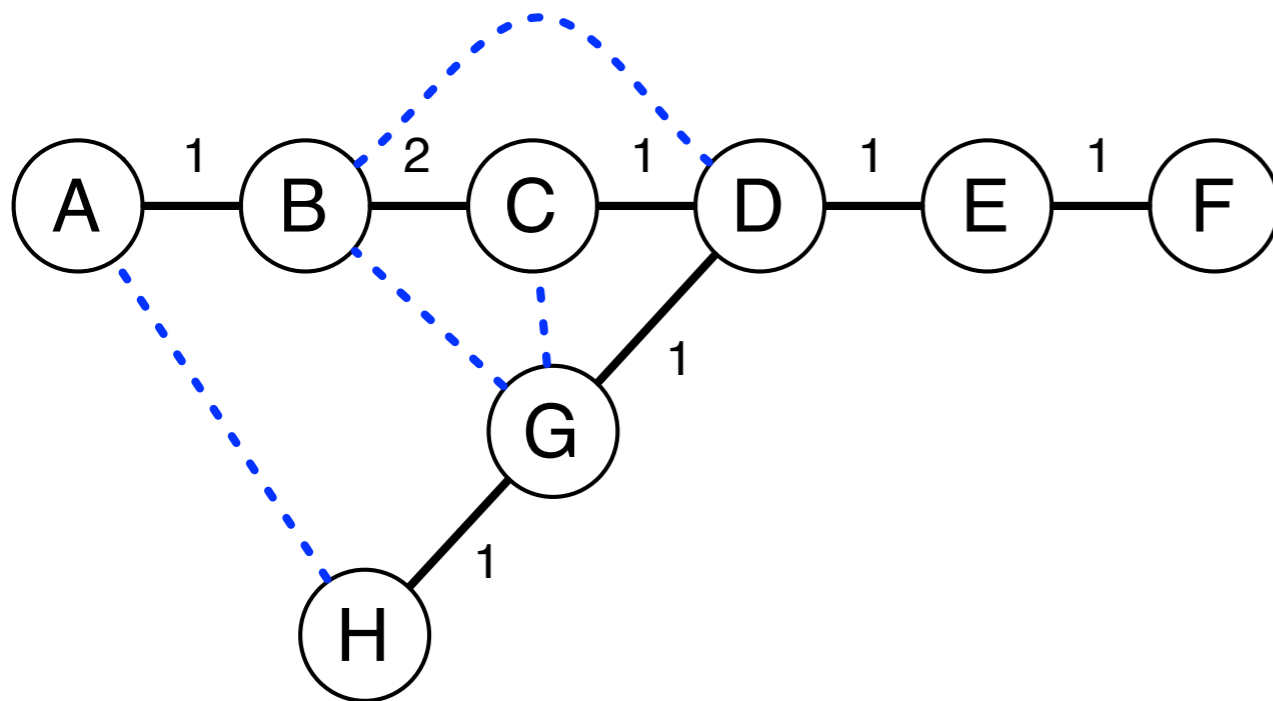
Length of plan

Inter-flow interference

Key challenge: assess the interference between pairs of flows

Conflict matrices

- Captures the **sequential execution** of plans \Rightarrow ordering of rows/columns
- Captures **links unreliability** \Rightarrow duplicate rows/columns
- Captures **conflicts** \Rightarrow “x”-es in the matrix



F_2 \downarrow

F_1 \longrightarrow

| | AB | BC | BC | CD | DE | EF |
|----|----------|----------|----------|----------|----------|----------|
| FE | | | | | X | X |
| ED | | X | X | X | X | X |
| DG | | X | X | X | X | |
| GH | X | | | | | |

Mapping executions onto conflict matrices

| | AB | BC | BC | CD | DE | EF |
|----|----|----|----|----|----|----|
| FE | | | | | X | X |
| ED | | X | X | X | X | X |
| DG | | X | X | X | X | |
| GH | X | | | | | ● |

F₁ exec, F₂ exec
 $I(2,1) = I(2,1) + 0$

| | AB | BC | BC | CD | DE | EF |
|----|----|----|----|----|----|----|
| FE | | | | | X | X |
| ED | | X | X | X | X | X |
| DG | | X | ● | X | X | |
| GH | X | | | | | |

