Hybrid Scheduling in Heterogeneous Half- and Full-Duplex Wireless Networks

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Full-Duplex Wireless

- Legacy half-duplex wireless systems separate transmission and reception in either:
  - Time: Time Division Duplex (TDD)
  - Frequency: Frequency Division Duplex (FDD)

- (Same channel) Full-duplex communication: simultaneous transmission and reception on the same frequency channel
Full-Duplex Wireless

• Benefits of full-duplex wireless:
  - Increased system throughput and reduced latency
  - More flexible use of the wireless spectrum and energy efficiency

• Viability is limited by self-interference
  - Transmitted signal is billions of times (10^9 or 90dB) stronger than the received signal
  - Requiring extremely powerful self-interference cancellation
The Columbia FlexICoN Project

- **Full-Duplex Wireless: From Integrated Circuits to Networks (FlexICoN)**
  - Development of full-duplex transceiver/system, algorithm design, experimental evaluation, etc.
  - Integration of full-duplex capability with the open-access ORBIT testbed

- Future integration with the **PAWR COSMOS** city-scale testbed (NSF PAWR Session on Wed. at 15:30pm in Tapa 1)
Motivation

• Gradual replacement and introduction of full-duplex (FD) devices into legacy half-duplex (HD) networks

• **Goal:** Develop **efficient** and **fair** scheduling algorithms in such **heterogeneous** half-duplex and full-duplex networks with performance guarantees
Related Work

- Full-duplex radio/system design
  - Laboratory bench-top design: [Choi et al. 2010], [Duarte & Sabharwal, 2010], [Aryafar et al. 2012], [Bharadia et al. 2013/2014], [Kim et al. 2013/2015], [Korpi et al. 2016], [Sayed et al. 2017]

- Throughput gains from full-duplex:
  - [Xie & Zhang, 2014], [Nguyen et al. 2014], [Korpi et al. 2015], [Marasevic et al. 2017/2018]

- Cellular/WiFi scheduling:

- CSMA/Scheduling in legacy half-duplex networks:
  - CSMA, Max-Weight, Greedy-Maximal, Longest-Queue-First, Q-CSMA, etc. [Kleinrock & Tobagi, 1975], [Tassiulas & Ephremides 1992], [Dimakis & Walrand, 2006], [Brzozowski et al. 2006], [Ni et al. 2012], [Birand et al. 2012], etc.

- **Heterogeneous** networks with both half- and full-duplex users were not considered
- **Fairness** between half- and full-duplex users was not considered
- Very little work provided *performance guarantees* (e.g., throughput optimality)
Model

- Time is slotted ($t = 1, 2, \ldots$)
- A single-channel, collocated, \textit{heterogeneous} network with one access point (AP) and $N$ users:
  - The AP and $N_F$ users are full-duplex (FD)
  - $N_H = N - N_F$ users are half-duplex (HD)
- $N$ downlink queues at the AP and one uplink queue at each user
  - The AP has information about \textit{all downlink queues}
  - A user has information about \textit{only its uplink queue}
- Unit link capacity and perfect self-interference cancellation

- \textbf{Feasible schedules}: a single half-duplex uplink or downlink, or a pair of full-duplex uplink and downlink
- A pair of full-duplex uplink and downlink are always scheduled at the same time
Problem Formulation

- Capacity Region: Convex hull of all feasible schedules

- For a legacy half-duplex user: $\lambda_{\text{uplink}} + \lambda_{\text{downlink}} \leq 1$

- For a full-duplex user:
  \[
  \begin{align*}
  \lambda_{\text{uplink}} &\leq 1 \\
  \lambda_{\text{downlink}} &\leq 1 \\
  \max\{\lambda_{\text{uplink}}, \lambda_{\text{downlink}}\} &\leq 1
  \end{align*}
  \]

- A scheduling algorithm is **throughput-optimal** if it can keep the network queues stable for all arrival rate vectors in the interior of the capacity region

**Goal**: Achieve maximum throughput in networks with heterogeneous half-duplex and full-duplex users in a distributed manner, while being **fair** to all the users and having favorable delay performance

**Solution**: H-GMS – A Hybrid scheduling algorithm that combines centralized Greedy Maximal Scheduling (GMS) and distributed Q-CSMA
Introducing Full-Duplex Users – Everyone Gains!

- A **homogeneous** network with $N = 10$ half-duplex users vs. A **heterogeneous** network with $N_H$ half-duplex users and $N_F$ full-duplex users ($N_H + N_F = N = 10$)

- Consider the a static CSMA algorithm with fixed transmission probabilities $p_H$ and $p_F$ for half-duplex and full-duplex users. Let $p_F = \gamma p_H$ with $\gamma \in (0, 1]$  

- With $p_H = 0.5$, throughput gain of the network:

- A heterogeneous network with fixed $N$ and varying $N_F$
Introducing Full-Duplex Users – Everyone Gains!

