Reconfiguration Delay based Network Scheduling for Time Varying Channels

Vanjiangi Jyotsna Devi¹, Jhansi Rani Singothu²
¹,² Computer Science and Technology Engineering Department,
¹,² Andhra University College of Engineering, Visakhapatnam, Andhra Pradesh., India.

Abstract:
We consider the optimal control problem for networks subjected to time-varying channels, reconfiguration delays, and interference constraints. We show that the simultaneous presence of time-varying channels and reconfiguration delays significantly reduces the system stability region and changes the structure of optimal policies. We first consider memory less channel processes and characterize the stability region in closed form. We prove that a frame-based Max-Weight scheduling algorithm that sets frame durations dynamically, as a function of the current queue lengths and average channel gains, is throughput-optimal. Next, we consider arbitrary Markov-modulated channel processes and show that memory in the channel processes can be exploited to improve the stability region. We develop a novel approach to characterizing the stability region of such systems using state-action frequencies, which are stationary solutions to a Markov Decision Process (MDP) formulation. Moreover, we develop a dynamic control policy using the state-action frequencies and variable frames whose lengths are functions of queue sizes and show that it is throughput-optimal. The frame-based dynamic control (FBDC) policy is applicable to a broad class of network control systems, with or without reconfiguration delays, and provides a new framework for developing throughput-optimal network control policies using state-action frequencies. Finally, we propose Myopic policies that are easy to implement and have better delay properties as compared to the FBDC policy.

Key words: Markov decision process, queueing, reconfiguration delay, scheduling, switching delay, time-varying channels.

INTRODUCTION
Scheduling in wireless networks subject to interference constraints has been studied extensively over the past two decades. However, to the best of our knowledge, the effects of reconfiguration delays have not been considered in the context of networks subject to interference constraints and time-varying channel conditions. Reconfiguration delay is a widespread phenomenon that is observed in many practical telecommunication systems. In satellite networks where multiple mechanically steered antennas are providing service to ground stations, the time to switch from one station to another can be around 10ms. Similarly, in optical communication systems, laser tuning delay for transceivers and optical switching delay can take significant time ranging from microseconds to tens of milliseconds depending on technology. In wireless networks, delays for electronic beam forming or channel switching that occurs in phased-lock loops in oscillators can be more than 200. Worse yet, such small delay is often impossible to achieve due to delays incurred during different processing tasks such as channel estimation, signal-to-interference ratio, transmit diversity and power control calculations in the physical layer and stopping and restarting the interrupt service routines of various drivers in upper layers. Moreover, in various real-time implementations, channel switching delays from a few hundreds of microseconds to a few milliseconds have been observed. We consider an optimal control problem for single-hop networks given by a graph structure of nodes and links, subject to reconfiguration delays, time-varying channels, and arbitrary interference constraints.

Fig. 1. System model. A single-hop wireless network with interference constraints, time-varying channels, and reconfiguration delays.
channels, and arbitrary interference constraints. For the time-varying channel states, we consider both independent and identically distributed (i.i.d.) or Markov modulated processes for which the structure of the stability region and the optimal policies differ significantly. Our system model can be used to abstract single-hop wireless networks as shown in Fig. 1, satellite networks with multiple satellite servers and ground stations as shown in Fig. 2, and optical switched networks [8], [34]. The network controller is to dynamically decide to stay with the current schedule of activations or to reconfigure to another schedule based on the channel process and the queue length information, where each decision to reconfigure leaves the network idle for an arbitrary but finite amount of time, corresponding to the reconfiguration delay. Note that in many networks, some nodes in the network may continue to function, while others are being reconfigured. Hence, assuming that all links are idle during network reconfiguration is a pessimistic assumption that may hold in some systems, such as optical switches, satellite transmitters, etc. However, in other cases, this assumption may be restrictive and provides a lower bound on performance. Our goal is to study the impact of reconfiguration delays on system stability and optimal algorithms. We show that, as compared to systems without reconfiguration delays, the stability region can be significantly reduced, and that optimal policies take on a different structure.

