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Hybrid Scheduling in Heterogeneous Half Duplex and Full Duplex Wireless Networks

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ABSTRACT

Full-duplex (FD) wireless is an attractive communication paradigm with high potential for improving network capacity and reducing delay in wireless networks. Despite significant progress on the physical layer development, the challenges associated with developing medium access control (MAC) protocols for heterogeneous networks composed of both legacy half-duplex (HD) and emerging FD devices have not been fully addressed. Therefore, we focus on the design and performance evaluation of scheduling algorithms for infrastructure based heterogeneous networks (composed of HD and FD users). We develop the hybrid Greedy Maximal Scheduling (H-GMS) algorithm, which is tailored to the special characteristics of such heterogeneous networks and combines both centralized GMS and decentralized Q-CSMA mechanisms. Moreover, we prove that H-GMS is throughput-optimal. We then demonstrate by simple examples the benefits of adding FD nodes to a network. Finally, we evaluate the performance of H-GMS and its variants in terms of throughput, delay, and fairness between FD and HD users via extensive simulations. We show that in heterogeneous HDFD networks, H-GMS achieves 5–10× better delay performance and improves fairness between HD and FD users by up to 50% compared with the fully decentralized Q-CSMA algorithm. Index Terms—Full- duplex wireless, scheduling, distributed throughput maximization

1-INTRODUCTION

The proliferation of wireless devices is at an unprecedented level. Whether it is our mobile phones, laptops, or any other smart device, the need for better, faster, and reliable wireless connectivity is more pressing than ever before. With close to 13 billion mobile devices, along an estimated 77 exabytes of monthly mobile traffic by the year 2022, the technology is barely able to keep up. For users, the failure of the infrastructure to keep abreast with the demand results in lost connectivity on a mobile device, or a weak signal in a crowded area. Symptoms of the problems that face wireless transmissions.

The troubles for wireless communications only increase once you consider the necessity for bidirectional communications. Any wireless device needs to transmit and receive in order to function properly. This is known as duplexing. Nonetheless, if two communicating wireless devices were to use the same radio resource at the same time to communicate, the generated interference would make it impossible for any signal to be properly received. As a result, two major mechanisms currently exist to allow duplexing.

1. Time Division Duplexing or TDD, consists of separating the transmitted and received signals in the time domain. The latter is broken down into transmission time intervals (TTIs), and the two communicating devices take turns transmitting and receiving. With the devices not transmitting at the same time, naturally no interference would be

generated. Technologies such as DECT and IEEE 802.116 WiMax implement TDD.

2. Frequency Division Duplexing or FDD, means that the nodes at either side of a communication link will use different frequencies to send and receive data. This will prevent the signals from interfering upon each other, even if the two devices are transmitting at the same time. Cellular systems such as GSM, CDMA2000, and WiMax as well implement FDD.In a TDD transmission, a wireless node is–at a certain instant in time–either transmitting or receiving.

2-HALF & FULL-DUPLEXWIRELESS NETWORKS

In this chapter, we give a general overview of where the state-of-the-art is at for half/full-duplex wireless communications. We classify the latter into three categories. The first deals with the development and progress of self-interference cancellation (SIC) techniques. It was essential for these technologies to be well established before researchers went any further with their work on full-duplex technologies. The second category encompasses early works in the domain which sought either to suggest different possible full-duplex scenarios, or merely to validate that gains could be extracted from full-duplex communications. The third category in the state-of-the-art, to which our work practically belongs, builds on the previous two to propose and simulate scheduling and power allocation algorithms for full-duplex wireless networks.

Self-Interference Cancellation Technologies

It was important for SIC technologies to be well developed and tested before any other work was done on full-duplex wireless. After all, the development of these technologies is what made half/full-duplex wireless communications feasible in the first place.

The authors in were among the first to discuss the direct impacts of developed SIC techniques on full-duplex communications. They state that these technologies invalidate long-held assumptions regarding wireless network design, and they overview what would be required of interference cancellation techniques in order to propel full- duplex wireless communications into reality. In one of the earliest works on in-band full-duplex for wireless networks, the authors in survey a range of SIC techniques and touch on the main chal- lenges facing full-duplex wireless networks. The articles in and aimed to evaluate the performance of self-interference in the context of full-duplex wireless communications. The authors in conclude that the SIC performance increases as the signal bandwidth decreases, while those in focus on the impact of amplitude and phase errors on the efficiency of interference cancellation technologies.