- A **homogeneous** network with $N = 10$ half-duplex users vs. A **heterogeneous** network with $N_H$ half-duplex users and $N_F$ full-duplex users ($N_H + N_F = N = 10$)
- Consider the a static CSMA algorithm with fixed transmission probabilities $p_H$ and $p_F$ for half-duplex and full-duplex users. Let $p_F = \gamma p_H$ with $\gamma \in (0, 1]$.
- With $p_H = 0.5$, throughput gain of *individual users*:

![Graph showing throughput gain with increasing priority of FD users](image)

**Even half-duplex users can gain!**

- Increased number of FD users
- Increased *priority* of FD users
Scheduling Algorithms

• Max-Weight Scheduling (MWS) is throughput-optimal
  - Q-CSMA can be applied

• What about the Greedy Maximal Scheduling (GMS)?
  - The returned schedule may not be Max-Weight

\[
\text{MWS} = \text{GMS}
\]

\[
\text{MWS} \neq \text{GMS}
\]
**Scheduling Algorithms**

- **Max-Weight Scheduling (MWS) is throughput-optimal**
  - Q-CSMA can be applied

- **What about the Greedy Maximal Scheduling (GMS)?**
  - The returned schedule may not be Max-Weight

- **Proposition**: The centralized Greedy Maximal Scheduling (GMS) algorithm is throughput-optimal in *any* collocated *heterogeneous* half-duplex and full-duplex networks
  - Proof is based on local-pooling

- **Question**: How to achieve GMS is a distributed manner?
- **Solution**: **H-GMS** — a Hybrid scheduling algorithm that combines centralized **GMS** and distributed Q-CSMA
Proposed Algorithm: H-GMS in slot $t$

If the previous slot is an *idle* slot:

- **Step 1: Initiation** (centralized GMS at the AP)
  - The AP selects the downlink with the longest queue
  - The AP draws an *initiator link* from all the uplinks and the selected downlink according to an access probability distribution $\alpha$
Proposed Algorithm: H-GMS in slot $t$

If the previous slot is an *idle* slot:

**Step 2: Coordination** (distributed Q-CSMA)
- If link $l$ is selected as the initiator link, it is activated w.p. $p(Q(t))$

Transmission probability and weight functions $f(Q(t))$

$$p(Q(t)) = \frac{\exp(f(Q(t)))}{1 + \exp(f(Q(t)))}$$
Proposed Algorithm: H-GMS in slot $t$

If the previous slot is an *idle* slot:

- **Step 2: Coordination** (distributed Q-CSMA)
  - If link $l$ is selected as the initiator link, it is activated w.p. $p(Q(t))$
  - If the initiator link is a full-duplex uplink (downlink), the corresponding downlink (uplink) will also be activated

Transmission probability and weight functions $f(Q(t))$

$$p(Q(t)) = \frac{\exp(f(Q(t)))}{1 + \exp(f(Q(t)))}$$
Proposed Algorithm: H-GMS in slot $t$

If the previous slot is an *idle* slot:

- **Step 3: Transmission**
  - One packet is transmitted on each activated link
Proposed Algorithm: H-GMS in slot $t$

If the previous slot is a *busy* slot:

- The AP keeps the same initiator link and repeats steps 2 & 3
Main Results

- **Theorem**: For any arrival rate vector inside the capacity region, the system Markov chain \((X(t), Q(t))\) is positive recurrent under the H-GMS algorithm. The weight function \(f\) can be any nonnegative increasing function such that \(\lim_{x \to \infty} f(x) / \log(x) < 1\) or \(\lim_{x \to \infty} f(x) / \log(x) > 1\).
  - Proof is based on fluid limit analysis

- Variants of **H-GMS**:
  - **H-GMS** (or **H-GMS-L**)
  - **H-GMS-R**: the AP selects a downlink queue uniformly at Random, \(\alpha\) is uniformly distributed
  - **H-GMS-E**: the AP selects the downlink with the longest queue, \(\alpha\) is proportional to the Estimated uplink queues

![Diagram of H-GMS variants](image)
Performance Evaluation – Queue Length

- Simulations with $N = 10$ users with $N_F = N_H = 5$ in a heterogeneous network
- Equal arrival rate on all the uplinks and downlinks with total arrival rate $\rho \in (0, 1]$
- Average queue length (packet) for every link

The largely reduced queue length resulted from (i) utilizing the centralized downlink queue information at the AP, and (ii) the introduction of full-duplex users
Performance Evaluation – Fairness

• Simulations with $N = 10$ users with $N_F = N_H = 5$ in a heterogeneous network
• Equal arrival rate on all the uplinks and downlinks with total arrival rate $\rho \in (0, 1]$
• *Fairness* between full-duplex and half-duplex users (i.e., ratio between their queue lengths)

$H$-GMS-L and $H$-GMS-E improve fairness by selecting the initiator link differently
Performance Evaluation – Effect of $N_F$

- Simulations with $N = 10$ users with $N_F = N_H = 5$ in a heterogeneous network
- Equal arrival rate on all the uplinks and downlinks with total arrival rate $\rho \in (0, 1]$ 
- **Fairness** under different values of $N_F$

![Diagram showing fairness under medium and high traffic intensities](image)
Summary

- Scheduling in heterogeneous half-duplex and full-duplex wireless networks
- All the users can gain (even for half-duplex users!) in terms of throughput when introducing full-duplex users into legacy half-duplex networks

- **H-GMS** – a hybrid scheduling algorithm combining centralized GMS and distributed Q-CSMA, and is proven to be throughput-optimal

- Performance evaluation of H-GMS

- Future directions:
  - Delay analysis of H-GMS
  - Experimental evaluation using existing/customized full-duplex testbeds

- Please come to our full-duplex demo *tomorrow at 9:30am* if you are interested!
Thank you!

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Tingjun Chen, Jelena Diakonikolas, Javad Ghaderi, and Gil Zussman, “Hybrid Scheduling in Heterogeneous Half- and Full-Duplex Wireless Networks”.

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