We first consider the case of memoryless (i.i.d.) channel processes where we characterize the stability region in closed form as the convex hull of feasible activation vectors weighted by the average channel gain of each link. This result shows that in the presence of reconfiguration delays, it is not possible to opportunistically take advantage of the diversity in time-varying channels because the i.i.d. channel processes refresh during each reconfiguration interval. Moreover, we show that a class of Variable-size Frame-based Max-Weight (VFMW) algorithms that make scheduling decisions based on time-average channel gains and queue lengths stabilize the system by keeping the current schedule over a frame of duration that is a function of the queue lengths. Next, we consider Markov modulated channel processes with memory and develop a novel methodology to characterize the stability region of the system using state-action frequencies, the steady-state solutions to a Markov Decision Process (MDP) formulation for the corresponding saturated system. We show that the stability region enlarges with the memory in the channel processes, which is in contrast to the case of no reconfiguration delays [17], [30], [40]. Furthermore, we develop a novel frame based dynamic control (FBDC) policy based on the state-action frequencies that achieves the full stability region. To our knowledge, this is the first throughout-optimal scheduling algorithm for reconfigured. Hence, assuming that all links are idle during network reconfiguration is a pessimistic assumption that may hold in some systems, such as optical switches, satellite transmitters, etc. However, in other cases, this assumption may be restrictive and provides a lower bound on performance. Our goal is to study the impact of reconfiguration delays on system stability and optimal algorithms. We show that, as compared to systems without reconfiguration delays [30], [31], [39], [40], the stability region can be significantly reduced, and that optimal policies take on a different structure. We first consider the case of memoryless (i.i.d.) channel processes where we characterize the stability region in closed form as the convex hull of feasible activation vectors weighted by the average channel gain of each link. This result shows that in the presence of reconfiguration delays, it is not possible to opportunistically take advantage of the diversity in time-varying channels because the i.i.d. channel processes refresh during each reconfiguration interval. Moreover, we show that a class of Variable-size Frame-based Max-Weight (VFMW) algorithms that make scheduling decisions based on time-average channel gains and queue lengths stabilize the system by keeping the current schedule over a frame of duration that is a function of the queue lengths. Next, we consider Markov modulated channel processes with memory and develop a novel methodology to characterize the stability region of the system using state-action frequencies, the steady-state solutions to a Markov Decision Process (MDP) formulation for the corresponding saturated system. We show that the stability region enlarges with the memory in the channel processes, which is in contrast to the case of no reconfiguration delays [17], [30], [40]. Furthermore, we develop a novel frame based dynamic control (FBDC) policy based on the state-action frequencies that achieves the full stability region. To our knowledge, this is the first throughout-optimal scheduling algorithm for
wireless networks with time-varying channels and reconiguration delays. The state-action frequency approach and the FBDC policy are applicable to many network control systems as they provide a general framework that reduces stability region characterization and throughput-optimal algorithm development to solving linear programs (LPs). Finally, we consider Myopic policies that do not require the solution of an LP. Simulation results in Section IV-D suggest that the Myopic policies may in fact achieve the full stability region while providing better delay performance than the FBDC policy for most arrival rates. Scheduling in communication networks has been a very active research topic over the past two decades (e.g., [13], [15], [17]). In the seminal paper [39], Tassiulas and Ephremides characterized the stability region of wireless networks and proposed the throughput-optimal Max-Weight scheduling algorithm. The same authors considered a parallel queuing system with randomly varying connectivity in [40], where they characterized the stability region of the system explicitly and proved the throughput-optimality of the Longest-Connected-Queue scheduling policy. Later, these results were extended to joint power allocation and routing in wireless networks in and optimal scheduling for switches and Suboptimal distributed scheduling algorithms with throughput guarantees have been studied more recently in [10], [22]and while [15] developed distributed algorithms that achieve throughput optimality (for a detailed review, see [17]). Networks with delayed channel state information were considered in [21], [35] and [45], which showed that the stability region is reduced and that a policy similar to the Max-Weight algorithm is throughput-optimal. Dynamic server allocation over parallel queues with time-varying channels and limited channel sensing was considered in [1]. These papers studied saturated system models, and the optimality of myopic policies was established for a single server and two channels in [47], for arbitrary number of channels in [1], and for arbitrary number of channels and servers in [2]. Switching delay has been considered in Polling models in the Queuing Theory literature for single-server systems (e.g., [4] and [43]). However, time-varying channels were not considered since they do not typically arise in classical Polling applications. A detailed survey of the works in this field can be found. Scheduling in optical or manufacturing networks under reconiguration delay was considered in [8], [9], [14], and again in the absence of time-varying channels. In [13], we considered a simple queuing system of two queues and a single-server subject to ON/OFF channels and a single-slot switchover delay, where we developed the state-action frequency approach and the throughput optimality of a frame-based policy. Here, we generalize this model to arbitrary single-hop networks. The main contribution of this paper is in solving the scheduling problem in single-hop networks under arbitrary reconiguration delays, time-varying channels, and interference constraints for the first time. We introduce the system model in detail in Section II. For systems with memory less channel processes, we characterize the stability region and propose the class of throughput-optimal VFMW policies in Section III. We develop the state-action frequency approach and characterize the stability region for systems with Markov modulated channels in Section IV-A. We develop the throughput-optimal FBDC policy in Section IV-B and present simulation results in Section IV-D.