F₁ exec, F₂ suspended
 $I(2,1) = I(2,1) + 1$

| | AB | BC | BC | CD | DE | EF |
|----|----|----|----|----|----|----|
| FE | | | | | X | X |
| ED | ↓ | ↓ | X | X | X | X |
| DG | ● | ● | X | X | X | |
| GH | X | | | | | |

F₁ suspended, F₂ exec
 $I(2,1) = I(2,1) + 0$

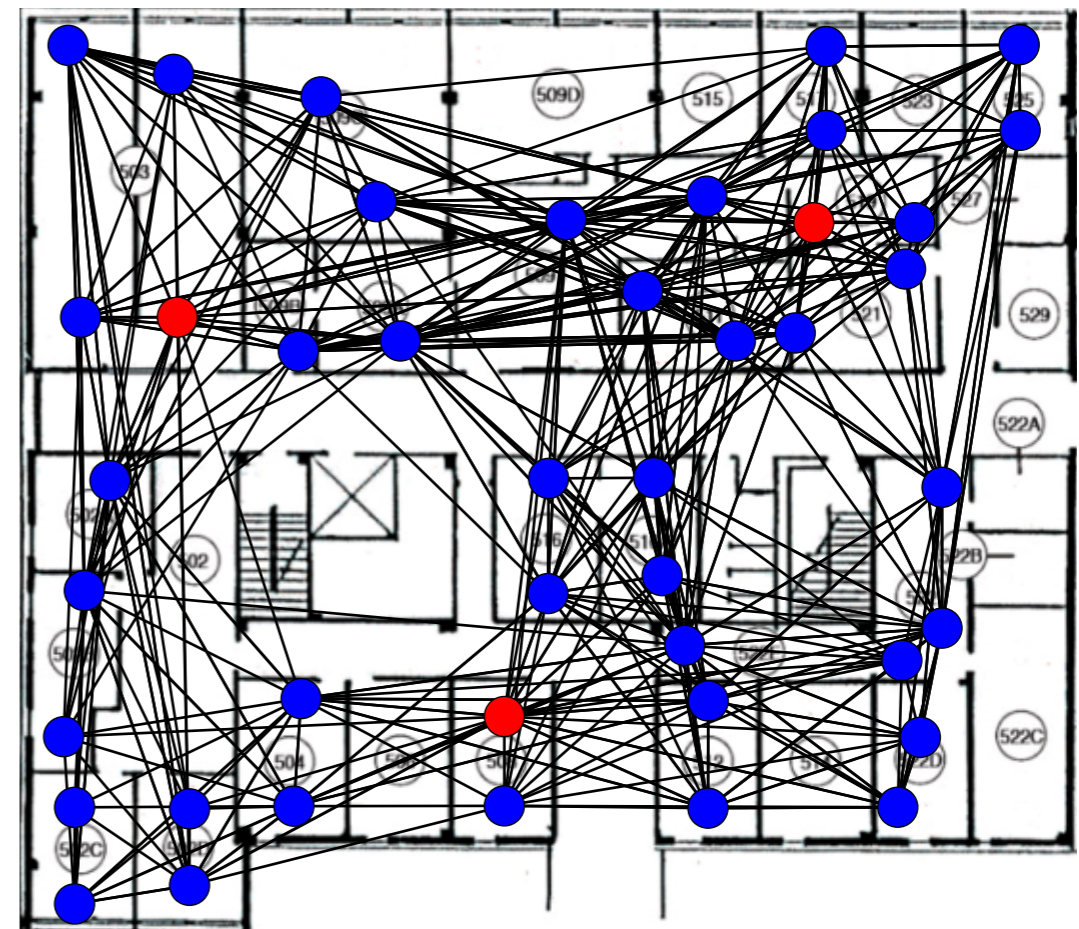
**worst-case interference =
 worst-case path in matrix
 solved through dynamic
 programming**

Two-level scheduler

- **Divide the network into neighborhoods**
 - nodes need to synchronize their schedules within the neighborhood
 - limits the storage and communication overheads
- **Two-level scheduling:**
 - RFS within neighborhood
 - graph coloring among neighborhoods: distributed TDMA
- **Release guard** synchronizes flows across neighborhoods
 - dynamic schedulers allows for efficient implementation of phase shifts
 - real-time analysis for release guard still applies