In the context of this dissertation, we are mostly concerned by the level of SIC provided by the current technology. In one of the most important papers in the domain of interference cancellation techniques, Bharadia et all. (2013) demonstrate that 110 dB of self- interference can be canceled at a transmitter of 25 dBm power. We consider this to be a benchmark for our work, although it is safe to assume that the technology has evolved far beyond this mark.

Half & Full-Duplex Wireless Networks

After a consensus was reached on the viability of SIC techniques and on the role that these technologies could play in making half & full-duplex communications feasible, research in the domain pivoted towards exploring what full-duplex wireless networks would look like, and whether impediments other than self-interference would hinder extracting gains from full-duplex wireless communications.

The works revolve around assessing the possible gains of full-duplex wireless networks. Their authors study different implementations of full-duplex

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systems alongside the limitations and obstacles facing them.

Aiming towards full-duplex inclusion in upcoming 5G 1 protocols, the authors in propose a full-duplex module with which they simulate two types of full-duplex networks: one where only the base station (BS) is full-duplex capable, and the other where both the user equipment (UEs) and the BS are full-duplex capable. Their aim was to assess the performance of full-duplex wireless communications in ultra-dense small cells. They conclude that more gains can be extracted when all the nodes in the network are full-duplex capable.

In, different scenarios and implementations of possible full-duplex wireless networks are discussed. Mainly, the authors present four representative scenarios: full- duplex MIMO networks, full-duplex cooperative networks, full-duplex OFDMA cellular networks, and full-duplex heterogeneous networks. The authors use resource management problems for the purpose of validating wireless full-duplex communications.

With a more practical approach, the papers in introduce more realistic models for full-duplex transmissions. In, the authors put forward a compact full-duplex receiver.

With it at hand, they demonstrate via numerical evaluations the capacity gains of full- duplex communications, and they bring insights onto the impact of SIC techniques on the performance of full-duplex wireless networks. In [25], the authors present a single- channel full-duplex receiver with tunable self-interference canceling capability.

Scheduling and Power Allocation

With SIC technologies now well established in the state-of-the-art, and with full- duplex technologies well motivated, it was only a matter of time before researchers in the wireless domain moved towards devising scheduling and power allocation algorithms for full-duplex wireless networks. Radio resource management has always been the pillar for any trans-mission technology. For full-duplex wireless networks specifically, there was more at stake. Scheduling and power allocation in this context is not only about better management of the radio resources, but also about mitigating full-duplex interferences. Without proper scheduling–capable of fighting off the effects on intra-cell co-channel interference–full- duplex communications would not be viable.

In a joint user selection and rate allocation algorithm is proposed. It is formulated as a nonlinear non-convex problem with mixed discrete and continuous optimization. The authors note that finding a global optimum through an exhaustive search method is computationally difficult, thus a suboptimal method is considered. The article concludes that full-duplex networks have the potential to significantly increase the capacity of small cells under the presence of efficient SIC.

The authors in propose an optimization problem with the purpose of allocating resources in what is described as a three-node system. The scenario implemented exhibits a full-duplex BS and half-duplex UEs which are paired on the radio resources. Constraints are added on the minimum SINR value for a UE to be allocated resources, and on the UE, transmission powers as well. The problem thus belongs to the category of mixed integer nonlinear programming with high complexity and computational intractability. A sub-optimal heuristic is introduced as a result.

Many other articles we covered in the state-of-the-art had similar approaches. The authors in all put forward joint power and resource allocation schemes. They propose optimization problems with greedy objectives focused on sum-rate maximization. The joint task of power allocation makes all these optimization problems of the category mixed integer nonlinear programming with high complexity and computational intractability. As such, the authors work on heuristic solutions which can produce near optimal performances, but bear less complexity.