II. MODEL

Consider a single-hop wireless network given by a graph structure of nodes and links, where Data packets arriving at each link are to be transmitted to their single-hop destinations, where we refer to the packets waiting for service at link as queue. We consider

![Markov modulated ON/OFF channel process](image)

Fig. 3. Markov modulated ON/OFF channel process. The case of \( P_{10} + P_{01} \leq 1 \) provides positive correlation.

We consider Markov modulated channel processes with memory and develop a novel methodology to characterize the stability region of the system using state-action frequencies, the steady-state solutions to a Markov Decision Process (MDP) formulation for the corresponding saturated system. We show that the stability region enlarges with the memory in the channel processes, which is in contrast to the case of no reconiguration delays. Furthermore, we develop a novel frame based dynamic control (FBDC) policy based on the state-action frequencies that achieves the full stability region. To our knowledge, this is the first throughout-optimal scheduling algorithm for wireless networks with time-varying channels and reconiguration delays. The state-action frequency approach and the FBDC policy are applicable to many network control systems as they provide a general framework that reduces stability region characterization and throughput-optimal algorithm development to solving linear programs (LPs). Finally, we consider Myopic policies that do not require the solution of an LP. Simulation results in Section IV-D suggest that the Myopic policies may in fact achieve the full stability region while providing better delay performance than the FBDC policy for most arrival rates.

**Advantages:**

1. Stabilize the network using markov chain efficient decisions.
2. Achieve greater throughput.
3. Reduces delays time.

**CHANNELS WITH MEMORY**

In this section we establish the stability region of the
system and propose a throughput-optimal dynamic control policy when the time-varying channels have memory. We generalize the novel framework of characterizing the stability region in terms of state-action frequencies that we introduced in [8] to wireless networks with reconfiguration delays, time-varying channels, and interference constraints. The state-action frequency approach is a general and unifying framework in that, for the simpler case of no-reconfiguration delay in the system, it provides the stability region characterizations of classical network control papers such as [18]. We show that the stability region expands with memory in the channel processes, in particular, it lies between the stability region for the case of i.i.d. channels and the stability region for the case of no reconfiguration delay. For classical network control systems such as [18], [19], [24], the memory in the channel processes does not affect the stability region [12]. Therefore, scheduling under reconfiguration delays and time varying channels calls for new control algorithms that can improve their performance with increases in channel memory.

CONCLUSION AND FUTURE ENHANCEMENTS

We investigated the optimal scheduling problem for systems with reconfiguration delays, time-varying channels, and interference constraints. We characterized the system in closed form for the case of i.i.d. channel processes and proved that a variable-size frame-based Max-Weight algorithm that makes scheduling decisions based on the queue lengths and the average channel gains is throughput-optimal. For the case of Markovian channels with memory, we characterized the system stability region using state-action frequencies that are stationary solutions to an MDP formulation.

REFERENCES

VANJANGI JYOTSNA DEVI is currently pursuing her 2 years of M.Tech in Computer Science and Systems Engineering, College of Engineering, Andhra University, Visakhapatnam, AP, India. Her area of interests includes Networks.

JHANSI RANI SINGOTHU was working as a Asst. Professor, in Computer Science and Systems Engineering, College of Engineering, Andhra University, Visakhapatnam, AP, India. Her research interest includes Image Processing.