Simulations results

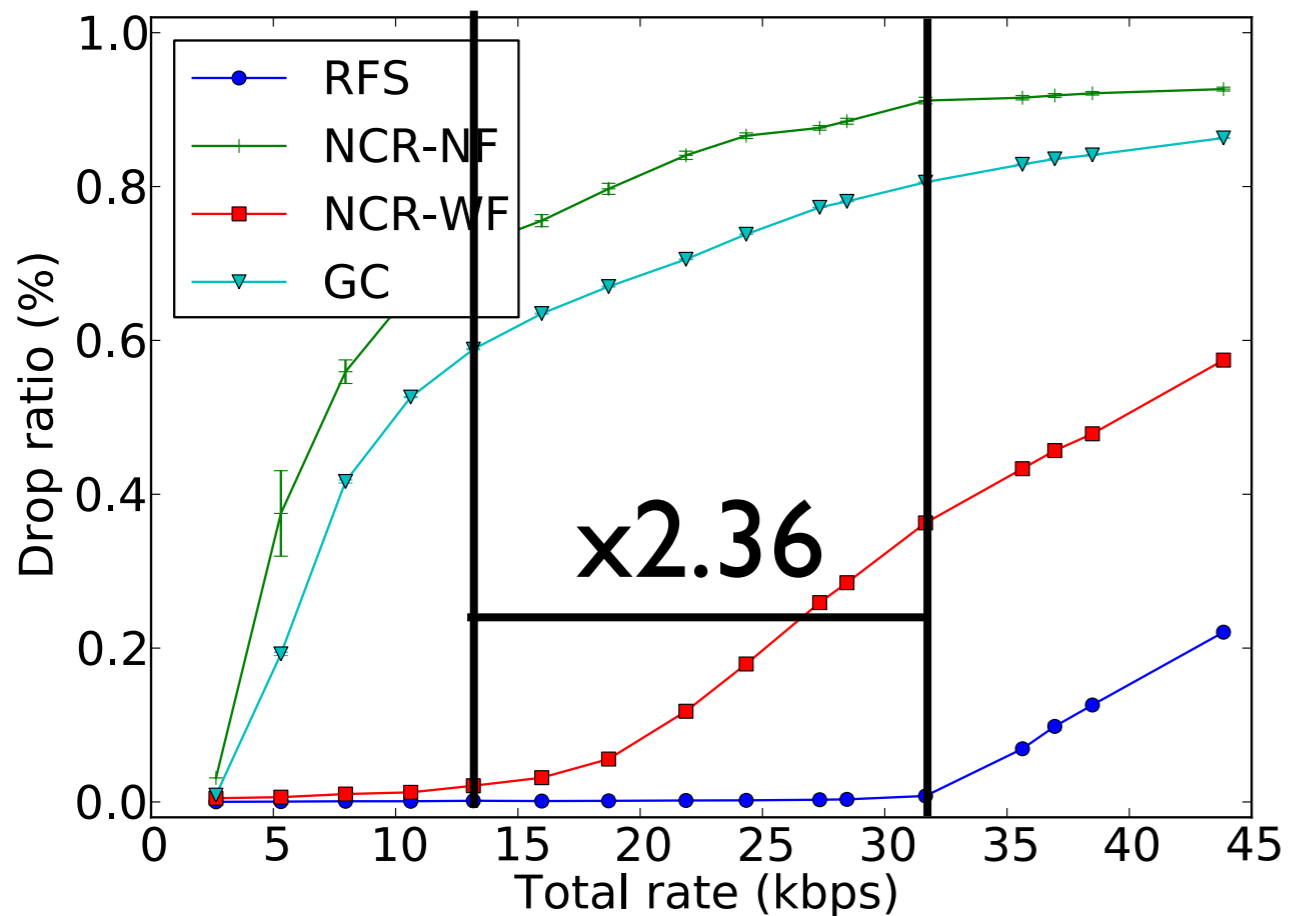
- Simulator based on real traces collected from WU testbed
- Interference estimated using RID protocol
- Four flows with rates $F_0:F_1:F_2:F_3$ with ratios 1:1.5:2.2:4.3
 - connect the corners of the topology
- Baselines:
 - graph coloring (GC)
 - NCR-NF: node fair
 - NCR-WF: workload fair