3-EXISTING SYSTEM

Network Model

The network model introduced in this chapter is the same one used for the remainder of this dissertation up until the multi-cell scenarios discussed in Chapter 7. It is comprised of a full-duplex base station (BS), and half-duplex user equipment (UEs). The main intent is to keep the costs and complexities of implementing self- interference cancellation (SIC) away from the UEs. The size, battery, and cost limitations of UEs make them imperfect recipients of SIC technologies.

Radio Model

We consider a single-cell full-duplex wireless network. This network is comprised of a full-duplex BS, and half-duplex UEs. The scheduling algorithms would pair between uplink and downlink UEs on the resource blocks (RBs) k of the set K, whereon one UE will transmit and the other will receive.

Channel State Information

Legacy half-duplex networks are concerned mainly with the channel in between the BS and the UEs. They would rely on feedback from the latter to determine the current channel state on the downlink. The channel state information (CSI) would be estimated at the receiver, quantized, and then fed back to the transmitter. A popular approach in estimating the CSI is by using a training (pilot) sequence, where a known signal is transmitted, and the channel matrix **H** is afterwards estimated using the combined knowledge of the transmitted and received signals

Hybrid Scheduling Model

This model is similar in form to the full-duplex model. All the variables are binary, and the constraints are linear, and dependent of the binary variables. The problem is thus also of type ILP and therefore NP-Complete. Containing more variables and more constraints, this problem would take slightly more time to solve than the previous one.

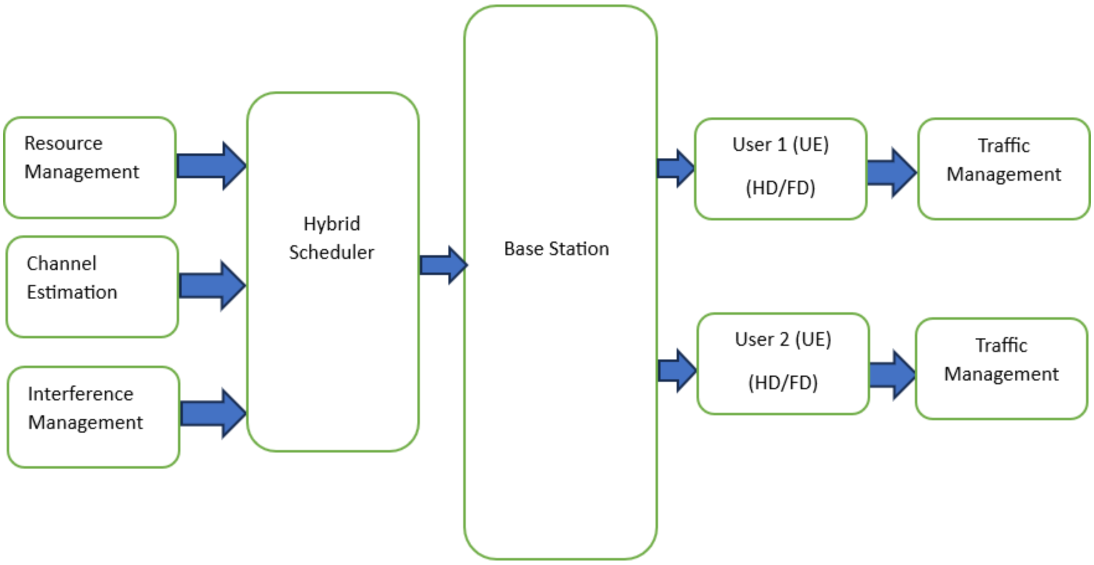
The complexity of the optimization problem, which can become prohibitive for an increased number of resources and UEs, motivates a heuristic approach. In the following section, we provide heuristic algorithms with the same objectives as the optimization problems, albeit bearing less complexity.

Proposed System:

We introduce a mathematical optimal algorithm for scheduling in full-duplex and hybrid full-duplex/half-duplex wireless networks. Our generic optimization problem is queue-aware and addresses the new challenges that arise from working with full-duplex wireless networks: self-interference and intra-cell co-channel interference. We apply this optimization with different scheduling objectives, tackling issues such as SINR maximization and user fairness. Accordingly, we first propose an optimal full-duplex Max-SINR scheduling algorithm and an optimal full-duplex Proportional Fair scheduling algorithm. Additionally, and since full-duplex communications may not always be profitable, we introduce an optimal hybrid Max-SINR scheduling algorithm and an optimal hybrid Proportional Fair scheduling algorithm. These algorithms switch between full-duplex and half-duplex transmissions, so as to enhance network performance. Moreover, to avoid possible intractability with the optimization problems, we propose heuristic versions of our algorithms. We assess the performance of our heuristic proposals in multiple challenging scheduling scenarios and show that they achieve near-optimal results.

Block Diagram

Block Diagram of proposed system



4-SCHEDULING & POWER ALLOCATION

In the previous chapter, we presented our approach to scheduling in full-duplex wireless networks in the presence of complete channel state information (CSI). Nonetheless, there is still no evident manner in which full-duplex networks can achieve this state of completeness. After all, no existing wireless network protocols count for estimating inter-user channels or for how such channel information could be relayed back to the base station (BS). In order to properly schedule and distribute resources among pairs of uplink-downlink user equipment (UEs), the network needs exact information on the channels between all the UEs, in addition to all the traditional half- duplex UE-to-BS channels.

The Effect of Incomplete Channel State Information

The state of a wireless channel is determined by the combined effect of several factors, the most pertinent of which, are the path loss, the shadowing, and the fast fading. Knowledge of the channel on a certain wireless link permits adapting the transmission to the communication channel. This is essential in achieving reliable communications, and for making efficient resource allocation decisions. Consequently, precisely estimating inter-UE channels might not be feasible. As we previously indicated, we statistically model the inter-UE channel as follows:

hij,k = GtGrLpAsAf ,

where Gt and Gr are the antenna gains at the transmitter and the receiver, respectively. Lp represents the path loss, or equivalently the mean attenuation the signal undergoes in this channel. As and Af are two random variables that respectively represent the shadowing effect, and the fast-fading effect.

Effect of Incomplete CSI on Greedy Maximal

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Scheduling Allocation

In this section, we study the effect of incomplete CSI on UE throughput in the case of greedy resource allocation. Note that under our simulation parameters of 50 resource blocks and 20 UEs, the system is considered to be under heavy load conditions. Figure 4.1 is a CDF plot of the throughput attained by the UEs across the different simulation scenarios. The lack of any information on the inter-UE channels incurs the most degradation in performance.

In the first part of this chapter, we studied the effects of incomplete CSI on scheduling in full-duplex wireless networks. We showed that significant losses in performance were to be expected when inter-UE CSI is not present at the scheduler. Furthermore, the losses incurred are likely to massively increase in the cases of low SIC or when UEs are situated farther away from the BS. In our work, we sought an alternative for knowing the exact states of the inter-UE channels.