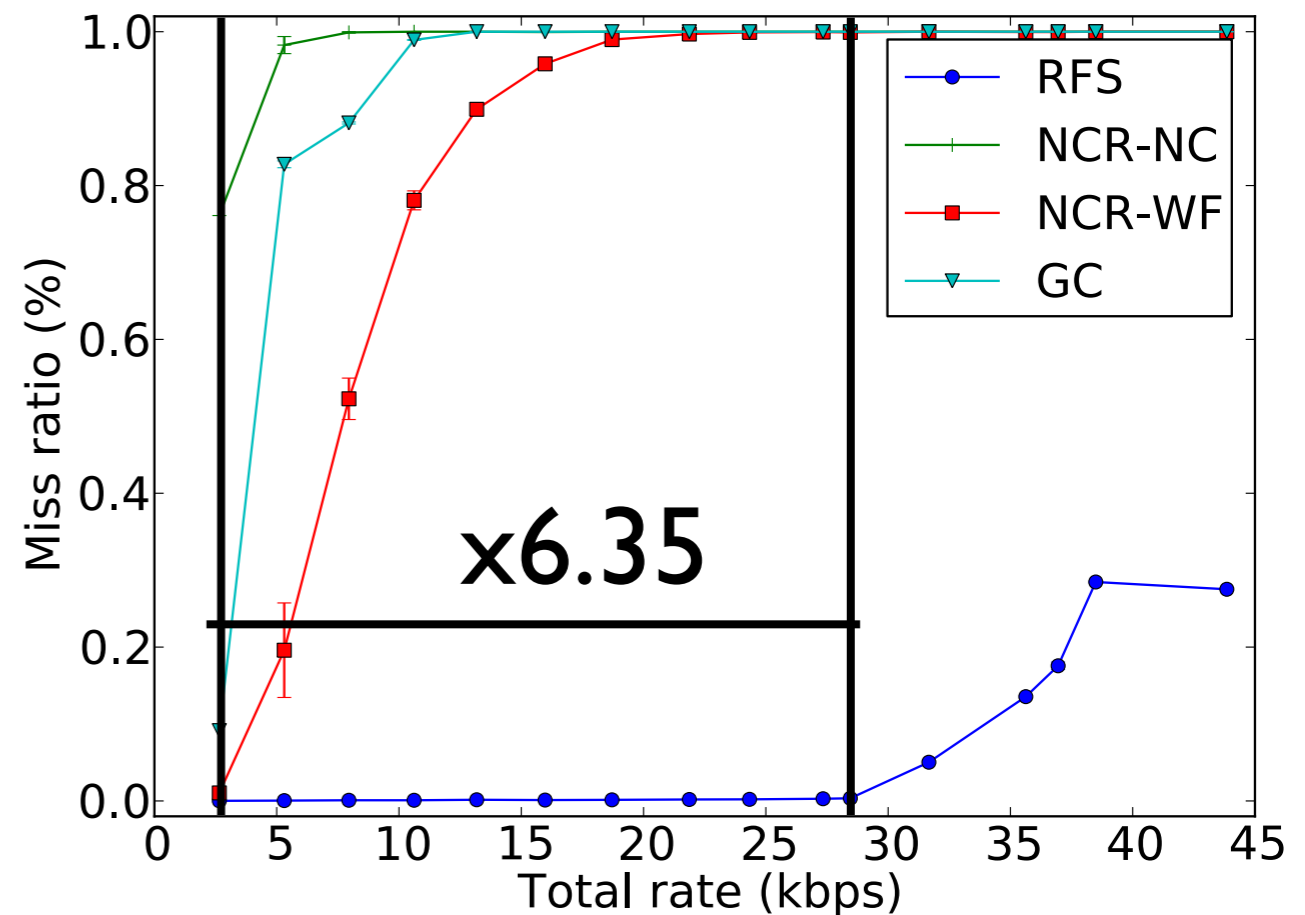
Test topology

Results

- **Significant improvements in capacity and real-time capacity**
 - account for the precedence constraints of hop-by-hop forwarding
 - provides prioritization among flows



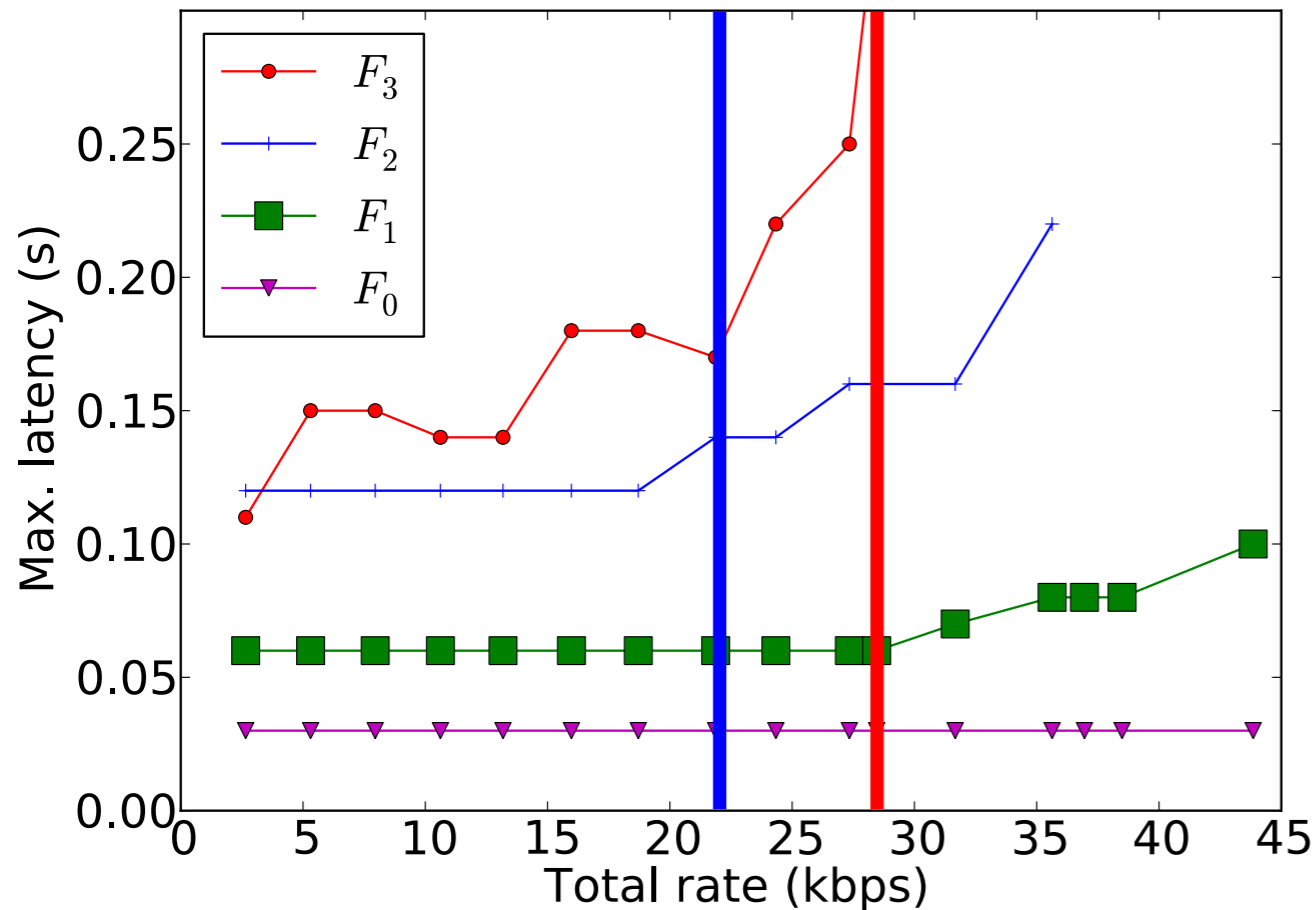
Drop ratio



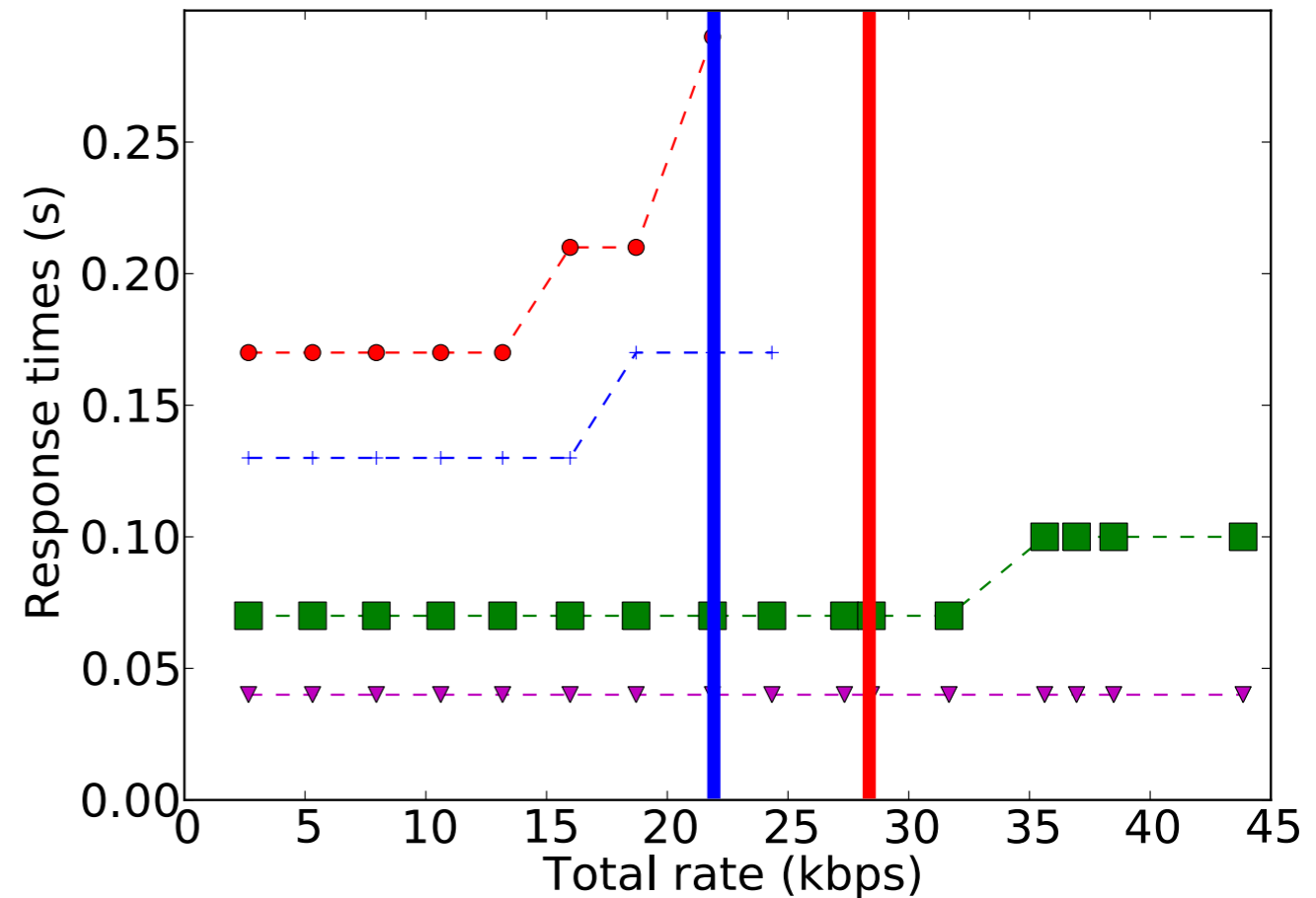
Miss ratio

Theoretical bound vs. Simulations

- Bounds are safe for tested configurations
- Pessimism: 23% lower real-time capacity
 - Still 63% higher than the network capacity under NCR-WF



Experimental



Theoretical

Conclusions

- **RFS: real-time flow scheduling for wireless sensor networks**
 - provides prioritization among flows with static priorities
 - achieves scalability via two-level scheduling
- **Novel schedulability analysis for real-time flows**
 - efficiently calculates inter-flow interference based on conflict matrices
- **Significant performance improvements over TDMA solutions**
 - 2x improvements in network capacity
 - 6x improvements in real-time capacity