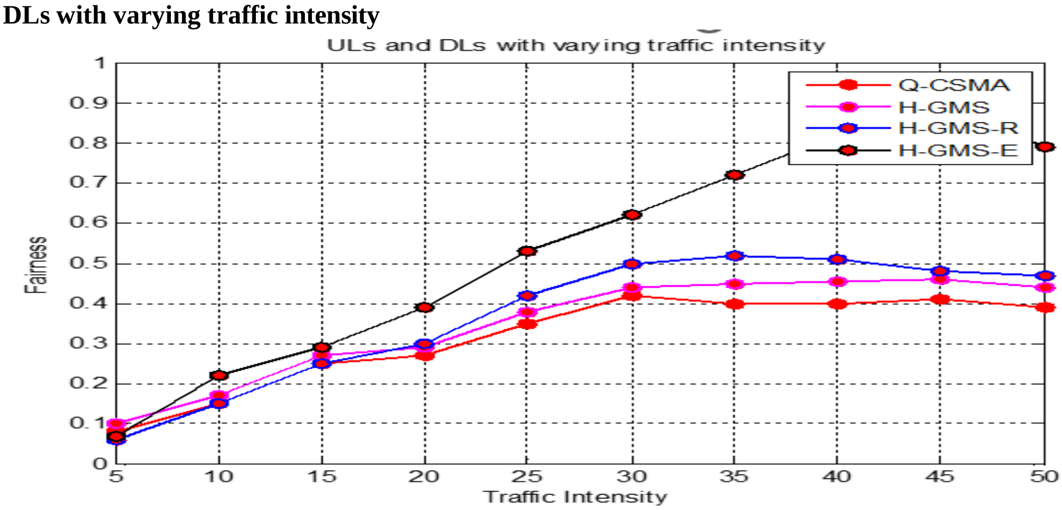
The Reinforcement Learning Problem

In this section, we briefly explain the general reinforcement learning problem. Reinforcement learning is the idea of learning from interaction to achieve a goal [59]. The learner i.e, the decision maker in such a problem, is known as the agent. Everything else interacting with this agent is known as the environment. The environment and the agent interact at a sequence of discrete time steps, t = 0,1,2,3,. At a moment in time t, the environment is in a state St.The agent takes an action At from the set of actions available in the current state A(St). As a consequence of the selected action, the agent will receive a reward Rt+1, and subsequently, it will find itself in a new state St+1. This agent-environment interaction model

5-RESULT

Phase I

UL & DLs with varying traffic intensity



1.-UL & DLs with varying traffic intensity

Above graph evaluates and compares the fairness performance of four scheduling algorithms: Q-CSMA, H-GMS, H-GMS-R, and H-GMS-E under varying traffic intensity levels. The X-axis shows the

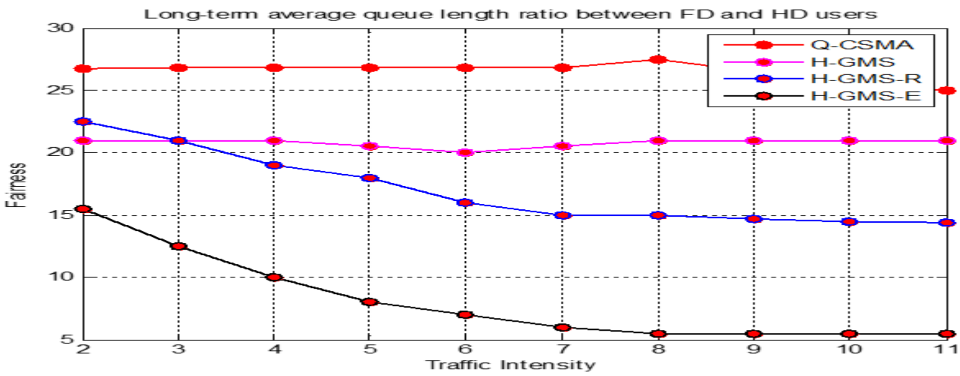
Traffic Intensity ranging from 5 to 50, while the Y-axis indicates the corresponding Fairness values.

As traffic intensity increases, all algorithms initially show an improvement in fairness. However, the rate and extent of this improvement vary by algorithm. H-GMS-E, represented by the black line with diamond markers, consistently achieves the highest fairness across all levels of traffic intensity. This indicates its superior ability to allocate resources more evenly in congested networks. H-GMS-R follows next in performance, while H-GMS and Q-CSMA lag slightly behind.

Between traffic intensity levels 25 to 50, the differences become more pronounced, with H-GMS-E maintaining a steady upward trend. This suggests that enhanced hybrid scheduling mechanisms are more effective in handling high-load scenarios in mixed

duplex environments. The plot validates the design goal of improving fairness in heterogeneous wireless systems through better scheduling strategies.

Long term average queue length ratio b/w FD & HD users



2-Long term average queue length ratio b/w FD & HD users

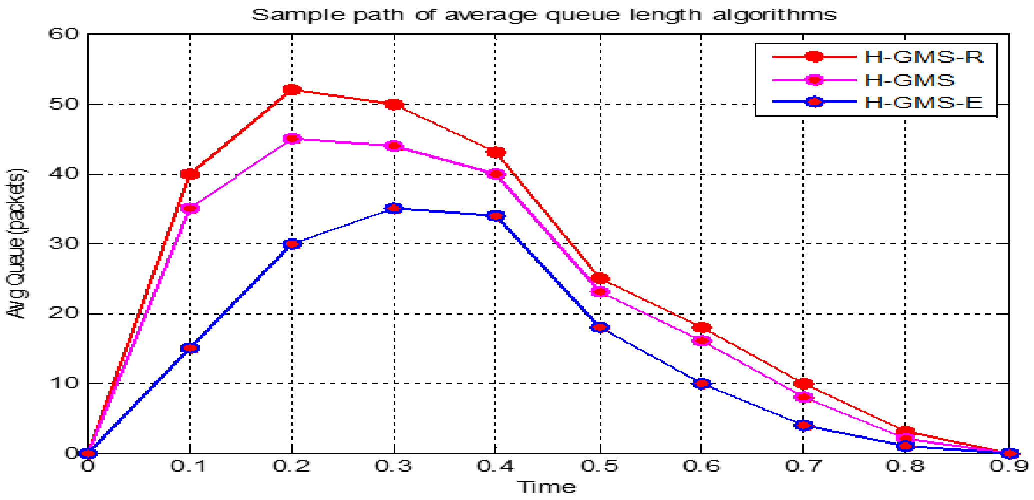
It depicts the long-term average queue length ratio between Full Duplex (FD) and Half Duplex (HD) users under different traffic intensities. The X-axis represents Traffic Intensity (ranging from 2 to 11), while the Y-axis shows the Fairness, interpreted here as the queue length ratio—lower values indicating better fairness between FD and HD users.

Four scheduling algorithms are compared: Q-CSMA, H-GMS, H-GMS-R, and H- GMS-E. Q-CSMA, marked in red, maintains a high and nearly constant queue length ratio, showing least fairness toward HD users. H-GMS performs slightly better but still favors FD users. H-GMS-R shows improvement in fairness with reduced queue length ratio as traffic intensity increases.

Most notably, H-GMS-E, indicated by the black line with red circles, demonstrates the best fairness, rapidly decreasing the FD-to-HD queue ratio and stabilizing around a low value. This implies that H-GMS-E effectively balances traffic between FD and HD users. The results validate that enhanced hybrid scheduling significantly improves equity in resource allocation under growing traffic demands.

Phase II

Sample path of average queue length algorithms



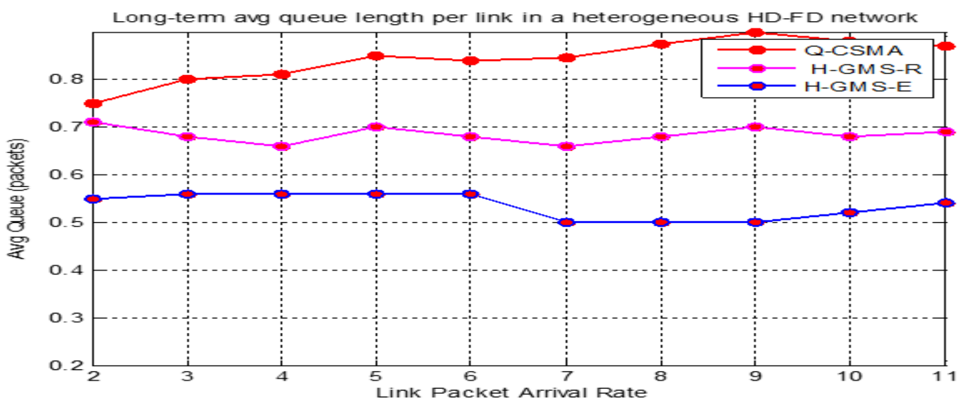
Sample path of average queue length algorithms

It shows the sample path of average queue length over time for three scheduling algorithms: H-GMS, H-GMS-R, and H-GMS-E. The X-axis represents Time, while the Y-axis indicates Average Queue Length in packets.

At the start, all algorithms begin with an average queue length near zero, which increases as the traffic builds up. H-GMS-R (red line) shows the highest peak queue length (above 50 packets), followed by H-GMS (magenta line), indicating relatively slower queue management. H-GMS-E (blue line) consistently maintains lower queue lengths throughout the observed period.

After reaching the peak (around time 0.2 to 0.3), all algorithms show a decline in queue length, representing traffic being cleared. However, H-GMS-E clears the queue more rapidly, reaching near-zero levels before others. This demonstrates that H-GMS-E provides more efficient and stable queue management under dynamic traffic conditions.

The graph supports the conclusion that enhanced hybrid scheduling improves
responsiveness and throughput, offering a better balance of network load.



Long-term avg queue length per link in a heterogeneous HD-FD n/w

It represents the long-term average queue length per link in a network consisting of both Half Duplex (HD) and Full Duplex (FD) users. The X-axis denotes the Link Packet Arrival Rate, while the Y-axis indicates the Average Queue Length in packets. The graph compares three scheduling algorithms: Q-CSMA, H-GMS-R, and H-

GMS-E. Q-CSMA (red line) consistently results in the highest average queue length, indicating poorer performance in handling packet arrivals. H-GMS-R (magenta line) shows moderate improvement, maintaining queue lengths below Q-CSMA.

In contrast, H-GMS-E (blue line) outperforms both by achieving the lowest and most stable queue lengths across all arrival rates. Even as the arrival rate increases, H- GMS-E maintains its efficiency, highlighting its robustness under load. This suggests better throughput and delay performance.

The consistent performance of H-GMS-E affirms its effectiveness in managing congestion in heterogeneous HD-FD environments. Overall, this graph supports the conclusion that enhanced hybrid scheduling offers superior queue stability and traffic handling efficiency.

The series of graphs from both Phase 1 and Phase 2 of the project reveal important insights into the comparative performance of various scheduling algorithms—namely Q-CSMA, H-GMS, H-GMS-R, and H-GMS-E. In terms of fairness, H-GMS-E consistently delivers the highest fairness scores as traffic intensity increases, ensuring a balanced allocation of resources between Half Duplex (HD) and Full Duplex (FD) users. The ratio of FD to HD queue lengths is significantly lower for H-GMS-E, suggesting that it effectively minimizes scheduling bias. While Q-CSMA and standard H-GMS exhibit limited fairness and higher disparity in performance, H- GMS-R shows moderate improvement but still falls short of the enhanced version. These findings highlight the superiority of H-GMS-E in maintaining equity and performance stability across different network conditions.

In Phase 2, the emphasis shifts to queue length dynamics and system responsiveness. H-GMS-E achieves faster reductions in average queue length compared to other algorithms, indicating more efficient traffic handling and lower latency. It also demonstrates superior stability across increasing packet arrival rates, maintaining the lowest long-term average queue lengths per link. In contrast, Q-CSMA shows high and growing queue lengths under load, while H-GMS-R struggles with consistency. The graphs collectively establish that H-GMS-E not only improves fairness but also enhances throughput, reduces delay, and ensures reliable performance under varying network loads. These results validate

6-CONCLUSION

This project has presented an in-depth exploration into the design, implementation, and analysis of a hybrid scheduling algorithm, H-GMS, tailored for heterogeneous Half-Duplex (HD) and Full-Duplex (FD) wireless networks. H-GMS has been developed to be distributed at the user level while leveraging different degrees of centralization at the Access Point (AP). The dual advantage of achieving strong delay performance and provable throughput-optimality underlines its practical viability and theoretical robustness.

Our work also established fundamental lower bounds on average queue lengths, which served as critical metrics to evaluate the delay performance of the proposed H- GMS algorithm. Through extensive simulations, the algorithm's effectiveness has been validated, particularly when compared to classical Q-CSMA scheduling protocols. These simulations highlight not only the efficiency of H-GMS but also its fairness and adaptability in mixed HD-FD network environments.

Incorporating FD users into legacy HD networks revealed additional complexities but also opened new avenues for improved network performance. We observed that careful scheduling could significantly mitigate self-interference and hidden terminal problems. For instance, FD access points contribute to alleviating the hidden terminal issue, a common pitfall in traditional Wi-Fi networks, by enabling nodes to receive real-time transmission information from the AP, thereby reducing packet collisions and improving overall throughput by substantial margins (up to 110% as reported).

Furthermore, the algorithm's flexibility allows it to adapt to real-world imperfections like non-ideal Self-Interference Cancellation (SIC), which is a crucial consideration for practical deployment. We have also laid foundational work for implementing H-GMS in actual wireless testbeds, thereby bridging the gap between theoretical constructs and hardware-level applicability.

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